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Use of Raw or Processed Natural Pozzolans in Concrete

Reported by ACI Committee 232

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This report provides a review of the state-of-the-art use of raw or processed natural pozzolans in concrete and an overview of the properties of natural pozzolans and their proper use in the production of hydraulic-cement concrete. Natural pozzolans mixed with lime were used in concrete construction long before the invention of portland cement because of their contribution to the strength of concrete and mortar. Today, natural pozzolans are used with portland cement not only for strength, but also for economy and beneficial modification of certain properties of fresh and hardened portland-cement concrete.

This report contains information and recommendations concerning the selection and use of natural pozzolans generally conforming to the applicable requirements of ASTM C 618 and CSA A23.5. Topics covered include the effect of natural pozzolans on concrete properties, a discussion of quality control and quality assurance, and guidance regarding handling and use of natural pozzolans in specific applications. References are provided that offer more information on each topic.

Keywords: alkali-silica reaction; cement; concrete; concrete strength; diatomaceous earth; lime; natural pozzolan; pozzolan; pozzolanic activity; sulfate attack (on concrete).

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ACI 232.1R-00 supersedes ACI 232.1R-94 and became effective December 6, 2000.

CHAPTER 1—GENERAL

1.1—History

Lime and limestone are among the oldest materials used by mankind for construction purposes. Structures built of limestone include the pyramids of Egypt. Long before the invention of portland cement in 1824, mortars and concretes composed of mixtures and fillers and raw or heat-treated lime were used for construction throughout the world (Malinowski 1991).

Malinowski et al. (1993) report that the oldest example of hydraulic binder, dating from 5000-4000 B.C., was a mixture of lime and natural pozzolan, a diatomaceous earth from the Persian Gulf. The next oldest reported use was in the Mediterranean region. The pozzolan was volcanic ash produced from two volcanic eruptions: one, sometime between 1600 and 1500 B.C. on the Aegean Island of Thera, now called Santorin, Greece; the other in 79 A.D. at Mt. Vesuvius on the bay of Naples, Italy. Both are volcanic ashes or pumicites consisting of almost 80% volcanic glass (pumice and obsidian).

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

During archaeological excavations in the 1970s at the ancient city of Camiros on the Island of Rhodes, Greece, an ancient water-storage tank having a capacity of 600 m^3 (785 yd^3) was found. Built in about 600 B.C., it was used until 300 B.C. when a new hydraulic system with an underground water tank was constructed. For almost three millennia this water tank has remained in very good condition, according to 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 (<2 mm [<0.08 in.]) and siliceous aggregates with sizes ranging between 2 and 20 mm (0.08 and 0.79 in.). The fresh concrete was placed into wooden sidewall molds. The compressive strength of a 20 mm (0.79 in.) cubic specimen was found to be 12 MPa (1740 psi). 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 of these structures are still standing along the coasts of Italy, Greece, France, Spain, and in harbors of the Mediterranean Sea. The Greeks and Romans built many such structures over 2000 years ago. Examples of such structures are the Roman aqueducts as well as more recent structures such as the Suez Canal in Egypt (built in 1860) (Luce 1969), the Corinthian Canal (built in 1880), the sea walls and marine structures in the islands of the Aegean Sea, in Syros, Piraeus, Nauplion, and other cities, and the harbors of Alexandria in Egypt, Fiume, Pola Spalato, Zara on the Adriatic Sea, and Constanta (Romania) on the Black Sea. All of these structures 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 lime-pozzolan mortars (Lea 1971).

1.2—Definition of a natural pozzolan

Pozzolan is defined in ACI 116R as:

> “...a siliceous or siliceous and aluminous material, which in itself possesses little or no cementitious value but will, in finely divided form and in the presence of moisture, chemically react with calcium hydroxide at ordinary temperatures to form compounds possessing cementitious properties.”

