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Report on the Use of Raw or Processed Natural Pozzolans in Concrete

Reported by ACI Committee 232

American Concrete Institute®
Report on the Use of Raw or Processed Natural Pozzolans in Concrete

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This report reviews the use of raw or processed natural pozzolans in concrete and provides an overview of the properties of natural pozzolans and their use in the production of hydraulic-cement concrete. Long before the invention of portland cement, natural pozzolans mixed with lime were used to strengthen concrete and mortar. Today, they can be used to enhance the properties of fresh and hardened concrete and may provide economic value in some cases.

Keywords: alkali-silica reaction; diatomaceous earth; lime; pozzolan; pozzolanic activity; strength; sulfate attack.

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CHAPTER 1—INTRODUCTION AND SCOPE

1.1—Introduction

Pozzolans are made up of siliceous or siliceous and alumi-
nous materials that, in finely divided form, will react with
calcium hydroxide to form cementitious materials. The term
“pozzolan” evolved from the name given to a deposit of
volcanic material located near Pozzuoli, Italy. This deposit,
originally referred to as pozzolana, consisted of pumice ash,
or tuff, comprised of trachyte found near Naples and Segni,
Italy. Trachyte is a volcanic rock comprised primarily of
feldspar crystals in a matrix of siliceous glass. Pozzolana
was formed from an explosive volcanic eruption in 79 AD
at Mount Vesuvius, which engulfed Herculaneum, Pompeii,
and other towns along the bay of Naples. Chapter 3 provides
historical information about the use of pozzolans.

The term “natural pozzolan” encompasses a broad range
of materials. A few of these materials are pozzolanic in their
natural state. However, most of the materials considered
natural pozzolans require some type of processing to render
the material pozzolanic. Some may require only drying and
grinding/classifying, while others may require heat treat-
ment and grinding to adequately activate the pozzolanic
nature of the material. Chapter 4 provides a brief descrip-
tion of the various materials classified as natural pozzolans,
which are the focus of this report.

1.2—Scope

This report contains information and recommendations
concerning the selection and use of natural pozzolans
generally conforming to the requirements of ASTM C618-
08. Topics covered include the effect of natural pozzolans
on concrete properties, a discussion of quality control and
quality assurance practices, and guidance regarding handling
and use of natural pozzolans in specific applications.

CHAPTER 2—DEFINITIONS

ACI provides a comprehensive list of definitions through
an online resource, “ACI Concrete Terminology,” http://
terminology.concrete.org.

CHAPTER 3—HISTORICAL USE OF NATURAL
POZZOLANS

3.1—Ancient history

Many people associate the use of quarried building stones
with the construction of structures by the Greeks, Romans,
and other similar ancient civilizations. Concretes and
mortars using various cementitious binders, however, were
likewise used to some extent during these ancient times.
These cementitious binders contained pozzolans of a natural
origin, such as volcanic ash, pulverized pumice, and diato-
maceous earth. When these pozzolans were combined with
burned limestone and mixed with water, the combination
would form a cementitious material. Therefore, pozzolans
have been used in mortar and concrete for several millennia.
prior to the invention of the portland cement we know today, which was first patented in 1824 (Kosmatka and Wilson 2011). Chapter 3 reviews examples of the important role that natural pozzolans have played in the development of mortars and concrete that has led to the development of today’s mortars and concretes.

In ancient times, construction throughout the world used mortar and concrete mixtures consisting of fillers and raw, or heat-treated, lime (Malinowski 1991). One of the oldest examples of a hydraulic binder dates back to approximately 5000 BC. The mixture consisted of lime and diatomaceous earth from the Persian Gulf (Malinowski and Frifelt 1993). The next-oldest reported use was in the Mediterranean region. This pozzolan was produced from the volcanic ash of two volcanic eruptions. The first eruption was recorded sometime between 1600 and 1500 BC on the Aegean Island of Thera—now Santorin, Greece—and the second was recorded in 79 AD at Mt. Vesuvius on the bay of Naples, Italy. Both materials are volcanic ashes or pumicites consisting of approximately 80 percent volcanic glass (pumice and obsidian).

Another example is an ancient water-storage tank with a holding capacity of 785 yd$^3$ (600 m$^3$) that was discovered during archaeological excavations in the 1970s at the ancient city of Camiros on the Island of Rhodes, Greece. This structure, which was built in approximately 600 BC, was used until 300 BC when a new hydraulic system with an underground water tank was constructed. This water tank has remained in very good condition for almost three millennia (Efstathiadis 1978). Examination of the materials used for this structure revealed that the concrete blocks and mortar used were made out of a mixture of lime, Santorin earth, fine sand (less than 0.08 in. [2 mm]), and siliceous aggregates with sizes ranging between 0.08 and 0.79 in. (2 and 20 mm). Blocks were cast by placing the fresh concrete into wooden sidewall molds. Tests on a 0.79 in. (20 mm) cubic specimen extracted from the structure found the compressive strength to be 1740 psi (12 MPa). Mortars like these were known to have a composition of six parts by volume of Santorin earth, two parts by volume of lime, and one part by volume of fine sand. These mortars were used as the first hydraulic cements in aqueducts, bridges, sewers, and structures of all kinds. Some structures are still standing along the coasts of Italy, Greece, France, Spain, and in harbors of the Mediterranean Sea.

Vitruvius, a Roman engineer who lived in first-century BC, wrote in The Ten Books On Architecture that the cements made by the Greeks and the Romans were of superior durability because “neither waves could break, nor water dissolve” the concrete (Vitruvius 1960; Morgan 1914). In describing the building techniques of masonry construction, Vitruvius indicated that the Romans developed superior practices of their own from the techniques of the Etruscans and the Greeks. The Greek masons, who discovered pozzolan-lime mixtures sometime between 700 and 600 BC, later passed their knowledge of concrete to the Romans in 150 BC. During the 600 years of their domination, the Romans discovered and developed a variety of pozzolans throughout their empire (Kirby et al. 1956).

The Greeks and Romans built many such structures over 2000 years ago. Examples are the Roman aqueducts, sea walls, and marine structures on the islands of the Aegean Sea; in Syros, Piraeus, Nauplion, and other cities; the harbors of Alexandria in Egypt; Fiume, Pola, Spalato, and Zara on the Adriatic Sea; and Constanta (Romania) on the Black Sea. All provide evidence of the durability of pozzolan-lime mortar under conditions of mild weathering exposure.

Roman monuments in many parts of Europe are in use today, standing as a tribute to the performance of pozzolan-lime mortars (Lea 1971). Perhaps one of the most notable buildings of the Roman era is the Pantheon in Rome. Constructed in approximately 125 AD, the Pantheon is still standing and in use today. As reported by Lea (1971), the 20 ft (6.4 m) thick walls are constructed of a tuff and pozzolana concrete. The dome, which spans 142 ft (43.3 m), is constructed of cast concrete that contains pumice and pozzolana, making it possibly the oldest known use of lightweight concrete.

3.2—Modern history

The advent of portland cement, which was developed and patented by Joseph Aspdin in 1824 (Kosmatka and Wilson 2011), did not preclude the use of natural pozzolans. Pozzolans remained an integral part of concrete technology in the years following the invention of modern-day portland cement. Structures such as the Suez Canal in Egypt built in 1860, and the Corinthian Canal built in 1880 to connect northern and southern Greece, used concrete containing natural pozzolans. Natural pozzolan technology continued to evolve throughout the first half of the twentieth century.

The use of natural pozzolans in concrete was investigated in the United States as early as 1908 by Bates et al. (1912). Continuing work demonstrated that concretes containing pozzolanic materials exhibited certain desirable properties such as lower cost, lower temperature rise, improved workability, improved sulfate resistance, and resistance to alkalisisica reactions (Price 1975; Meissner 1950; Mielenz et al. 1950; Davis 1950).

The Los Angeles aqueduct constructed from 1910 to 1912 is an example of the first large-scale use of portland-pozzolan cement that was composed of equal parts of portland cement and a rhyolitic pumicite (Price 1975). In the 1920s and 1930s, natural pozzolans were used as a mineral admixture in concrete for the construction of dams and other structures then being constructed by the Los Angeles County Flood Control District. The California Division of Highways used specially made portland-pozzolan cement in several structures because of its proven resistance to sulfate attack from seawater and its lower heat of hydration (Davis 1950).

According to Mielenz et al. (1950), the United States Bureau of Reclamation (USBR) began an intensive study in 1933 to determine the effect of natural pozzolans on the heat of hydration of concrete and to identify other benefits suitable for mass concrete applications, such as large dams. In these studies, more than 200 prospective natural pozzo-
lans were evaluated. The results revealed the positive effect of calcination of natural pozzolans on their properties and performance in concrete. Properties reported were:
(a) Mineralogical and chemical composition
(b) Pozzolanic activity, water requirement, and strength
(c) Control of expansion from alkali-silica reactivity

Mielenz et al. (1950) concluded that calcination of clay minerals was essential to develop satisfactory pozzolanic activity, and the response to heat treatment varied with the type of clay minerals present.

There were some sources of natural pozzolan located in the United States, mainly west of the Mississippi River, that did not require calcining to make them active (Price 1975). Many natural pozzolans were usable in their raw state. If moist, they usually required drying and grinding before use. The best natural pozzolans owed their activity to volcanic glass with a SiO₂ content of 70 to 73 percent, of which 40 to 100 percent of the SiO₂ was in the form of rhyolitic glass.

Studies of natural pozzolans by the USBR in the 1930s and 1940s encouraged their use for controlling heat of hydration and alkali-silica reaction (ASR) of concrete in large dams. Generally, the pozzolanic deposit was in the vicinity of the particular project and the amount required was sufficient to support mining and processing costs. The deposit was usually abandoned at completion of the project.

Siliceous shales of the Monterey Formation in Southern California have been produced commercially and used extensively in the surrounding areas. A portland-pozzolan cement containing 25 percent interground calcined Monterey shale was produced during the 1930s and 1940s (Meissner 1950). The California Division of Highways used this cement in the 1930s in several structures, including the Golden Gate Bridge and the San Francisco-Oakland Bay Bridge. Another portland-pozzolan cement containing 25 percent interground calcined pozzolan was used in 1935 for the construction of the Bonneville Dam Spillway on the lower Columbia River.

From 1940 to 1942, the USBR built the Friant Dam on the San Joaquin River in California with a portland cement-pozzolan combination. The pozzolan was a naturally fine rhyolite pumiceite, which was batched separately in the concrete mixer at the rate of 20 percent by mass of cement. This pozzolan was obtained from a deposit along the San Joaquin River near Friant.

Stanton (1917) described the Cretaceous volcanic ash bed on the Great Plains near Linton, ND. At one exposure, 1 mile (1.6 km) southeast of Linton, the thickness of the white bed is 26 ft (8 m) and the rock is very fine-grained and mostly massive, although it contains some thin-bedded layers. A sample examined by G. F. Loughlin (Manz 1961) consisted of 80 percent volcanic glass, 15 percent quartz and feldspar, and 2 to 3 percent biotite. The Linton area ash bed is generally overlain by sand and underlain by shale. Contamination of the ash by this adjacent material is detrimental. If the ash is carefully mined, with no contamination of sand or shale, the volcanic ash need only be dried at 212°F (100°C) and finely ground to comply with ASTM C618-08. Tests were performed in 1961 (Manz 1961) on composite samples of volcanic ash from the Linton deposit. The samples were first crushed and ground in a ball mill and then calcined in an electric kiln for different times and temperatures. Separate samples were calcined as follows: 15 minutes at 1000°F (538°C) and 15 minutes at 1400°F (760°C), as well as 1 hour at 1400°F (760°C) and 1 hour at 1700°F (927°C). All samples were then reground prior to testing. The results of the heat treatments are shown in Tables 3.2a and 3.2b and the results are compared to those of samples that had been ground but not calcined. Based on these tests, the volcanic ash in the uncalcined state complied with most of the ASTM requirements and the performance was improved when calcined at a temperature above 1400°F (760°C).

During the 1960s and early 1970s, a natural pozzolan was used in nearly all of the concrete in the California State Water Project at the rate of 70 lb/yc (42 kg/m³), including the lining of the California Aqueduct (Tuthill 1967; Tuthill and Adams 1972). This was the most extensive use of a natural pozzolan in a project in U.S. history. The performance of this pozzolan exceeded the requirements of ASTM C618-08.

Large deposits of diatomite were discovered decades ago in the coastal ranges of central California and the peninsular ranges of Southern California. The largest reserves of freshwater diatomite are in the northeastern counties of Shasta, Siskiyou, Modoc, and Lassen (Burnett 1991). In 1993, a study was undertaken to appraise a lacustrine deposit located approximately 30 miles (48.3 km) north of Reno, NV, as a source of a natural pozzolan. The deposit is an intermingling of diatomaceous earth and dacite pumicite that was calcined and ground before use in concrete. During the period of 1970 to 1989, this natural pozzolan was used in concrete for the construction of structures, bridges, roadways, the Trans-Canada Highway, the Auburn Dam, and the Los Melones Dam and Power Plant. It was also used in research projects by the California Department of Transportation from January 1987 to August 1991.

An accounting of the history and background on mineral admixtures, along with the use of natural pozzolans (raw and calcined), is provided by Mielenz (1983). The experiences in the use of large quantities of fly ash and natural pozzolans in the western United States by the USBR are reported by Elfert (1974). Table 3.2c lists the types of mineral admixtures used in the construction of some concrete dams built from 1915 to 1964.

High-reactivity metakaolin (HRM) has been known as a pozzolanic material for many decades; however, HRM use in concrete did not receive much attention until the mid-1980s. In the United Kingdom, large-scale trials have been conducted using HRM concretes subjected to aggressive environments (Ashbridge et al. 1996). Their research shows excellent strength development, reduced permeability, and increased chemical resistance. In addition, strength, pozzolanic activity, and cement hydration characteristics have been studied in superplasticized metakaolin concrete (Wild et al. 1996).

In the United States, HRM has been evaluated as a pozzolan in various research studies and in the field. In one air-entrained high-performance concrete mixture, the metakaolin-containing concrete provided increased strength
and reduced chloride-ion penetration compared with the portland cement control design. Likewise, the HRM concrete maintained good workability and had an air-void system that produced good resistance to cycles of freezing and thawing and to deicer scaling (Caldarone et al. 1994). Benefits of using HRM in ternary systems with ground slag cement and fly ash have also been reported (Caldarone and Gruber 1995a,b). From 1962 to 1972, approximately 227,300 tons (250,000 metric tons) of calcined kaolinitic clay were used in the construction of four hydroelectric dams in Brazil (Saad et al. 1982). Kaolin clay from Brazil has been used since 1965 as an ingredient in concrete in the construction of large dams at a cost of approximately one-third that of portland cement (Saad et al. 1982). This natural pozzolan is produced by calcining kaolin clay and grinding it to a Blaine fineness of 700 to 900 m²/kg. Because of this high fineness and activity, HRM can be used for cement replacement up to 50 percent by volume, with a 90-day compressive strength similar to concrete made with portland cement. At Jupia Dam, the use of this natural pozzolan, at 20 to 30 percent of the volume of cement, resulted in lower temperature rise, improved cohesiveness, and reduction of expansion from ASR (Andriolo 1975). When first used for general concrete construction, the natural pozzolan replaced 30 percent of the portland cement by volume and, when used for structural concrete construction, the rate of replacement was 20 percent. The use of this high-reactivity natural pozzolan in mass concrete construction provided substantial improvements to the concrete properties (Saad et al. 1982).

Calcined kaolinitic clay (with a metakaolin content in the range of 85 to 90 percent) has been extensively used in the midwestern United States since 1993 in the construction of highway pavements, bridge decks, and parking structures. Calcined kaolinitic clay is used specifically to provide for ASR mitigation or impart low permeability, or both, to the concrete (Barger et al. 1997). This material was commer-

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**Table 3.2a—Cretaceous volcanic ash from North Dakota calcined for 15 minutes (Manz 1961)**

<table>
<thead>
<tr>
<th>Testing parameters</th>
<th>Samples</th>
<th>ASTM C618-08</th>
</tr>
</thead>
<tbody>
<tr>
<td>Processing temperature</td>
<td>212°F (100°C)</td>
<td>1000°F (538°C)</td>
</tr>
<tr>
<td>Specific gravity</td>
<td>2.26</td>
<td>—</td>
</tr>
<tr>
<td>Blaine fineness, m²/kg</td>
<td>977</td>
<td>—</td>
</tr>
<tr>
<td>Mean particle diameter, µm</td>
<td>2.7</td>
<td>—</td>
</tr>
<tr>
<td>Amount retained on 45 µm (No. 325) sieve, percent</td>
<td>7.9</td>
<td>—</td>
</tr>
<tr>
<td>Strength activity index: with lime at 7 days, psi (MPa), 2 x 4 in. (50 x 100 mm) cylinders</td>
<td>611 (4.2)</td>
<td>685 (4.7)</td>
</tr>
<tr>
<td>Strength activity index: with lime at 7 days, psi (MPa), 2 in. (50 mm) cubes</td>
<td>670 (4.6)</td>
<td>—</td>
</tr>
<tr>
<td>Strength activity index: with portland cement, at 28 days, percent of control</td>
<td>64</td>
<td>—</td>
</tr>
<tr>
<td>Water requirement, percent of control</td>
<td>107</td>
<td>—</td>
</tr>
<tr>
<td>Soundness: autoclave expansion or contraction, percent</td>
<td>0.32</td>
<td>—</td>
</tr>
<tr>
<td>Increase of drying shrinkage of mortar bars at 28 days, difference, in percent over control</td>
<td>—</td>
<td>—</td>
</tr>
</tbody>
</table>

Notes: Conducted by the Northwest Laboratories, Seattle, WA, in 1960. These tests were performed on composite samples of volcanic ash from 20 test holes. The portions from each test hole were taken from 1 to 23 ft and 23 to 30 ft (0.3 to 7 m and 7 to 9 m) levels. The material was crushed, ground in a ball mill, and calcined at 1000°F (538 and 760°C) for 15 minutes and then reground before testing.

**Table 3.2b—Test results of North Dakota volcanic ash calcined for 1 hour (Manz 1961)**

<table>
<thead>
<tr>
<th>Testing parameters</th>
<th>Samples</th>
<th>Specification</th>
</tr>
</thead>
<tbody>
<tr>
<td>Processed calcinations temperature</td>
<td>212°F (100°C)</td>
<td>1400°F (760°C)</td>
</tr>
<tr>
<td>Specific gravity</td>
<td>2.37</td>
<td>2.50</td>
</tr>
<tr>
<td>Amount retained on No. 325 sieve (45 µm), percent</td>
<td>2.9</td>
<td>3.2</td>
</tr>
<tr>
<td>Strength activity index: with lime at 7 days, psi (MPa), 2 x 4 in. (50 x 100 mm) cylinders</td>
<td>952 (6.6)</td>
<td>1385 (9.5)</td>
</tr>
<tr>
<td>Strength activity index: with portland cement, at 28 days, percent of control</td>
<td>118</td>
<td>111</td>
</tr>
<tr>
<td>Water requirement, percent over control</td>
<td>110</td>
<td>112</td>
</tr>
<tr>
<td>Color of sample</td>
<td>Light gray</td>
<td>Light buff</td>
</tr>
</tbody>
</table>

Notes: The materials tested were ground with a muller. Calcining was conducted at 1400 and 1700°F (760 and 927°C) for a period of 1 hour and then reground before testing.
4.1—Calcined clay
Calcined clay is a naturally occurring raw material comprised essentially of aluminosilicate minerals. Examples of clay are kaolinite, dickite, halloysite, and illite. The purity of these naturally occurring deposits can vary from relatively pure mineral types (98 percent) to mixtures of multiple mineral types. Because clays are, by definition, very fine-grained materials, they are easily quarried and stockpiled. Stockpiles of kaolinite clay compacted fines often weather and dry and return to the uncompacted state and, therefore, require little or no additional deagglomeration.

The calcining of clay to remove bound water, or dehydroxylation, is typically done in rotary kilns or flash calciners where the clays are heated to a temperature adequate to decompose the clay's crystal structure and render it amorphous. For kaolinite clays, this temperature is usually approximately 1020 to 1380°F (550 to 750°C). Other clay types may require different thermal activation temperatures to optimize the material's pozzolanic reactivity. This process is easily monitored by X-ray diffraction.

Depending on the purity of the clay material, the calcined clay may result in one or more phases present (amorphous and crystalline). Calcined clays have been used as manufactured pozzolans in concrete for many years. In the midwestern United States, calcined kaolinite clays have been documented in the literature (Barger et al. 1997) as containing a mixture of approximately 85 to 90 percent metakaolin, 5 to 10 percent quartz, and residual thermally treated mixed clays of illite and montmorillonite or smectite. Higher purity calcined clays (greater than 95 percent metakaolin), specifically kaolinite, are discussed in 4.4 on metakaolin.

4.2—Calcined shale
The raw material is shale or slate, which consists largely of aluminosilicate clay minerals. In addition, there may be varying amounts of calcite (limestone), quartz, feldspar, and mica. The shale or slate is quarried by conventional means, crushed to a maximum size of 1.5 in. (38 mm), and then calcined (heat-treated) in a rotary kiln. Calcining temperatures vary depending on the source, but are typically in the range of 1800 to 2000°F (980 to 1090°C) with a residence time in the kiln of approximately 45 minutes. This results in a clinker ranging in size from 0.25 to 2 in. (6 to 51 mm) that is air-quenched at the discharge of the kiln. The finished product is achieved by grinding the clinker in a ball mill to a high Blaine fineness of 600 to 800 m²/kg. This will result in a finely divided powder with a median particle size on the order of 5 microns, similar in fineness to Type III portland cement. Calcined shale may have a typical elemental analysis of 50 percent silica, 20 percent alumina, 8 percent iron, and 8 percent calcium.

The aluminosilicate clay minerals, derived from the shale or slate, provide the necessary elements needed for a pozzolanic reaction. Heat treatment alters the crystalline structure of the aluminosilica clay minerals, making them capable of participating in a pozzolanic reaction. The amorphous (noncrystalline) phases of the calcined shale will range from...
50 to 75 percent, depending on the particular source and heat-treating process.

The loss on ignition (LOI) of calcined shale may range from 1 to 5 percent. The LOI of calcined shale is not related to the presence of carbon, as is the case with fly ash. The LOI of fly ash is due to the presence of residual carbon particles from the coal combustion process and this carbon can have adverse effects on air entrainment in concrete. The LOI of calcined shale is due to the presence of both residual water molecules bound in the clay mineral structure and residual uncalcined calcite. Therefore, the LOI of calcined shale does not have any adverse effect on air entrainment in concrete.

Reported cases of calcined shale being used as a pozzolan date back to as early as 1932. Calcined shale has been commercially available in the Mid-Atlantic and midwestern United States since the mid-1990s (Neal and Ramsburg 2002).

4.3—Diatomaceous earth

Diatomaceous earth is composed of the siliceous skeletal remains of microscopic aquatic plants called diatoms. The silica is present as an amorphous hydrous silica termed opal. Diatomite is diatomaceous earth sufficiently pure to be mined and occurs as a fine, granular, lightweight, porous aggregate with an appearance similar to chalk. Diatomite is also known as kieselgur in Germany and tripolite in Libya. Tripolite should not be confused with the sedimentary rock tripoli, which is a residual silica resulting from the weathering of chert or siliceous limestone that is generally not opaline. Moler is a diatomaceous earth from Denmark containing volcanic ash and up to 30 percent smectite clay (Christensen et al. 2001). Most diatomite deposits commercially mined in the United States, which are highly pure, are found in California, Nevada, Oregon, and Washington (Founie 2006).