Table 1.1—Typical chemical and mineralogical analysis of some natural pozzolan (Mehta 1987)

Pozzolan	%						Estimated Ignition Loss, %	Non-crystalline matter, %	Major crystalline minerals
	SiO_2	Al_2O_3	Fe_2O_3	CaO	MgO	Alkalies*			
Santorin earth	65.1	14.5	5.5	3.0	1.1	6.5	3.5	65 to 75	Quartz, plagioclase
Rhenish trass	53.0	16.0	6.0	7.0	3.0	6.0	—	50 to 60	Quartz, feldspar, analcime
Phonolite	55.7	20.2	2.0	4.2	1.1	10.8	3.6	—	Orthoclase, albite, pyroxene, calcite
Roman tuff	44.7	18.9	10.1	10.3	4.4	6.7	4.4	—	Herschelite, chabazite, phillipsites
Neapolitian glass	54.5	18.3	4.0	7.4	1.0	11.0	3.1	50-70	Quartz, feldspar
Opaline shale	65.4	10.1	4.2	4.6	2.7	1.4	6.3	—	—
Diatomite	86.0	2.3	1.8	—	0.6	0.4	5.2	—	—
Rhylolite pumicite	65.7	15.9	2.5	3.4	1.3	6.9	3.4	—	—
Jalisco pumice	68.7	14.8	2.3	—	0.5	9.3	5.6	90	Sanidine

*%Na_2O + 0.658% K_2O

Natural Pozzolan is defined as:

"...either a raw or calcined natural material that has pozzolanic properties (for example, volcanic ash or pumicite, opaline chert and shales, tuffs, and some diatomaceous earths)."

ASTM C 618 and CSA A23.5 cover coal fly ash and natural pozzolan for use as a mineral admixture in concrete. The natural pozzolans in the raw or calcined state are designated as Class N pozzolans and are described in the specifications as:

"Raw or calcined natural pozzolans that comply with the applicable requirements for the class as given herein, such as some diatomaceous earth; opaline chert and shales; tuffs and volcanic ashes or pumicites, any of which may or may not be processed by calcination; and various materials requiring calcination to induce satisfactory properties, such as some clays and shales."

Similar materials of volcanic origin are found in Europe, where they have been used as an ingredient of hydraulic-cement concrete for the past two centuries.

Raw or processed natural pozzolans are used in the production of hydraulic-cement concrete and mortars in two ways: as an ingredient of a blended cement, or as a mineral admixture. This report deals with the second case. Blended cements are covered in ACI 225R. Fly ash and silica fume are artificial pozzolans and are covered in ACI 232.2R and 234R.

1.3—Chemical and mineralogical composition

The properties of natural pozzolans vary considerably, depending on their origin, because of the variable proportions of the constituents and the variable mineralogical and physical characteristics of the active materials. Most natural pozzolans contain substantial amounts of constituents other than silica, such as alumina and iron oxide, which will react with calcium hydroxide and alkalies (sodium and potassium) to form complex compounds. Pozzolanic activity cannot be determined just by quantifying the presence of silica, alumina, and iron. The amount of amorphous material usually determines the reactivity of a natural pozzolan. The constituents of a natural pozzolan can exist in various forms, ranging from amorphous reactive materials to crystalline products that will react either slowly or not at all. Because the amount of amorphous materials cannot be determined by standard techniques, it is important to evaluate each natural pozzolan to confirm its degree of pozzolanic activity. There is no clear distinction between siliceous materials that are considered pozzolans and those that are not. Generally, amorphous silica reacts with calcium hydroxide and alkalies more rapidly than does silica in the crystalline form (quartz). As is the case with all chemical reactions, the larger the particles (the lower the surface area per unit volume) the less rapid the rate of reaction. Therefore, the chemical composition of a pozzolan does not clearly determine its ability to combine with calcium hydroxide and alkalies.

Volcanic glasses and zeolitic tuffs, when mixed with lime, produce calcium silicate hydrates (CSH) as well as hydrated calcium aluminates and calcium aluminosilicates. These materials were proven to be good pozzolans long ago. Natural clays and shales are not pozzolanic, or only weakly so, as clay minerals do not react readily with lime unless their crystalline structure is partially or completely destroyed by calcination at temperatures below 1093 C (2000 F).

High-purity kaolin may be processed to form a high-quality pozzolan called high-reactivity metakaolin. Italian researchers who have studied volcanic glasses and the relationship to pozzolanic activity believe that "reactive glass originated from explosive volcanic eruptions" like the ones from the volcanoes of Thera and Mount Vesuvius, which produced the natural pozzolans with unaltered aluminosilicate glass as their major component (Malquori 1960). Both are pumicites, one third of which is in the amorphous state (glass), and are highly reactive with lime and alkalis at normal temperatures

1.4—Classification

Mehta (1987) classifies natural pozzolans in four categories based on the principal lime-reactive constituent present: unaltered volcanic glass, volcanic tuff, calcined clay or shale, and 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. In Table 1.1, the chemical

Table 1.2—Mineral admixtures and structures that used them (Elfert 1974)

Name	Date completed	Type of pozzolan
Arrowrock Dam	1915	Granite*
Lahontan Dam	1915	Siliceous silt*
Elephant Butte Dam	1916	Sandstone*
Friant Dam	1942	Pumicite
Altus Dam	1945	Pumicite
Davis Dam	1950	Calcined opaline shale
Glenn Anne Dam	1953	Calcined oil-impregnated diatomaceous shale
Cachuma Dam	1953	Calcined oil-impregnated diatomaceous shale
Tecolote Tunnel	1957	Calcined oil-impregnated diatomaceous shale
Monticello Dam	1957	Calcined diatomaceous clay
Twitchell Dam	1958	Calcined diatomaceous clay
Flaming George Dam	1963	Calcined montmorillonite shale
Glen Canyon Dam	1964	Pumice

*By present standards, these materials have very little pozzolanic activity.

and mineralogical composition is given for some of the well-known pozzolans.

A classification of natural pozzolans based on the identity of the pozzolanic constituents was devised by Mielenz, Witte, and Glantz (1950). Substances that are pozzolanic or whose pozzolanic activity can be induced by calcination were classified as volcanic glass, opal, clays, zeolites, and hydrated oxides of aluminum. Activity type 3 (clays) was subdivided into five subtypes: 3a kaolinite, 3b montmorillonite, 3c illite, 3d clay mixed with vermiculite, and 3e palygorskite.

1.5—Examples

Following is a discussion of some natural pozzolans produced in various parts of the world.

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 Santorin, which was formed about 1600-1500 B.C. after a tremendous explosive volcanic eruption (Marinatos 1972).

Pozzolana—Pozzolana is produced from a deposit of pumice ash or tuff comprised of trachyte found near Naples and Segni in Italy. Trachyte is a volcanic rock comprised primarily of feldspar crystals in a matrix of siliceous glass. Pozzolana is a product of an explosive volcanic eruption in 79 A.D. at Mount Vesuvius, which engulfed Herculaneum, Pompeii, and other towns along the bay of Naples. The deposit near Pozzuoli is the source of the term “pozzolan” given to all materials having similar properties. Similar tuffs of lower silica content have been used for centuries and are found in the vicinity of Rome.

Rhenish trass—Rhenish trass, a natural pozzolan of volcanic origin (Lovewell 1971), has been well known since ancient Roman times. The material is a trachytic tuff that differs from place to place and is found in the Valley of the Rhine River in Germany. Similar tuffs have been used in Bavaria.

Gaize—Gaize is a pozzolan found in France that is not of volcanic origin but a porous sedimentary rock consisting mainly of opal. The material is usually calcined at temperatures around 900 C (1620 F) before it is used as a pozzolan or as a component of portland-pozzolan cement.

Volcanic tuffs, pumicites, diatomaceous earth, and opaline shales—In the United States, volcanic tuffs and pumicites, diatomaceous earth, and opaline shales are found principally in Oklahoma, Nevada, Arizona, and California. Natural pozzolans were investigated in this country by Bates, Phillips, and Wig as early as 1908 (Bates, Phillips, and Wig 1912) and later by Price (1975), Meissner (1950), Mielenz, Witte, and Glantz (1950), Davis (1950), and others. They showed that concretes containing pozzolanic materials exhibited certain desirable properties such as lower cost, lower temperature rise, and improved workability. According to Price (1975), an example of the first large-scale use of portland-pozzolan cement, composed of equal parts of portland cement and a rhyolitic pumicite, is the Los Angeles aqueduct in 1910-1912.

The studies of natural pozzolans by the United States Bureau of Reclamation (USBR) in the 1930s and 1940s encouraged their use for controlling heat of hydration and alkali-silica reaction of concrete in large dams. Siliceous shales of the Monterey Formation in Southern California have been produced commercially and used extensively in the surrounding areas. Price (1975) also states that sources of natural pozzolan that do not require calcining to make them active are located mainly west of the Mississippi River. 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 the completion of the project.