All diatomite has pozzolanic reactivity to varying degrees. Diatomite is a highly reactive pozzolan due to its high content of amorphous silica and its high specific surface area. It has a specific surface area approximately 10 times higher than that of portland cement. Lacustrine, or freshwater deposits of diatomite, appear to have higher pozzolanic reactivity. Diatomite can be calcined and finely ground to achieve optimum pozzolanic reactivity and performance characteristics. The temperature of calcination should be below 1650°F (900°C) to avoid loss of opal through cristobalite crystallization (Christensen et al. 2001).

4.4—Metakaolin

Metakaolin (\(4Al_2O_3·2SiO_2\)) is a natural pozzolan produced by heat treating kaolinite clays. Kaolinite has a chemical composition of \(Al_2O_3·2SiO_2·2H_2O\). When it is heat treated, in the temperature range of approximately 1100 to 1650°F (600 to 900°C), the chemically combined water is driven away to form an amorphous aluminosilicate called metakaolin. The calcination temperature will depend on the characteristics of the parent kaolin clay, such as degree of crystallinity and particle size. At higher temperatures, it will recrystallize, resulting in the formation of mullite (\(Al_6Si_2O_{13}\)) or spinel (\(MgAl_2O_4\)) and amorphous silica (Murat et al. 1985) that will reduce its pozzolanic reactivity. The reactivity of metakaolin is dependent upon the amount of kaolinite contained in the original clay material. The average particle size of metakaolin varies and can be controlled during processing to change its properties. Metakaolin is typically white in color, has a mean particle size in the range of 2 to 10 µm, and has a bulk density in the range of 18 to 40 lb/ft³ (290 to 640 kg/m³).

High-reactivity metakaolin (HRM), as described in AASHTO M321-04, is derived from highly refined kaolinite clay that has been processed to remove impurities prior to calcination. The resulting product has a very high content of silica and alumina (greater than 90 percent). The kaolin used to produce HRM is selectively mined to achieve a desired particle size distribution, morphology, and chemical composition. The crude kaolin is dispersed into a slurry and processed, generally by centrifuge, to remove impurities and produce the desired particle size distribution. Additional processing may include magnetic separation and chemical bleaching. The refined slurry is then spray-dried and calcined at an optimal temperature to achieve the desired level of pozzolanic activity.

Although the use of metakaolin as a pozzolanic mineral admixture has been known for many years, its use has grown rapidly since the mid-1980s. In the United States, metakaolin and HRM are primarily manufactured from deposits of kaolin found in Georgia.

4.5—Opaline shales

Opaline shales are described as cherts, shales, and clays containing substantial quantities of opaline silica and sometimes nearly pure opal (Davis 1950). Opal is a hydrous silica formed both as a low-temperature mineral in sedimentary rocks and as skeletal material by organisms like diatoms and sponges. Opal is composed of spherical silica particles and is largely amorphous. When present in coarse aggregates, opal can lead to deleterious expansion in concrete from an alkali-silica reaction (ASR) between the reactive opal and cement alkalies. When present in a fine particle size <250 µm, however, it is a highly active pozzolan-like glass (Shayan and Xu 2004). Because clay minerals present in shales have to be thermally treated to be activated, opaline shales will generally be activated by calcining. In the United States, opaline shales are found principally in states west of the Mississippi River. The Monterey Formation of California is an example of opaline shale.

Gaize is a pozzolan found in France that is not of volcanic origin but is a porous sedimentary rock consisting mainly of opal. The presence of opal is from organisms like sponges, which build siliceous skeletons. Opal is found in the Ardennes and Meuse Valleys in France and is still used in that region. The material is usually calcined at temperatures of approximately 1620°F (900°C) before it is used as a pozzolan or as a component of portland-pozzolan cement.

4.6—Volcanic materials

The earliest pozzolans used were of volcanic origin. These materials formed as a result of volcanic eruptions. Depending
on their composition, mechanism of formation, or alterations over time, the volcanic materials may be classified or identified by different names. Often, a specific material may be named after the geographic area from which it comes. Other classifications may be more general in nature, related to the material’s composition or alterations. Sections 4.6.1 through 4.6.6 provide a description and brief discussion related to the more commonly known volcanic materials.

4.6.1 Pumice, pumicite—During an explosive eruption, volcanic gases dissolve in the liquid portion of magma and expand rapidly to create a foam or froth. Once above ground, the liquid part of the froth quickly solidifies to form glass. Pumice is actually a kind of glass and not a mixture of minerals. It is colorless or light gray and has the general appearance of rock froth. The viscosity of the lava, the quantity of water vapor and gas, and the rate of cooling together determine the fineness of the vesicular substance. Large amounts of gas result in a finer-grained disaggregated variety known as pumicite. The chemical composition is that of rhyolite and granite. Figure 4.6.1 shows the scanning electron microscope (SEM) micrograph of a pumice sample from Guatemala before grinding (Day and Shi 1995). The honeycomb-like structure can be observed with the help of SEM under low magnification. The channels inside the pumice range up to 100 μm in diameter with the majority being less than 20 μm after grinding. Very small, irregular particles without pores form, while some big particles with pores are still observed. Because pumice consists mainly of vitreous phase, ground pumicite can be a good pozzolanic material (Day and Shi 1995).

One of the main uses for pumice and pumicite is lightweight aggregate for concrete blocks and assorted building products. Other major applications include abrasives, absorbents, and filter aids. In 2000, the total consumption of pumice and pumicite in the United States for these other uses was 769,000 tons (697,000 metric tons) (Bolen 2000).

4.6.2 Trass—Trass is a natural pozzolan of volcanic origin (Lovewell 1971) that has been well known since ancient Roman times. The material is a trachytic tuff that differs from place to place. One source is found in the Valley of the Rhine River in Germany. Similar tuffs have been used in Bavaria. Generally, the only processing required is to grind the materials to a sufficient fineness.

Rhenish and Bavarian trass, composed primarily of volcanic tuff, is a highly pozzolanic material in an untreated state that can become less reactive if heated. Tuffs containing clay (smectite) and zeolite (phillipsite) can be activated by calcining to 1470°F (800°C) (Liebig and Althaus 1998). In a study of uncalcined Turkish trass composed of rhyolitic to rhyodacitic tuff altered to produce varying amounts of zeolites, the compressive strength of mortars was strongly correlated with the zeolite content. The selective ion-exchange or adsorption properties of the microporous crystalline structure of the zeolite (heulandite-clinothilitolite) or both the ion-exchange and adsorption properties, was found to be more important than glass content for pozzolanic activity (Esenli 1995).

4.6.3 Santorin earth—Santorin earth is produced from a natural deposit of volcanic ash of dacitic composition on the island of Thera in the Agean Sea, also known as Santorini. This deposit was formed from approximately 1600 to 1500 BC from a tremendous explosive volcanic eruption (Marnatos 1972).

4.6.4 Tuff—Tuff is a rock composed of greater than 75 percent volcanic ash. Volcanic tuff is essentially solidified volcanic ash, derived from the smaller particles (less than 0.08 in. [2 mm]) in a volcanic deposition. The mineralogical and pozzolanic properties of tuff are similar to the volcanic ash originally deposited, provided that the volcanic ash has not been altered over time. Tuff consists mainly of various amounts of glass and minerals. Depending on the conditions present after deposition, the glass phase can be transformed into secondary mineral phases due to thermodynamic instability. Volcanic ash altered in a moist, acid environment (coal swamp) will form the kaolinite rich rock tonstein. Alteration of ash in mildly alkaline water (marine) results in the smectite rich rock bentonite. In strongly alkaline or saline lakes, ash is altered to zeolite, sometimes with potassium feldspar (Triplehorn and Bohor 1993; Hay 1986).

4.6.5 Volcanic ash—Volcanic ash is formed during explosive eruptions by violent separation of magma, or molten rock, into tiny pieces called pyroclasts and other associated shattering of solid rocks. Explosive eruptions are generated when magma reaches the surface and the volcanic gases dissolved in the molten rock expand and escape, or explode, into the air rapidly. Explosive eruptions also occur when groundwater is heated by magma and abruptly converted to steam. Volcanic ash is composed of fragments of rock, minerals, and glass that are less than 0.08 in. (2 mm) in diameter (LeMaitre 2002; Williams et al. 1982; Day and Shi 1995; Shi 2001). Figure 4.6.5a shows the particle size distribution of two volcanic ashes from Bolivia and Guatemala. Although these two ashes are from different regions, they
have similar particle size distributions and consist mainly of particles ranging between 20 and 300 μm.

Figure 4.6.5b shows the raw volcanic ash particles from Bolivia before and after grinding. The raw volcanic particles are irregular and pitted. Many tiny particles are stacked in the pits on the surface of pozzolan particles. After grinding, most pits are destroyed and more small, irregular particles are produced. Some pits with tiny particles can still be seen on coarse particles, even after grinding. The pozzolanic reactivity of a volcanic ash depends on its chemical and mineralogical compositions, glass content, and fineness.

4.6.6 Zeolites—Zeolites are hydrated alumino-silicates with symmetrically stacked alumina and silica tetrahedra that result in an open and stable three-dimensional honeycomb framework of consistent diameter interconnecting channels. Natural zeolites are formed from the alteration of volcanic ash in alkaline waters under elevated pressure and then crystallized. They have pozzolanic properties and can be used as a cement replacement (Kasai et al. 1992; Feng 1993; Guo and Liang 1980).

4.7—Other material

4.7.1 Rice husk ash—Rice husk ash (RHA) is produced from rice husks, which are the shells produced during the dehusking operation of rice. Raw rice husks are comprised of approximately 50 percent cellulose, 30 percent lignin, and 20 percent silica. Figures 4.7.1a and 4.7.1b show scanning electron micrographs that illustrate the typical cellular structure of a rice husk. The rice husks are incinerated by controlled combustion to remove the lignin and cellulose, leaving behind an ash composed mostly of silica. Silica retained in the ash is in a noncrystalline form. The ash will represent approximately 20 percent of the mass of the raw rice husks. RHA is highly pozzolanic when produced by controlled combustion under oxidizing conditions at relatively low temperatures and short holding time (Mehta 1992). RHA has a high internal surface area and consists mainly of amorphous silica. Chemical analysis of fully burnt RHA shows that the amorphous silica content ranges between 90 and 96 percent. Depending on the carbon content, RHA can have a range of colors, from nearly white to black. As a highly active pozzolan, it is suitable for making high-quality cement and concrete products. The benefits of using RHA are higher compressive strength, decreased permeability, resistance to sulfate attack, resistance to acid attack, reduction of surface cracking in structures, resistance to chloride-ion penetration, and excellent performance under freezing-and-thawing cycling (Mehta and Folliard 1995; Zhang and Malhotra 1996). To obtain lower-permeability concrete, RHA can be added in amounts of 5 to 15 percent by mass of cement.
CHAPTER 5—REACTION MECHANISMS, CLASSIFICATION, AND COMPOSITION

5.1—General reaction mechanisms

In very simplistic terms, the amorphous or poorly crystallized silica and alumina present in the natural pozzolan will react with calcium hydroxide and alkalies derived from the hydration of portland cement to form calcium silicate hydrate (CSH) and other complex hydration products such as calcium aluminate and calcium alumino-silicate hydrates. When a mixture of portland cement and a natural pozzolan react, the pozzolanic reaction progresses like an acid-base reaction of lime and alkalies from the cement with the oxides of \( \text{SiO}_2 \), \( \text{Al}_2\text{O}_3 \), and \( \text{Fe}_2\text{O}_3 \) found in the pozzolan. In this reaction, two alterations occur in the cementitious paste. First, there is a gradual decrease in the amount of free calcium hydroxide with time (Fig. 5.1a and 5.1b), and second, there is an increase in formation of CSH and calcium alumino-silicates that are similar to the hydration products of portland cement. The result is the hardened cement paste contains less calcium hydroxide, more CSH, and other products of low porosity. Research on the hydration of blended cements made with natural pozzolans of volcanic origin (Santorin earth, pozzolana) indicates that pore refinement resulting from the pozzolanic reaction is important for enhancing chemical durability and mechanical strength (Mehta 1987). According to Lea (1971), the partial replacement of portland cement by pozzolan of high SiO\(_2\)/R\(_2\)O ratio has been found to increase the resistance of concrete to sulfate and seawater attack (R\(_2\)O is approximately the summation of the Al\(_2\)O\(_3\) and Fe\(_2\)O\(_3\) contents). This is, in part, attributable to the removal of free calcium hydroxide (Ca(OH)\(_2\)) formed in the hydration of portland cements. In addition to the consump-
alkalies up in the pozzolan hydration products. This reducing the soluble alkali hydroxides of sodium and potassium, which ties these alkalis up in the pozzolan hydration products. This reducing the soluble alkali hydroxides in the cementitious paste is one of the mechanisms believed to account for the beneficial influence of natural pozzolans on alkali-silica reactions.