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 fresh-water diatomite are in the northeastern counties of Shasta, Siskiyou, Modoc, and Lassen (Burnett 1991). Diatomite consists of microscopic opaline silica frameworks. Some diatomaceous shale deposits contain hydrocarbon impregnants that provide some of the fuel for their calcination (see Table 1.2).

In 1993, a study was undertaken that appraised as a source of pozzolan a lacustrine deposit located about 48.3 km (30 mi) north of Reno, Nevada. The material is an intermingling of diatomaceous earth and dacite pumicite. The raw material was calcined and ground for marketing under the trade name Lassenite. It was used (1970-1989) for the concrete construction of structures, bridges, roadways, the trans-Canada highway, the Auburn dam, and the Los Melones dam and power plant. It has also been used in research projects by the Department of Transportation of the State of California during the period from January 1987 to August 1991.

Pumicite is a finely divided volcanic ash composed of angular and porous particles of siliceous glass and varying proportions of crystal fragments differing from pumice only in grain size. Pumicites are mainly rhyolitic or dacites in composition. They occur as stratified or massive deposits, commonly as lake beds.

Table 1.3—Cretaceous volcanic ash from North Dakota (copy of report submitted to Minnesota Electronics Company, St. Paul, Minn.)*†

Testing parameters	Samples			ASTM C 618
Processing temperature	100 C 212 F	538 C 1000 F	760 C 1400 F	—
Density, Mg/m^3	2.2624	—	2.404	—
Blaine fineness, m^2/kg	9770	—	9767	—
Mean particle diameter, μm	2.715	—	2.555	—
Amount retained on 45 μm (No. 325) sieve, %	7.85	—	10.26	34.0 max.
Strength activity index: with lime at 7 days, MPa (psi), 50 x 100 mm cylinders (2 x 4 in.)	4.2 (611)	4.7 (680)	7.1 (1030)	—
50 mm cubes (2 in.)	4.6 (665)		7.7 (1120)	—
Strength activity index: with portland cement, at 28 days, % of control	64	—	80	75 min.
Water requirement, % of control	107	—	108	115 max.
Soundness: autoclave expansion or contraction, %	0.32	—	0.26	0.80 max.
Increase of drying shrinkage of mortar bars at 28 days, difference, in % over control	—	—	0.025	0.03 max.

*By the Northwest Laboratories, Seattle, Wash., in 1960.

†These tests were performed on composite samples of volcanic ash from 20 test holes. The portions from each test hole are taken from 0.3 m to 7 to 9 m (1 ft to 23 to 30 ft) levels. The material was crushed, ground in a ball mill, and calcined at 538 and 760 C (1000 and 1400 F) for 15 min.

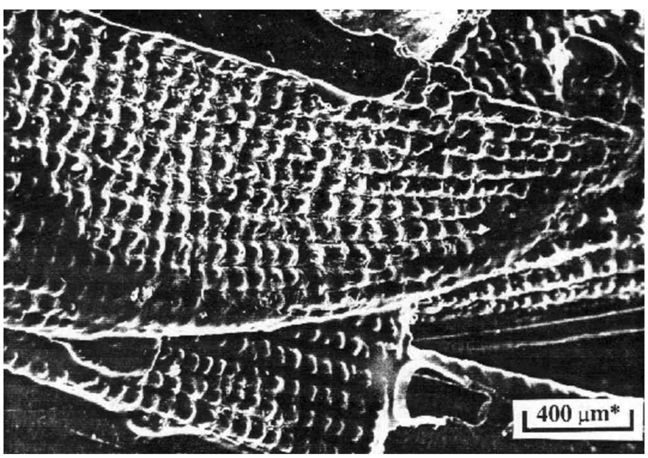

Fig. 1.1—Scanning electron micrograph of rice husk (Mehta 1992).

A deposit in the Upper Fox Hills, 9.7 km (6 mi) north and east of Linton, North Dakota (Fisher 1952, Manz 1962), was examined at the University of North Dakota by N. N. Kohanowski of the Geology Department and was found to be altered pozzolanic volcanic ash. Crawford (1955) describes similar deposits in Saskatchewan and refers to them as pumicite, which he described as a finely divided powder of a white to gray or yellowish color composed of small, sharp, angular grains of highly siliceous volcanic glass, usually rhyolitic in composition.

Table 1.4—Test results of North Dakota volcanic ash

Testing parameters	Samples					Specification
	61-1	61-1	61-1	61-5	61-13	ASTM C 618
Processed calcination temperature	100 C (212 F)	760 C (1400 F)	927 C (1700 F)	100 C (212 F)	100 C (212 F)	—
Density, Mg/m^3	2.37	2.50	2.39	—	—	—
Amount retained on 45 μm (No. 325) sieve, %	2.9	3.2	—	0.6	—	34 max.
Strength activity index with lime at 7 days, MPa (psi), 50 x 100 mm cylinders (2 x 4 in.)	6.6 (9.52)	9.5 (1375)	7.0 (1015)	7.5 (1090)	7.0 (1.10)	—
Strength activity index with portland cement at 28 days, % of control	118	111	—	—	—	75 min.
Water requirement, % of control	110	112	114	110	110	115 max.
Color of sample	Light gray	Light buff	Dark buff	Light gray	Light gray	—

Note: The materials tested were grounded with a muller. Calcining was done at 760 C (1400 F) and 927 C (1700 F) for a period of 1 h.

Stanton (1917) described the Cretaceous volcanic ash bed on the Great Plains near Linton, North Dakota, as several conspicuous white outcrops that suggest chalk or diatomaceous earth. At one exposure, 1.6 km (1 mi) southeast of Linton, the thickness of the white bed is 8 m (26 ft) and the rock is very fine-grained and mostly massive, although it contains some thin-bedded layers. A sample examined by G. F. Loughlin consisted of 80% volcanic glass, 15% quartz and feldspar, and 2 to 3% 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 admixture of sand or shale, the volcanic ash need only be dried at 100 C (212 F) and finely ground to comply with ASTM C 618. Tests were performed in 1961 on composite samples of volcanic ash, crushed and ground in a ball mill and calcined at 538, 760, and 927 C (1000, 1400, and 1700 F), respectively, for 15 min and 1 h. The results are shown in Tables 1.3 and 1.4. Based on these tests conducted on the samples submitted, the material, when calcined at 760 C (1400 F), complied with ASTM C 618.

Rice husk ash—Rice husk ash (RHA) is produced from rice husks, which are the shells produced during the dehusking operation of rice. Rice husks are approximately 50% cellulose, 30% lignin, and 20% silica. A scanning electron micrograph illustrating the typical cellular structure of rice husks where the silica is retained in noncrystalline form shown in Fig. 1.2. To reduce the amount of waste materials, rice husks are incinerated by controlled combustion to remove the lignin and cellulose, leaving behind an ash composed mostly of silica (retaining 20% of the mass of rice husks) as seen in Fig. 1.3.

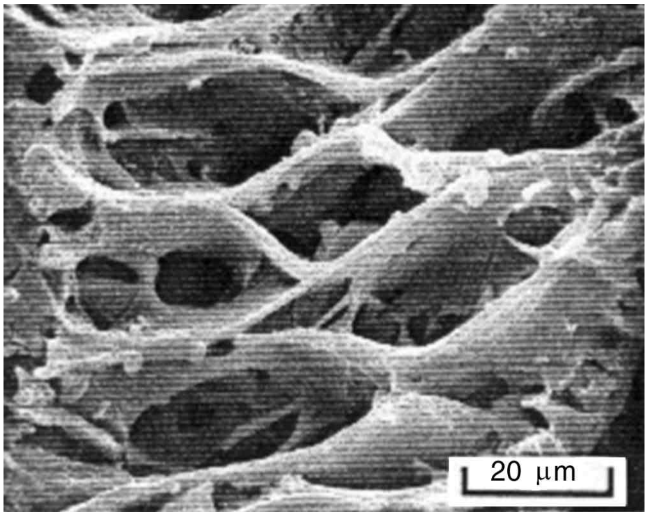

Fig. 1.2—Scanning electron micrograph of rice husk ash (Mehta 1992).