5.2—Classification systems

Several systems have been proposed for the classification of natural pozzolans. Some of these systems classify the natural pozzolans based on their chemical or mineralogical composition, while others classify the natural pozzolans based on strength properties of the natural pozzolan when it is reacted with either portland cement or lime. Included are a few examples.

5.2.1 Mehta (1987) classified natural pozzolans into four categories based on the principal lime-reactive constituent present: 1) unaltered volcanic glass; 2) volcanic tuff; 3) calcined clay or shale; and 4) raw or calcined opaline silica. This classification is not readily applicable to pozzolans of volcanic origin (Categories 1 and 2) because volcanic tuffs commonly include both altered and unaltered siliceous glass. These are the sole or primary sources of pozzolanic activity in siliceous glass, opal, zeolites, or clay minerals—the activity of the last two being enhanced by calcination.

5.2.2 Mielenz et al. (1950) classified natural pozzolans into six types according to their mineral composition. This classification system is shown in Table 5.2.2. In this system, the classification of clays (Type 3) was divided into five subtypes based on the different clay minerals.

5.2.3 With respect to the nature of pozzolans, they can be divided into three groups. The first is of a glassy structure such as volcanic ash, pumice, and pumicite; the pozzolanic reactivity of these pozzolans mainly results from the activity of their glassy structure. The second shows an amorphous structure such as silica fume, metakaolin, or RHA. The third consists of those pozzolans possessing a crystalline structure; a typical example is zeolite.

5.2.4 An Indian system uses the strength of lime-pozzolan mortars cured 8 days at 122°F (50°C) as a means of classifying the natural pozzolan according to its strength-producing properties, as shown in Table 5.2.4 (Hammond 1983).

5.3—Chemical and mineralogical composition

The chemical composition of natural pozzolans is dependent on the mineral composition of the raw or processed parent material. Therefore, within the same general class of a natural pozzolan, the chemical composition may differ depending on the source. Tables 5.3a and 5.3b summarize the chemical composition of some common natural pozzolans reported in the literature. Although most natural pozzolans contain substantial amounts of silica, additional elements are present, such as alumina and iron oxide, which also react with calcium hydroxide and alkalis (sodium and potassium) to form complex hydration compounds.

Although the chemical composition of natural pozzolans may vary substantially from one source to another, there is no general relationship between the chemical composition of a natural pozzolan and its pozzolanic reactivity. The mineralogical constituents of natural pozzolans may also vary substantially, ranging from amorphous materials to crystalline compounds. The presence and composition of amorphous compounds account for the pozzolanic reactivity of the material. Generally, amorphous silica reacts with calcium hydroxide and alkalis more rapidly than does silica that is in the crystalline form. The crystalline compounds react with lime either slowly or not at all.

Volcanic glasses and zeolitic tuffs, when mixed with lime, produce calcium silicate hydrates (CSHs), hydrated calcium aluminates, and calcium alumino-silicates. These materials were proven to be good pozzolans long ago. Italian researchers who study volcanic glasses and the relationship to pozzolanic activity believe that reactive glass originated from explosive volcanic eruptions, like the ones from Thera and Mount Vesuvius that produced the natural pozzolans with unaltered alumino-silicate glass as their major component (Malquori 1960). Both are pumicites where one-third is in the amorphous state (glass), making it highly reactive with lime and alkalis at normal temperatures.

Raw or unprocessed natural clays and shales are not pozzolanic, or only weakly so, as raw clay minerals do not react readily with lime. However, if the crystalline structure of the clay minerals is partially or completely destroyed by calcination at temperatures below 2000°F (1093°C), these materials will possess pozzolanic properties. High-purity kaolin may be processed to form HRM.
5.4—Pozzolanic reactivity

Many chemical test methods have been developed to characterize pozzolanic reactivity. These methods are summarized by Shi (2001) and shown in Table 5.4. Measurements of change in either the chemical or electrical properties of the test solutions from the addition of a pozzolan can be a relative indicator of pozzolanic reactivity and, for some pozzolans, may correlate well with physical performance tests.

The performance of a hardened paste depends not only on the rate and degree of reaction but also on the nature of the reaction products formed. Performance standards are now becoming more important due to the diversity of materials and their combinations used to produce satisfactory prod-
ults. In practice, concern is primarily based on performance over individual characteristics of the product (Shi 2001).

Malquori (1960) states that the evaluation of pozzolanic materials added to portland cement should be based on two factors: 1) the mechanical strength of mortars and concretes made with a portland cement-natural pozzolan mixture; and 2) the reduction of free calcium hydroxide in the hardened pozzolanic cement. Takemoto and Uchikawa (1980) also thought that the quality of natural or artificial pozzolanic cements should be evaluated by strength tests. Many standards now use the compressive or tensile strength of mortars. The mortars are prepared with a specified ratio of natural pozzolan to portland cement or natural pozzolan to lime and closely controlled curing conditions.

5.5—Factors affecting pozzolanic reactivity

As discussed previously, the chemical composition of a natural pozzolan does not necessarily have a direct relationship with its reactivity. However, there are factors that have a more direct bearing on the performance of a natural pozzolan, such as mineralogical composition, processing temperature for calcined materials, and specific surface area or fineness.

5.5.1 Glass content—The pozzolanic reactivity of natural pozzolans results from their vitreous or amorphous structure. The structure, morphology, and chemical composition of a glass determine its reactivity. It is the presence and composition of the amorphous compounds that account for the pozzolanic reactivity of the material.

Raverdy et al. (1980) suggested that the consumed lime in lime absorption tests was proportional to the glass content in both artificial and industrial pozzolans. Sersale (1980) found that a vitreous state index, calculated on the basis of the diffused band of diffraction patterns of approximately 4 to 5 Å, appeared to indicate a good correlation with mechanical strength. Other research, however, indicated that no general correlation exists between the strength and the glass content for different pozzolans (Heath and Brandenburg 1953).

### Table 5.3b—Typical chemical and mineralogical analysis of some natural pozzolans (Mehta 1987)

<table>
<thead>
<tr>
<th>Pozzolan</th>
<th>SiO$_2$</th>
<th>Al$_2$O$_3$</th>
<th>Fe$_2$O$_3$</th>
<th>CaO</th>
<th>MgO</th>
<th>Alkalies$^*$</th>
<th>Estimated ignition loss, percent</th>
<th>Noncrystalline matter, percent</th>
<th>Major crystalline minerals</th>
</tr>
</thead>
<tbody>
<tr>
<td>Santorin earth</td>
<td>65.1</td>
<td>14.5</td>
<td>5.5</td>
<td>3.0</td>
<td>1.1</td>
<td>6.5</td>
<td>3.5</td>
<td>65 to 75</td>
<td>Quartz, plagioclase</td>
</tr>
<tr>
<td>Rhenish trass</td>
<td>53.0</td>
<td>16.0</td>
<td>6.0</td>
<td>7.0</td>
<td>3.0</td>
<td>6.0</td>
<td>—</td>
<td>50 to 60</td>
<td>Quartz, feldspar, analcime</td>
</tr>
<tr>
<td>Phonolite</td>
<td>55.7</td>
<td>20.2</td>
<td>2.0</td>
<td>4.2</td>
<td>1.1</td>
<td>10.8</td>
<td>3.6</td>
<td>—</td>
<td>Orthoclase, albite, pyroxene, calcite</td>
</tr>
<tr>
<td>Roman tuff</td>
<td>44.7</td>
<td>18.9</td>
<td>10.1</td>
<td>10.3</td>
<td>4.4</td>
<td>6.7</td>
<td>4.4</td>
<td>—</td>
<td>Herschelite, chabazite, phillipsites</td>
</tr>
<tr>
<td>Neapolitan glass</td>
<td>54.5</td>
<td>18.3</td>
<td>4.0</td>
<td>7.4</td>
<td>1.0</td>
<td>11.0</td>
<td>3.1</td>
<td>50 to 70</td>
<td>Quartz, feldspar</td>
</tr>
<tr>
<td>Opaline shale</td>
<td>65.4</td>
<td>10.1</td>
<td>4.2</td>
<td>4.6</td>
<td>2.7</td>
<td>1.4</td>
<td>6.3</td>
<td>—</td>
<td>—</td>
</tr>
<tr>
<td>Daitomite</td>
<td>86.0</td>
<td>2.3</td>
<td>1.8</td>
<td>—</td>
<td>0.6</td>
<td>0.4</td>
<td>5.2</td>
<td>—</td>
<td>—</td>
</tr>
<tr>
<td>Rhylolite pumicite</td>
<td>65.7</td>
<td>15.9</td>
<td>2.5</td>
<td>3.4</td>
<td>1.3</td>
<td>6.9</td>
<td>3.4</td>
<td>—</td>
<td>—</td>
</tr>
<tr>
<td>Jalisco pumice</td>
<td>68.7</td>
<td>14.8</td>
<td>2.3</td>
<td>—</td>
<td>0.5</td>
<td>9.3</td>
<td>5.6</td>
<td>90</td>
<td>Sanidine</td>
</tr>
</tbody>
</table>

$^*$Percent Na$_2$O + 0.658 percent K$_2$O.

### Table 5.4—Summary of methods for evaluation of pozzolanic reactivity of pozzolans (Shi 2001)

<table>
<thead>
<tr>
<th>Method</th>
<th>Evaluation criteria</th>
</tr>
</thead>
<tbody>
<tr>
<td>Lime absorption</td>
<td>Amount of absorbed lime in a pozzolan/saturated Ca(OH)$_2$ solution at different ages.</td>
</tr>
<tr>
<td>Setting time</td>
<td>Setting time of 1:4 lime-pozzolan pastes by Vicat test.</td>
</tr>
<tr>
<td>Solubility</td>
<td>Change of electrical conductivity in saturated Ca(OH)$_2$ solution or HF (HF + HNO$_3$) solution within certain time after the addition of a pozzolan.</td>
</tr>
<tr>
<td>Mechanical strength</td>
<td>Tensile strength difference of mortars cured at 64 and 122°F (18 and 50°C).</td>
</tr>
<tr>
<td></td>
<td>Strength ratio of portland-pozzolan cement to pure portland-cement mortars.</td>
</tr>
<tr>
<td></td>
<td>Strength of lime-pozzolan mixtures cured under controlled conditions at a specified age.</td>
</tr>
</tbody>
</table>

$^*$R is Al or Fe.
The reactivity of a volcanic glass also depends on the chemical composition of its glass phase. According to Zachariasen (1932), the components of glass can be divided into three groups: 1) network formers; 2) network modifiers; and 3) intermediates. From the bond energies of network formers and network modifiers, it can be anticipated that the more network formers, the less reactive the glass (Shi 2001).