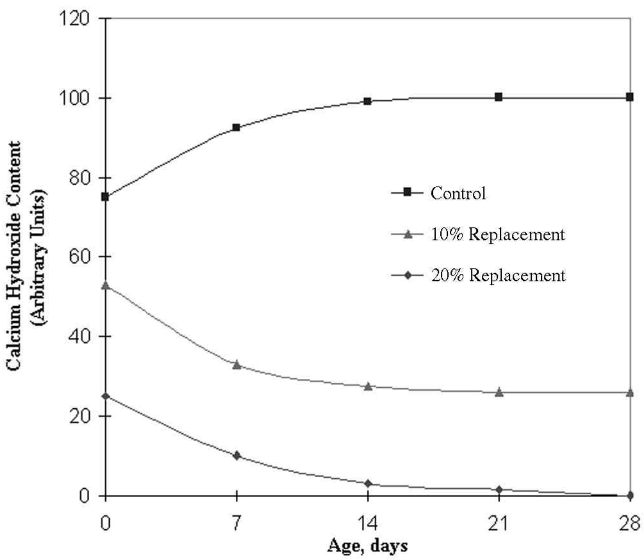

Fig. 1.3—Effect of replacing part of portland cement in concrete by metakaolin on calcium hydroxide content of concrete as it cures (Kostuch, Walters, and Jones 1993).

Mehta (1992) has shown that RHA, produced by controlled incineration under oxidizing conditions at relatively low combustion temperatures and short holding time, is highly pozzolanic with high surface area (50 to 100 m^2/g by nitrogen adsorption), and consists mainly of amorphous silica. By varying the temperature, RHA can be produced with a range of colors, from nearly white to black. The chemical analysis of fully burnt RHA shows that the amorphous silica content ranges between 90 and 96%. It is a highly active pozzolan, suitable for making high-quality cement and concrete products. The average particle size of ground RHA varies from 10 to 75 mm (No. 1500 – 200 sieve).

To obtain lower-permeability concrete, RHA can be added in amounts of 5 to 15% by mass of cement. The benefits of using RHA, as shown by Mehta and Folliard (1995) and

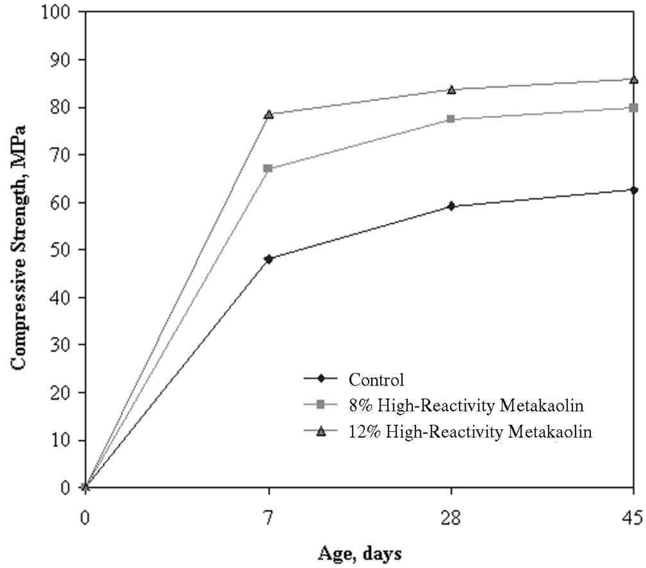

Fig. 1.4—Effect of high-reactivity metakaolin at 0.4 w/cm *ratio on compressive strength of concrete (Hooton, Gruber, and Boddy 1997).*

Zhang and Malhotra (1996), are higher compressive strength, decreased permeability, resistance to sulfate attack, resistance to acid attack, reduction of surface cracking in structures, excellent resistance to chloride penetration, and excellent performance under freezing-and-thawing cycling.

Metakaolin—Metakaolin (Al_2O_3:$2SiO_2$) is a natural pozzolan produced by heating kaolin-containing clays over a temperature range of about 600 to 900 C (1100 to 1650 F) above which it recrystallizes, rendering it mullite ($Al_6Si_2O_{13}$) or spinel ($MgAl_2O_4$) and amorphous silica (Murat, Ambroise, and Pera 1985). The reactivity of metakaolin is dependent upon the amount of kaolinite contained in the original clay material. The use of metakaolin as a pozzolanic mineral admixture has been known for many years, but has grown rapidly since approximately 1985. The average particle size of metakaolin varies and can be controlled during the processing to change the properties of the fresh concrete. In general, the average particle size of high-reactivity metakaolin ranges from 0.5 to 20 µm.