5.5.2 Calcination—Most often, calcination is required to activate the pozzolanic nature of materials such as clay, shale, and slate. The required calcination temperature may be different depending on the mineral composition of the parent material. Research has indicated that the metakaolin produced under heating temperatures of 1110 to 1650°F (600 to 900°C) shows the highest pozzolanic reactivity (Gao et al. 1989). If the calcination temperature of metakaolin is above 1650°F (900°C), crystalline mullite (Al₂SiO₃) or spinel (MgAl₂O₄) and amorphous silica will form and the reactivity of metakaolin decreases.

Shale or slate might require a higher calcination temperature than kaolinitic clays. In commercial applications in the United States, it was found that a calcination temperature in the range of 1950 to 2100°F (1065 to 1150°C) was necessary to achieve optimum pozzolanic reactivity of a shale composed primarily of illite.

Research conducted on the calcination of volcanic ashes found that the density of these materials increased as the calcination temperature increased (Mielenz et al. 1949; Forchielli and Rossi 1976; Costa and Massazza 1977). At the same time, the specific surface area of the materials also changed during calcination, but no general correlation was observed between specific surface area and reactivity. The effect of calcination on the volcanic ashes was found to have two opposite effects:

1. An activation depending on the reactivity of the vitreous, zeolitic, and clay phases.
2. A deactivation depending on the specific surface area and the decrease of soluble fraction, and the increase of crystallinity.

5.5.3 Fineness—The pozzolanic reaction is a dissolution-precipitation process dependent on the dissolution of pozzolans during early stages. An increase in fineness that exposes more surface area of the natural pozzolan may accelerate the early pozzolanic reactions. There are several ways to express the fineness of a material, including particle size distribution, Blaine fineness, and a BET absorption surface area analysis. However, many studies indicate that there is a very good relationship between the strength of pozzolan cement and concrete and the Blaine fineness of the pozzolan. As shown in Fig. 5.5.3, the strength of lime-pozzolan mixtures is linearly proportional to the Blaine fineness of the pozzolan.

Blaine fineness alone may not be an adequate measure of the fineness of a natural pozzolan. It has been found in work with calcined shale that the relatively smooth-vitreous morphology of the particles leads to increased packing in the Blaine apparatus in comparison with portland cement. Although the calcined shale had a Blaine fineness of 750 m²/kg, its particle size distribution was similar to that of Type III portland cement at a Blaine fineness of 500 m²/kg. As a result, the Blaine measurement overestimated the fineness of the calcined shale, making particle size distribution useful in characterizing the fineness of certain natural pozzolans.

5.5.4 Curing temperature—As with most chemical reactions, an increase in temperature is a catalyst to the reaction of both portland cement and a natural pozzolan-portland cement mixture. Because the pozzolanic reactions have higher apparent hydration activation energies, natural pozzolan-portland cement mixtures could be more sensitive to temperature than the hydration of portland cement alone.

5.5.5 Chemical activation—A series of papers was published (Shi 1992, 1996; Day and Shi 2000a,b) on the chemical activation of natural pozzolans. The addition of Na₂SO₄ or CaCl₂ increases the strength of lime-pozzolan pastes significantly. The addition of 4 percent Na₂SO₄ significantly improves the early strength development and increases the rate of strength gain and ultimate strength by 50 to 90 percent. Although the presence of 4 percent CaCl₂·2H₂O is not helpful to the early strength of lime-pozzolan pastes, especially at low temperatures, it greatly improves the ultimate strength by two or more times in comparison to the control pastes. CaSO₄·0.5H₂O improves the strength of lime-pozzolan cement at 28 days. NaCl, at dosages up to 5 percent, does not have an effect on the strength development of hardened lime-pozzolan cement pastes at an age of 180 days. Further results confirmed that the aforementioned findings are applicable for natural pozzolans, fly ashes, and blast-furnace slag. Figure 5.5.5 shows the effect of activators on the strength development of lime-natural-pozzolan pastes at 73°F (23°C). The addition of 4 percent Na₂SO₄ was found to significantly amplify the early strength of the lime-natural-pozzolan pastes. CaCl₂-activated pastes display lower strength than the control pastes during the early ages and then surpass the control and Na₂SO₄ pastes at later ages. The addition of CaCl₂ or Na₂SO₄ can also effectively activate the potential pozzolanic reactivity of metakaolin-based materials (Day and Shi 2000b). The use of these chemical activators change the hydration products and accelerate the pozzolanic reactions, which results in faster strength devel-
CHAPTER 6—EFFECTS OF NATURAL POZZOLANS ON CONCRETE PROPERTIES

6.1—Concrete mixture proportions

The most effective method for evaluating the performance of a concrete containing a natural pozzolan and establishing proper mixture proportions for a specific application is the use of trial batches and a testing program. Any of the conventional methods for proportioning a concrete mixture, like those referred to in ACI 211.1-91, are applicable for establishing trial mixture proportions for concrete containing a natural pozzolan. As with all mixture proportioning techniques, trial batches are required to validate the mixture proportions and make adjustments accordingly.

Because the performance characteristics will vary for different natural pozzolans, the optimum combination of a natural pozzolan and portland cement is determined through a testing program or is based on prior experience. Procedures, like those reported by Lovewell and Hyland (1974), for determining the optimum portland cement and fly ash blends could be useful in establishing an optimum content of portland cement and natural pozzolan. A natural pozzolan should be considered a part of the cementitious material (U.S. Bureau of Reclamation 1975). In most cases, the natural pozzolan is used as a partial replacement for the portland cement, which is based on equal volume or mass replacement. Replacement on an equal mass basis is more common. The density of natural pozzolans is typically less than that of portland cement; when the portland cement replacement is based on an equal mass basis, there is a resulting higher volume of cementitious material. Occasionally, it is advantageous to add a greater mass of natural pozzolan than mass of portland cement replaced to achieve optimum performance. Performance criteria, such as ASR mitigation, sulfate resistance, or temperature rise, could dictate the required minimum quantity of natural pozzolan incorporated as a percent of the total cementitious material. The amount of natural pozzolan required could vary based on the activity of the pozzolan. Some natural pozzolans are used in a range of 15 to 35 percent, based on the mass of the total cementitious material in the concrete. More reactive natural pozzolans can be used in lower concentrations of 5 to 15 percent by mass of total cementitious material.

6.2—Properties of fresh concrete

6.2.1 Water demand—Many natural pozzolans, such as calcined clay and calcined shale, have little or no influence on the water demand of concrete (Kosmatka et al. 2002). Some natural pozzolans, however, could significantly increase the water demand (Mather 1958). The influence on water demand is largely a function of the characteristics of the specific natural pozzolan related to factors such as fineness, particle shape, particle structure (cellular or noncellular), and composition. The effect of a particular natural pozzolan on the mixing water requirement of a given concrete mixture is easily determined by laboratory tests or field experience.

6.2.2 Cohesion and segregation resistance—Most natural pozzolans produce a cohesive concrete mixture that maintains a plastic consistency, improving workability. Improvements to the cohesion of concrete are attributed partly to an increase in the volume of cementitious material in the concrete from natural pozzolans. Several natural pozzolans absorb water from the mixture, holding the water in the system and allowing for improved finishing.

The increased cohesiveness of a mixture made with natural pozzolans allows the concrete to consolidate readily and flow freely under vibration. The increased cohesiveness also helps reduce segregation. Excessive bleeding and segregation can be a problem in concrete when the available concrete aggregates are deficient in finer particle sizes, particularly material passing the No. 200 (75 μm) sieve. The use of a natural pozzolan can reduce bleeding and segregation and increase the strength of concrete by supplying those fines missing from the aggregate (refer to ACI 211.1-91). When an appropriate quantity of natural pozzolan is used to correct such grading deficiencies, the total water content of the concrete required to achieve a given consistency or slump may actually decrease depending on the water demand characteristics of the particular natural pozzolan.

A natural pozzolan whose particles are coarse, irregular shaped, rough textured, or retain a vesicular interconnect pore structure could, however, require an increase in the water content for a given slump of the concrete and contribute to the increased bleeding and segregation of the fresh concrete. These physical characteristics can lead to an increased water demand in concrete and may be improved or corrected by finish grinding the natural pozzolan to a sufficiently high fineness.

6.2.3 Air entrainment—The proportion of air-entraining admixture (AEA) required to achieve the desired air content in concrete may differ considerably among different sources and types of natural pozzolans. Many natural pozzolans will have only a minimal effect on the required AEA dose in concrete, whereas some may require higher dosages of AEA to entrain the desired air content (Lovewell and Hyland 1974). The influence on AEA dose may be a function of both
than one-to-one for the cement replaced. A natural pozzolan on an equal mass basis or at a volumetric amount greater substituting the pozzolanic material for the portland cement may be reduced. However, the strengths can be increased by volume basis, early strengths and even later-age strength activity and is used to replace portland cement on an equal of rich mixtures. If the natural pozzolan is of low chemical definitively low in chemical activity can often increase the strength (Philleo 1986). For the latter reason, materials that are rela-
natural pozzolan, which results in improved particle packing pozzolan can occur due to the physical characteristics of the concrete. Calcined clay and calcined shale have been reported to have little effect on setting time (Kosmatka et al. 2002). Other natural pozzolans may exhibit an increase in the time of set, mostly due to the quantity of portland cement being replaced.

As with all concrete, the setting-time characteristics of concrete containing a natural pozzolan are influenced by ambient and concrete temperature; cement type, source, content, and fineness; water content of the paste; water-soluble alkalies; use and dosages of other admixtures; the amount of portland cement replaced; and the fineness and chemical composition of the natural pozzolan. When these factors are given proper consideration in the concrete mixture proportioning, an acceptable time of setting can usually be obtained. The actual effect of a given natural pozzolan on time of setting may be determined by testing, when a precise determination is needed, or by observation, when a less precise determination is acceptable.

6.3—Properties of hardened concrete

Concrete containing a pozzolan typically provides lower permeability; reduced heat of hydration; reduced alkali-aggregate reactivity; higher strengths at later ages; and increased resistance to attack from sulfates, seawater, or other sources when compared with concrete that does not contain pozzolan (Mather 1958).

6.3.1 Strength—The effect of a natural pozzolan on the compressive strength of concrete is directly dependent on the pozzolanic properties of the particular natural pozzolan and with the characteristics of the concrete mixture in which it is used. The compressive strength development is a function of the chemical interaction between the natural pozzolan and the portland cement during hydration. In addition, increased strength of concrete containing a natural pozzolan can occur due to the physical characteristics of the natural pozzolan, which results in improved particle packing (Philleo 1986). For the latter reason, materials that are relatively low in chemical activity can often increase the strength of lean mixtures even though they may decrease the strength of rich mixtures. If the natural pozzolan is of low chemical activity and is used to replace portland cement on an equal volume basis, early strengths and even later-age strength may be reduced. However, the strengths can be increased by substituting the pozzolanic material for the portland cement on an equal mass basis or at a volumetric amount greater than one-to-one for the cement replaced. A natural pozzolan of high chemical activity, such as metakaolin, may increase both early- and later-age strengths when used on either an equal mass or equal volume replacement basis for the portland cement. Work by Hooton et al. (1997) demonstrates the effect of HRM on compression strength, as shown in Fig. 6.3.1a and 6.3.1b. Zhang and Malhotra (1996) conducted tests on a total of 10 air-entrained concrete mixtures to evaluate the effects of the use of RHA as a cement replacement. Their test results indicate that RHA is pozzolanic and can be used to produce concrete with compressive strengths that equal or exceed the control. Figure 6.3.1c shows the compressive strength development of concrete with different percentages of RHA.

It has been shown in Europe and the United States that blended cements made by intergrinding natural pozzolans with portland cement clinker can improve the strength performance of the blended cement compared with that of portland cement alone. Results from an investigation by Mehta (1981) on the effect of curing time on the compressive strength of ASTM C109/C109M-08 mortar cubes, made with portland-pozzolan cements containing 10, 20, and 30 percent Santorin earth, are shown in Fig. 6.3.1d and 6.3.1e. It is clear from these results that the contribution of the pozzolan to compressive strength development increases as a function of time. At 28 days, the compressive strength of a concrete with 10 percent Santorin earth was higher than that of the reference portland-cement concrete. At 90 days, the concrete that used 10 and 20 percent pozzolan showed compressive strengths higher than that of the reference portland-cement concrete; at 1 year, the concrete that used 30 percent pozzolan had similar strength to that of the reference portland-cement concrete, as shown in Fig. 6.3.1e. Costa and Massazza (1979) reported similar results on the effect of substituting varying proportions of portland cement with an Italian natural pozzolan, as shown in Fig. 6.3.1f.

6.3.2 Sulfate resistance—Use of natural pozzolans with portland cement in concrete generally increases resistance to aggressive attack by seawater and sulfate-bearing soil solu-

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**Fig. 6.2.3—Relationship between requirement of air-entraining admixture and RHA content (Zhang and Malhotra 1996).**
tions. Mather (1982) reported that the sulfate resistance of mortar is highest when a silica fume or a highly siliceous natural pozzolan is used. The relative improvement is greater for concrete with low cement content and with portland cements of higher C$_3$A contents. A proportionate increase in the indicated sulfate resistance may not be seen when a pozzolan is used in conjunction with a Type V portland cement because the expansion may already be low owing to the high sulfate resistance of the Type V portland cement itself. As with all materials, the influence on sulfate resistance of a natural pozzolan should be prequalified by laboratory tests.

ASTM C1012/C1012M-10 is a suitable performance test method developed to evaluate the sulfate resistance performance of mortars made with portland cements; blended cements; and blends of portland cements with fly ash, natural

![Fig. 6.3.1](image_url)

(a) Effect of HRM at 0.4 w/cm on compressive strength of concrete (Hooton et al. 1997); (b) effect of HRM at 0.3 w/cm on compressive strength of concrete (Hooton et al. 1997); (c) development of compressive strength of concrete with different percentages of RHA as cement replacement (w/cm = 0.40) (Zhang and Malhotra 1996); (d) effect of curing time on compressive strength of mortar cubes up to 28 days made with portland-pozzolan cements containing Santorin earth (Mehta 1981); (e) effect of curing time on compressive strength of mortar cubes up to 12 months made with portland-pozzolan cements containing Santorin earth (Mehta 1981); and (f) effect of substituting Italian natural pozzolan for portland cement on compressive strength of ISO mortar (Costa and Massazza 1979).
pozzolans, or slags (Patzias 1987). A series of ASTM C1012/C1012M-10 tests with 20 cements and blends of Type I with Class F fly ash, Santorin earth, and silica fume showed that blended cements containing highly siliceous natural or artificial pozzolans, slag, or silica fume had better sulfate resistance than portland cements (Patzias 1987).

Costa and Massazza (1979) studied the effect of substituting portland cement with 10, 30, and 40 percent of an Italian pozzolan on the expansion of 1:3 mortar prisms stored for more than 5 years in 1 percent MgSO₄ solution, as shown in Fig. 6.3.2. The authors attribute the improved sulfate resistance to the reduced content of calcium hydroxide and to lower permeability of the concretes containing the pozzolan.

6.3.3 Temperature rise—Most natural pozzolans will have a lower heat of hydration than that of portland cement (Kosmatka et al. 2002). Figure 6.3.3a shows the results of the substitution of an Italian natural pozzolan for portland cement on the heat of hydration of the cementitious system (Costa and Massazza 1979). Because the total heat of hydration is reduced with a partial replacement of portland cement with a natural pozzolan, the heat rise in concrete can likewise be reduced. Figure 6.3.3b compares the temperature rise of concretes with a 30 percent substitution of portland cement with either diatomaceous shale or fly ash (Elfert 1974). For these reasons, natural pozzolans have been used as a partial replacement for portland cement in mass concrete to reduce both the temperature rise and maximum temperature in concrete (Saad et al. 1982). However, the reduction in the heat of hydration should be accounted for when concrete is placed under low ambient temperature conditions, as the setting time might be increased and strength gain may be slower.

Some of the more active natural pozzolans, however, such as HRM, may increase the temperature rise in concrete. Figure 6.3.3c shows the autogenous temperature rise of concrete mixtures containing either metakaolin or silica fume as a partial replacement of portland cement by volume. As can be seen, the rate of heat rise and maximum temperature of the concretes containing metakaolin was somewhat higher than that of the control and the concrete containing silica fume (Zhang and Malhotra 1995).

6.3.4 Expansion due to alkali-silica reaction—The alkali-silica reaction (ASR) involves the interaction of hydroxyl ions associated with alcalies in portland cement with certain siliceous constituents of the aggregates in concrete. Products of the reaction can cause excessive expansion, cracking, and general deterioration of the concrete. The term alkalies refers to the sodium and potassium oxides present in portland cement, in relatively small proportions expressed as a sodium oxide equivalent (Na₂Oₑq), which is the sum of the percentage of Na₂O, and 0.658 times the percentage of K₂O. When this particular type of concrete distress was first described by Stanton (1940), the only apparent remedies were the use of low-alkali portland cement (0.60 percent or less computed as Na₂Oₑq) or the avoidance of reactive aggregates.

The evaluation of long-term performance of concrete has shown that pozzolans can be beneficial in reducing or eliminating map cracking and expansion resulting from ASR. Many investigations have shown that natural pozzolans can be effective in controlling the ASR. Pepper and Mather (1959) found that the necessary percentage replacement of portland cement by solid volume with a natural pozzolan varied from 20 percent with diatomite and 20 to 30 percent with calcined shale to achieve an adequate reduction in ASR expansion. In the case of volcanic glass, 30 to 35 percent cement replacement was needed to provide an adequate reduction in expansion when tested in accordance with ASTM C441-05. As shown in Fig. 6.3.4a, the results of an investigation by Mehta (1981) demonstrated that the use of Santorin earth at a replacement rate of 20 to 30 percent of a high-alkali portland cement (1.0 percent Na₂O equivalent) satisfactorily controlled the alkali-silica expansion. Likewise, Fig. 6.3.4b and 6.3.4c show the effectiveness of several other types of pozzolans in reducing the expansion due to the ASR. However, an insufficient quantity of a natural pozzolan may actually increase the detrimental effects of ASR (Mather 1993). Therefore, the minimum content of a natural pozzolan, expressed as a percentage of the total cementitious material, necessary to control deleterious ASR should be determined by tests using ASTM C441-05 as described in ASTM C311-11.

6.3.5 Permeability—In most cases, the use of a natural pozzolan will reduce the permeability of concrete. Although some natural pozzolans may decrease permeability at early ages, the greatest reductions in permeability are generally seen at later ages. Davis (1950) concluded that the use of a moderate-to-high proportion of a suitable pozzolan in mass concrete results in lower water permeability than would otherwise be obtainable. Part of the role of pozzolans in reducing permeability of concrete can be attributed...
to decreased segregation and bleeding and a reduction of water requirement. The more important role of a natural pozzolan in reducing permeability, however, comes from the pozzolanic reaction itself, which increases the formation of calcium silicate hydrate (CSH) gel and reduces the free calcium hydroxide within the cementitious paste. This results in a more refined pore structure, discontinuous pore structure, or both, within the cementitious paste.

Reduced permeability, as it relates to resistance to chloride-ion penetration, is important for corrosion protection of reinforcing steel embedded in concrete. Hooton et al. (1997) showed that decreases in diffusion, permeability, and conductivity could be achieved by both increasing the concentration of a natural pozzolan, such as HRM, and decreasing the water-to-cementitious material ratio (w/cm). In their work, the addition of 8 and 12 percent by mass of HRM improved the chloride penetration resistance of both 0.30 and 0.40 w/cm concretes. Chloride diffusion tests (ASTM C1556-03), chloride ponding tests (AASHTO T259-02), and electrical resistivity tests (ASTM C1202-10) all ranked concretes in the same order. They showed that 12 percent metakaolin improved chloride-ion penetration resistance more than reducing the w/cm of the concrete mixture containing no metakaolin from 0.40 to 0.30. Rapid chloride-ion permeability values (ASTM C1202-10) were also found to be significantly lower with 10 percent metakaolin in concrete at a w/cm = 0.36 compared with a concrete at a w/cm = 0.40 without metakaolin (Caldarone et al. 1994). Metakaolin was found to increase the chloride-binding capacity of pastes (Coleman and Page 1997), which further reduces chloride penetration.

6.3.6 Freezing-and-thawing resistance—The effect of a natural pozzolan on concrete’s resistance to freezing and thawing, and to the action of deicing chemicals during freezing depends on the proportioning, maturity, compressive strength, degree of saturation of the concrete, and adequacy of the air-void system at the time of exposure (Lovewell 1971). Zhang and Malhotra (1996) concluded that the RHA concrete had excellent resistance to chloride-ion penetration and excellent performance under freezing-and-thawing cycling. The resistance to deicing salt scaling was similar to that of the control concrete and marginally better than that...
of the silica fume concrete. In work reported by Neal and Ramsburg (2002), the freezing-and-thawing resistance of air-entrained concrete containing 30 percent replacement of portland cement with a calcined shale was compared with that of a control air-entrained concrete as tested in accordance with ASTM C666/C666M-03, Procedure B. The results showed that the concrete with 30 percent calcined shale had equal freezing-and-thawing durability compared with the control, with both having durability factors of 96 percent after 300 cycles of freezing and thawing.

6.3.7 Drying shrinkage—The drying shrinkage of products made with portland-pozzolan cements is dependent on the hydration products and water demand of the mixtures. Tests should be conducted to determine the drying shrinkage of natural pozzolan and portland cement combinations to determine the properties for a particular project. Because concrete containing pozzolans typically has a lower modulus of elasticity than a similar concrete without pozzolans, the cracking tendency resulting from drying shrinkage in concrete containing pozzolans is less than that in similar concretes without pozzolans. Mehta (1981) found that the drying shrinkage of concretes made with cements replaced by 10, 20, and 30 percent Santorin earth was not significantly different from that of the concrete containing the reference portland cement (refer to Fig. 6.3.7a). As shown in Fig. 6.3.7b, work by Zhang and Malhotra (1995) found that the drying shrinkage strain of concretes containing 10 percent replacement by silica fume and metakaolin was less than the control mixture.

CHAPTER 7—SPECIFICATIONS, TEST METHODS, QUALITY CONTROL, AND QUALITY ASSURANCE

7.1—Introduction
The specification requirements for natural pozzolans are covered in ASTM C618-08. In Canada, natural pozzolans are covered in CSA-A3000-08. Prior to 1968, natural pozzolans were addressed separately in ASTM C402-65 and fly ash was addressed separately in ASTM C350-65. In 1968, however, when ASTM C618-08 was established, both natural pozzolans and fly ash were combined in one standard specification. When natural pozzolans are used in blended cement, the applicable specifications are ASTM C595/C595M-10 or ASTM C1157/C1157M-11.

7.2—Chemical requirements
ASTM C618-08 requires that a natural pozzolan have a minimum of 70 percent by mass for the sum of the oxides of SiO$_2$, Al$_2$O$_3$, and Fe$_2$O$_3$. The intent of this requirement is to ensure that sufficient quantities of the potentially pozzolanic reactive constituents are present. This requirement is based on early studies that sought, with little success, to relate pozzolan performance with the chemical analysis for the oxides of silica, alumina, and iron. However, experience has shown that the oxide analysis of the natural pozzolan is not necessarily a good predictor of the performance of the material. ASTM C618-08 also has the following chemical requirements for a natural pozzolan: 10.0 percent maximum loss on ignition (LOI), 4.0 percent maximum SO$_3$, and 3.0 percent maximum moisture content.

7.3—Physical requirements
The available surface area or fineness of a natural pozzolan is an important factor in the reactivity of the material. ASTM C618-08 has requirements for the fineness of a natural pozzolan expressed as the amount retained when the material is wet-sieved over a No. 325 (45 µm) sieve, with a maximum limit of 34 percent retained. Reactivity has been found to be directly related to the quantity passing this sieve, as the coarser particles generally do not react in a reasonable time in concrete. Although not required in ASTM C618-08, it is often beneficial to control the fineness of a natural pozzolan.
pozzolan by measuring the fineness by air permeability or particle size distribution.

ASTM C618-08 requires that a natural pozzolan be tested to determine its strength activity index with portland cement. In this strength test, specimens are prepared in accordance with ASTM C109/C109M-08, per ASTM C311-11. The strength of the test mixture containing 20 percent natural pozzolan and 80 percent portland cement by mass is compared with the strength of a control mixture with portland cement only. Strength tests are made at ages of 7 and 28 days. The strength activity index of the natural pozzolan is then calculated and reported as a percent of the strength of the control mixture. ASTM C618-08 requires that a natural pozzolan have a minimum strength activity index of 75 percent at either 7 or 28 days. However, the strength activity index with portland cement is considered only as an indicator of reactivity and does not necessarily predict the relative strength contribution of the natural pozzolan when used in concrete. Likewise, the strength activity index with portland cement does not provide information on the optimum proportion of a natural pozzolan for use in concrete.

ASTM C618-08 has additional mandatory and optional requirements related to the physical properties of a natural pozzolan, which include the following:

1. Water requirement of the mortar—The water demand should not exceed 115 percent of the control mixture based on the amount of water required to achieve a flow equal to within ±5 percent of the control mixture.

2. Soundness—The test for soundness protects against delayed expansion that can occur if sufficient amounts of MgO in the form of crystalline periclase or CaO in the form of hard-burned free lime are present in the natural pozzolan. The soundness is determined by measuring the autoclave expansion or contraction of a paste made with 25 parts by mass of the pozzolan and 100 parts by mass of portland cement. The maximum length change allowed is 0.8 percent.

3. Uniformity requirements—Limits on the maximum variation for density and fineness are specified for a natural pozzolan to keep them within practical limits of shipments over a period of time. There is also an optional limit on the permitted variation of air-entraining admixture demand caused by the pozzolan when it is used in air-entrained concrete.

4. Increase in drying shrinkage of mortar bars dried for 28 days—An optional limit is provided to avoid the use of a natural pozzolan that may exhibit a tendency to substantially increase the drying shrinkage as measured in mortars.

5. Effectiveness in controlling alkali-silica reactions—An optional mortar-bar expansion test (ASTM C441-05) can be requested if a natural pozzolan is to be used in concrete in conjunction with a high-alkali cement when an aggregate is regarded as deleteriously reactive with cement alkalis. In this optional requirement, the ASTM C441-05 expansion value of a mixture of high-alkali cement and natural pozzolan is compared with the ASTM C441-05 expansion value of a low-alkali control mixture where the alkali content of the control cement is in the range of 0.5 to 0.6 percent expressed as Na₂O equivalent. The natural pozzolan is considered effective if the ASTM C441-05 expansion value of the test mixture is less than or equal to that of the control mixture.

6. Sulfate resistance—An optional requirement is provided to assess the influence of a natural pozzolan on the sulfate resistance of the natural pozzolan/portland cement combination. The optional requirement limits the maximum expansion of the natural pozzolan/portland cement combination when tested in accordance with ASTM C1012/C1012M.

7.4—General specification provisions

ASTM C618-08 requires that the purchaser or a representative have access to stored natural pozzolan for the purpose of inspection and sampling. It also states that "the purchaser has the right to reject material that fails to conform to the requirements of the specification."

7.5—Methods of sampling and testing

ASTM C311-11 outlines the procedures for testing samples of a natural pozzolan to determine compliance with requirements of ASTM C618-08. ASTM C311-11 addresses the methods and procedures for sampling, chemical analysis, and physical testing of a natural pozzolan. ASTM C311-11 references other ASTM test methods for cement, mortar, or concrete. In some cases, ASTM C311-11 will indicate specific modifications to another ASTM standard test method regarding proportions, preparation procedures, or test parameters. Many of these procedures use arbitrary proportions and do not necessarily replicate the proportions proposed to be used on a project.

7.5.1 Sampling methods—Either individual grab samples or composite samples may be used depending on the circumstances. ASTM C311-11 provides detailed procedures for sampling of a natural pozzolan from the conveyor delivering to bulk storage, bulk storage at points of discharge, bulk storage by means of sampling tubes, and railroad cars or trucks.

7.5.2 Chemical analysis methods—The procedures for determining the chemical composition of a natural pozzolan are prescribed in ASTM C311-11. In general, the chemical analysis is conducted in accordance with ASTM C114-11. In addition, the procedures are given to determine the moisture content by drying to constant mass and the LOI. The latter requires igniting the dried sample to constant mass in a muffle furnace at 1382 ± 90°F (750 ± 50°C) using an uncovered porcelain crucible instead of a platinum crucible, which is used for cement testing.

7.5.3 Physical test procedures—The specified physical test procedures for a natural pozzolan are addressed in ASTM C311-11 and include such tests as determining the density, amount retained on the No. 325 (45 µm) sieve, soundness, and strength activity index.

7.6—Quality control and quality assurance

The first recommended step in starting a natural pozzolan quality-control program is to establish the quality history for each source of a natural pozzolan. This quality history should include ASTM C618-08 certification, as well as at least 40 individual test results for LOI, amount retained on
Due to the similar appearance of a natural pozzolan and portland cement, it is prudent to color-code and label the fill pipes or to take other precautions to minimize the possibility of cross-contamination. Care should also be taken to clearly identify which storage compartments contain the natural pozzolan and to establish proper materials management procedures (Gaynor 1994). Bins should be completely cleaned out when being switched to handle a different type of material. As with portland cement from different mills, pozzolan from different sources should not be mixed in the same bin or silo.

Natural pozzolans flow readily when aerated. This characteristic increases the potential of leakage from bins and silos. When portland cement and a natural pozzolan are stored in different compartments of the same bin or silo, the dividing partition separating the materials should be inspected frequently, otherwise the natural pozzolan or portland cement may move from one bin to the other through the dividing partition at faulty welded connections or holes caused by wear. A double wall with an intervening air space is highly recommended. Because of the difficulty in detecting cross-contamination between portland cement and a natural pozzolan, care should be exercised to avoid intermingling of portland cement and natural pozzolan. Each storage bin and silo should be equipped with a positive shutoff valve to control the flow of pozzolan into the weigh batcher. Rotary valves, rotary valve feeders, and butterfly valves are generally suitable for this purpose. A conventional scissors-gate valve may be used if it is well maintained. Independent dust collectors are recommended on the bins for portland cement and the natural pozzolan.

8.2—Batching

A natural pozzolan may be batched cumulatively in the same weigh batcher along with other cemenitious materials. Portland cement should be batched first so that an accidental over-batching of the natural pozzolan or other material will not cause under-batching of the portland cement.

Transfer of the natural pozzolan from a bin or silo to the weigh batcher can be accomplished by various methods, such as gravity flow, pneumatic conveyors, screw conveyors, or air slides. The method depends on the location of the natural pozzolan bin relative to the batch hopper. When the natural pozzolan is stored overhead, it is normally conveyed to the weigh batcher by gravity flow or air slide. If the natural pozzolan storage is close to the same level as the weigh batcher, an air slide or a screw conveyor can be used. Because natural pozzolans flow very easily when aerated, a positive shutoff valve should be installed to ensure that the natural pozzolan does not flow through the air slide or screw when the conveying device is stopped. A natural pozzolan can be conveyed from lower-level storage by a pneumatic conveyor.
CHAPTER 9—USES OF NATURAL POZZOLANS IN CONCRETE AND CONCRETE PRODUCTS

9.1—Structural concrete

All types of structural concrete can be produced incorporating a natural pozzolan. The percent replacement of portland cement, the addition rate of the natural pozzolan, or both, is based on the particular characteristics of the natural pozzolan and the intended use of the concrete. ACI 318-08 permits the use of natural pozzolans, as well as other supplementary cementitious materials. In ACI 318-08, the only limitation placed on the use of a natural pozzolan is when the concrete is exposed to deicing chemicals. In deicer exposure only, the natural pozzolan content permitted is limited to 25 percent of the total cementitious material. Similar restrictions apply to all supplementary cementitious materials, such as fly ash and slag.

The use of a natural pozzolan in structural concrete may be desirable for many reasons. As discussed in Chapter 5, natural pozzolans can improve the plastic properties of concrete and they generally have no negative effects on the stability of the air content of the concrete. The incorporation of a natural pozzolan in the concrete mixture will often increase the cohesion and workability of the mixture, which reduces segregation and facilitates consolidation.

Natural pozzolans are most often used to impart specific beneficial characteristics in the hardened concrete. Due to the nature of the pozzolanic reaction, concretes with a natural pozzolan can be proportioned to have lower permeability than ordinary portland-cement concrete. The lower permeability impedes the ingress of aggressive or harmful fluids, ions, and gases. This will aid in improved durability and protection of the reinforcing steel. In addition, a natural pozzolan can increase the resistance to sulfate attack and reduce the expansion associated with alkali-silica aggregate reactions. Chapter 6 addressed this topic in more detail. Because of these benefits in the hardened concrete, natural pozzolans have been used in the production of high-performance concrete.

9.2—Precast, prestressed concrete products

Precast and prestressed concrete elements are routinely used in the construction of bridges, buildings, parking garages, drainage, and other structures. The concrete used in these applications should meet two critical criteria: 1) a high-early-age strength development; and 2) a high level of durability.

In both precast and prestressed applications, the development of early-age strength in the concrete is critical to maintain an efficient production schedule. To meet this schedule, the design release or stripping strength of the concrete should be achieved in a period of approximately 12 to 18 hours. For prestressed applications, a compressive strength of 3480 to 4060 psi (24 to 28 MPa) is generally required at the time of form removal or stripping to transfer the prestress forces from the form or prestressing bed to the concrete. The high compressive strengths at transfer are necessary to obtain good bond of the concrete to the prestressing steel, to control camber of the member, to control creep and shrinkage of the concrete, and to reduce prestress losses. Precast elements could have lower strength requirements of 2000 to 3500 psi (14 to 24 MPa) that are necessary for form removal and product handling. These early-age concrete strengths are generally achieved with portland cement contents of 600 to 750 lb/yd³ (355 to 445 kg/m³), use of conventional or high-range water-reducing admixtures, and accelerated heat curing of the concrete. Nonchloride accelerating admixtures could also be used. Therefore, when a natural pozzolan is used in these applications, it should have sufficient reactivity to maintain satisfactory early-age strength properties of the concrete. Highly reactive natural pozzolans, such as high-reactivity metakaolin (HRM), are suited to these applications. A calcined shale, at 30 percent replacement of portland cement, has been successfully used in precast concrete applications (Neal and Ramsburg 2002).

Because precast, prestressed products are often used in moderate to severe exposure conditions, the concrete should have a high level of durability. The concrete used in these applications may have to possess the properties of low permeability, high sulfate resistance, high resistance to freezing and thawing and deicer scaling, and high resistance to deleterious expansion from ASR. As discussed in Chapter 6, natural pozzolans can be used in concrete to modify the cementitious paste to provide increased durability.

The use of natural pozzolans in concrete generally results in an improvement to the finish of formed surfaces, having fewer surface air voids or bugholes. This is attributed to the improved workability of the concrete.

9.3—Mass concrete

Natural pozzolans have been used extensively in the United States in mass concrete structures. Some examples where natural pozzolans were used in the construction of mass concrete include the Los Angeles Aqueduct; the San Francisco Bay and Golden Gate Bridges; and the Friant, Bonneville, Davis, Glen Canyon, Flaming Gorge, Wanapum, and John Day Dams (Davis 1950; Mielenz 1983).

Mass concrete was one of the first types of concrete where natural pozzolans were used in the United States (ACI 207.1R-05). Davis (1950) reports on extensive evaluations and experiences in the use of natural pozzolans in these applications. Mather (1971) provides a review of their use in construction of concrete dams. Valuable reports on natural pozzolan use in mass concrete are given by Davis (1963), Price and Higginson (1963), Waugh (1963), Kokuba (1963), and Tuthill et al. (1963). Elfert (1974) gives an extensive report on USBR experience with fly ash and natural pozzolans over the period of 1942 to 1973, with additional reference to the use of natural pozzolans in mass concrete in the period of 1915 to 1916. Today, practically all concrete used in mass dams contains natural pozzolan, fly ash, or ground slag.

The heat of hydration can be reduced in concrete by using a natural pozzolan to replace a sufficient portion of the portland cement (Blanks et al. 1938; Carlson et al. 1979). This reduction in the heat of hydration is beneficial in
mass concrete because it will decrease the thermal stresses within the concrete that can cause cracking. By using natural pozzolan concrete in massive dam construction, it is possible to achieve this reduction of the temperature rise without incurring the undesirable effects associated with very lean mixtures (that is, poor workability, bleeding, tendency to segregate, and tendency for increased permeability [Price 1982]). Improved sulfate resistance and a reduction of the potential for expansion from alkali-silica reactions can be provided by the proper incorporation of a natural pozzolan into concrete mixtures used in the construction of concrete dams and other mass structures.

9.4—Concrete pipes

The use of a natural pozzolan can provide significant benefits in the manufacture of concrete pipe. In a packerhead pipe operation, concrete with a very dry consistency and low water content is compacted into a vertical pipe form using a revolving compaction tool. To obtain the required workability of the concrete mixture, it is often necessary to use portland cement contents higher than necessary for strength. A natural pozzolan can be used to reduce the portland cement content while maintaining or improving desirable properties of the concrete. Natural pozzolan can increase the cohesiveness of these no-slump concrete mixtures, which facilitate compaction of the concrete in the form, resulting in an increase in the density of the concrete in the pipe. This will improve the water-tightness and chemical resistance of concrete pipe. An additional benefit is reduced wear on forms and compaction equipment.

The incorporation of a natural pozzolan will result in a reduction in the permeability of the cementitious paste, which further enhances the performance of the concrete pipe. This reduction in permeability, along with the higher degree of compaction, can make concrete pipe more resistant to weak acids and sulfates (Davis 1954; Mather 1982). The degree of increase in sulfate resistance will depend on the cement type and type of natural pozzolan. A reduction in the heat of hydration of concrete mixtures containing pozzolan can reduce the amount of hairline cracks on the inner surface of stored pipe sections (Cain 1979).

9.5—Concrete masonry units

Natural pozzolans can be used in the manufacture of concrete masonry units. A natural pozzolan reportedly gives added plasticity to the relatively harsh mixtures used in concrete masonry units (Belot 1967). The improvement in plasticity and cohesion aids in compaction of the concrete in the masonry unit mold. This will increase the density of the masonry unit that, in turn, might reduce the moisture absorption. Efflorescence may also be reduced because the natural pozzolan will result in lower permeability and a partial consumption of the hydroxides of calcium, sodium, and potassium derived from the portland cement.

When concrete products are cured in an autoclave at temperatures of 275 to 374°F (135 to 190°C) and pressures of 75 to 170 psi (0.5 to 1.2 MPa), a natural pozzolan content of 30 to 35 percent can be used. In autoclave applications, particular care should be taken to ensure that the natural pozzolan meets the soundness requirement of ASTM C618-08. In low-pressure steam-curing applications, a natural pozzolan content of 15 to 35 percent of the total cementitious material content may be used. With some curing systems that provide little supplemental heat, there can be problems with early strength development if the natural pozzolan has a low rate of activity.

Tests for resistance to freezing and thawing of concrete masonry units containing natural pozzolans indicate that the units can be expected to perform well in vertical construction, such as walls. Although air entrainment is not practical at the extremely low or zero slumps used for concrete masonry units, it could be applicable to slump block or quarry tile.

To provide adequate resistance to freezing and thawing for units made with concrete having appreciable slump, air entrainment is needed (Redmond 1969). When proportioning mixtures, concrete product producers should first check the grading and types of aggregates, cements, equipment, and curing temperatures and then adjust trial batches with various amounts of pozzolans to achieve specific technical or economic objectives (Valore 1970).

9.6—Controlled low-strength materials

Formulations containing a natural pozzolan, portland cement, water, and fine aggregate have been used as controlled low-strength fill material in place of compacted soil. These formulations, delivered by truck mixers, can be proportioned to flow like a liquid during placement, but after hardening are capable of supporting normal loads. No tamping or compaction is necessary during the placement of these materials to achieve the required density, strength, and load-bearing capacity. Such materials can be used for trench backfilling; pipe bedding; foundation sub-base; paving sub-base; floor fills; culvert backfill; and filling abandoned tanks, manholes, and sewer lines. The primary use of controlled low-strength materials is as a replacement for compacted granular materials where installation and subsequent settlement could be problematic. Compressive strengths ranging from approximately 50 to 1200 psi (0.35 to 8.28 MPa) can be achieved, which provides the necessary rigidity, load-bearing capacity, and volume stability needed for these uses. Controlled low-strength materials can later be excavated, provided that the strength is limited to a maximum of 50 psi (0.3 MPa) for manual excavation or a maximum of 200 psi (1.4 MPa) when the excavation will be performed by mechanical equipment such as a backhoe (ACI 229R-99). Economy is achieved in the use of these materials because no backfill labor crews and equipment are necessary. The material can be self-leveling and support normal loads, such as those carried by well-compacted soil. The amount of bleed water that comes to the surface after placement of these very wet mixtures, however, should be considered in some applications. Natural pozzolan can also be used as a fill material by itself in some applications. The necessary moisture requirements and packing densities can be determined through the use of laboratory and field testing. Work on this
9.7—Grout and mortar

The primary purpose of grout is to fill spaces or voids. Mortar contains the same basic ingredients but with a less fluid consistency. Mortar that is used in masonry construction is addressed in ASTM C270-10. This specification permits the use of natural pozzolans in a blended cement. Although the effects of using natural pozzolans in mortars have not been fully investigated, they may affect bond strength, time of setting, and other important properties.

The benefits derived from using natural pozzolan in grouts are the same as for concrete—that is, economy, improved workability, lower heat of hydration, reduced alkali-silica reaction expansion, reduced permeability, and improved sulfate resistance. Common uses of grout include:

1. Preplaced aggregate concrete, where grout is injected into the voids of previously placed coarse aggregate to produce concrete (ACI 304.1R-92).
2. Contact grouting, either under machinery to fill the space between a base plate and the substrate concrete or between the surface of concrete placed or pumped under existing concrete or rock, as in tunnel linings.
3. Deep mine applications to provide support.
4. Curtain grouting, where very fluid mixtures (often without aggregate) are used to fill cracks or fissures in rock.
5. Soil and hazardous waste stabilization to fill voids in the soil or between particles to decrease permeability, increase density, and generally improve its load-carrying capacity.
6. Slab jacking to raise and realign concrete slabs or structures that have settled.
7. Underwater placing and slope protection, where grout is generally injected into preplaced inflatable cloth bags or blankets that are flexible enough to conform to the surrounding contour to fill the void and provide continuous contact.

CHAPTER 10—REFERENCES

Committee documents are listed first by document number and year of publication followed by authored documents listed alphabetically.

American Association of State Highway and Transportation Officials
AASHTO M321-04—Standard Specification for High-Reactivity Pozzolans for Use in Hydraulic-Cement Concrete Mortar and Grout
AASHTO T259-02—Standard Method of Test for Resistance of Concrete to Chloride Ion Penetration

American Concrete Institute
ACI 207.1R-05—Guide to Mass Concrete
ACI 211.1-91 (Reapproved 2009)—Standard Practice for Selecting Proportions for Normal, Heavyweight, and Mass Concrete
ACI 225R-99—Guide to the Selection and Use of Hydraulic Cements
ACI 229R-99—Controlled Low-Strength Materials
ACI 304.1R-92 (Reapproved 2005)—Guide for the Use of Preplaced Aggregate Concrete for Structural and Mass Concrete Applications
ACI 318-08—Building Code Requirements for Structural Concrete and Commentary

ASTM International
ASTM C270-10—Standard Specification for Mortar for Unit Masonry
ASTM C311-11—Standard Test Methods for Sampling and Testing Fly Ash or Natural Pozzolans for Use in Portland Cement Concrete
ASTM C402-65—Standard Specification for Raw or Calcined Natural Pozzolans for Use as Admixtures in Portland Cement Concrete (withdrawn 1967)
ASTM C441-05—Standard Test Method for Effectiveness of Pozzolans or Ground Blast Furnace Slag in Preventing Excessive Expansion of Concrete due to the Alkali Silica Reaction
ASTM C595/C595M-10—Standard Specification for Blended Hydraulic Cements
ASTM C618-08—Standard Specification for Coal Fly Ash and Raw or Calcined Natural Pozzolan for Use in Concrete
ASTM C666/C666M-03—Standard Test Method for Resistance of Concrete to Rapid Freezing and Thawing
ASTM C1012/C1012M-10—Standard Test Method for Length Change of Hydraulic Cement Mortars Exposed to a Sulfate Solution
ASTM C1202-10—Standard Test Method for Electrical Indication of Concrete’s Ability to Resist Chloride Ion Penetration
ASTM C1556-03—Standard Test Method for Determining the Apparent Chloride Diffusion Coefficient of Cementitious Mixtures by Bulk Diffusion

Canadian Standards Association
CSA A3000-08—Cementitious Materials Compendium

CESP Publication, Companhia Energetica de Sao Paolo, Brazil.


Davis, R. E., 1963, “Historical Account of Mass Concrete,” Symposium on Mass Concrete, SP-6, American Concrete Institute, Farmington Hills, MI, pp. 1-35.


Downey, P., and Drarva, T., 1989, “30 Years’ Experience with Natural Pozzolans in Chile,” *Proceedings of the Third International Conference on Fly Ash, Silica Fume, Slag, and Natural Pozzolans in Concrete*, SP-114, Supplementary Volume, American Concrete Institute, Farmington Hills, MI, pp. 795-860.


Mather, K., 1982, “Current Research in Sulfate Resistance at the Waterways Experiment Station,” *George Verbeck Symposium on Sulfate Resistance of Concrete*, SP-77, American Concrete Institute, Farmington Hills, MI, pp. 63-74.


Mielenz, R. C., 1983, “Mineral Admixtures—History and Background,” *Concrete International*, V. 5, No. 8, pp. 34-42.


Mass Concrete, SP-6, American Concrete Institute, Farmington Hills, MI, pp. 77-87.


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