The pozzolanic properties of metakaolin are well documented. Kostuch, Walters, and Jones in 1993 indicate that calcium hydroxide released during cement hydration is consumed if the formulation contains a sufficient quantity of high-reactivity metakaolin (Fig. 1.3). The consumption of calcium hydroxide causes the formation of calcium silicate hydrate (CSH) and stratlingite (C_2ASH_8). DeSilva and Glasser (1991) report that metakaolin can react with sodium, potassium, and calcium hydroxides, as well as gypsum and portland cement. Gruber and Sarkar (1996) confirm the reduction of calcium hydroxide by the use of high-reactivity metakaolin, having an average particle size of about 2 µm.

From 1962-1972, approximately 250,000 metric tons (227,300 tons) of calcined kaolinitic clay was used in the construction of four hydroelectric dams in Brazil (Saad , Andrade, and Paulon 1982). In the United Kingdom, large-scale

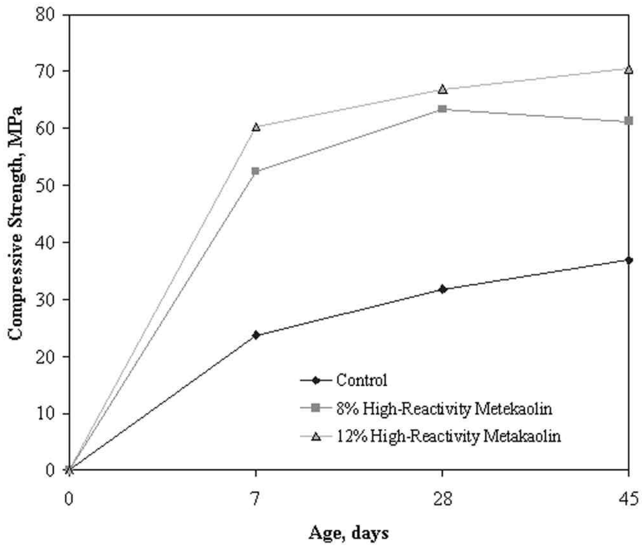

Fig. 1.5—Effect of high-reactivity metakaolin at 0.3 w/cm *ratio on compressive strength of concrete (Hooton, Gruber, and Boddy 1997).*

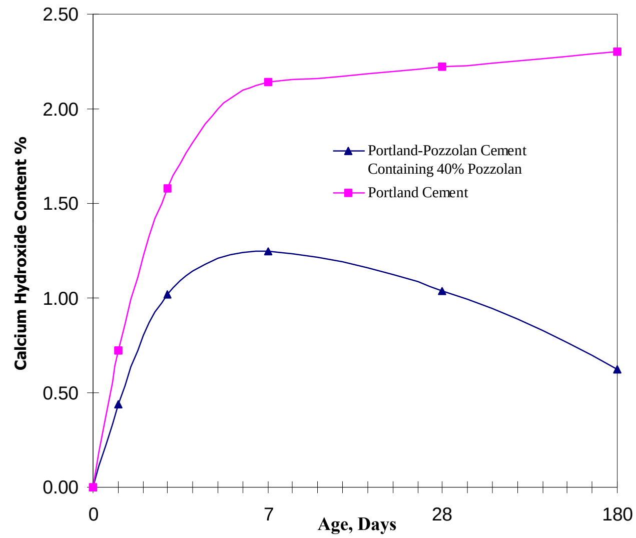

Fig. 1.6—Changes in calcium hydroxide content of hydrating portland-pozzolan cement (Lea 1971).

trials have been conducted using high-reactivity metakaolin concretes subjected to aggressive environments (Ashbridge, Jones, and Osborne 1996). Their research shows excellent strength development, reduced permeability, and chemical resistance. In addition, strength, pozzolanic activity, and cement hydration characteristics have been studied in superplasticized metakaolin concrete (Wild, Khatib, and Jones 1996).

In the United States, metakaolin has been evaluated as a pozzolan in various research studies as well as in the field. In one air-entrained high-performance concrete mixture, the metakaolin-containing concrete showed increased strength and reduced chloride penetration compared to the portland cement control design, while maintaining good workability and an air-void system that produced good resistance to cycles of freezing and thawing and to deicer scaling (Caldarone, Gruber, and Burg 1994). Benefits of using high-reactivity metakaolin in ternary systems with ground granulated blast-furnace slag and fly ash have also been reported (Caldarone and Gruber 1995). Fig. 1.4 and 1.5 shows the effect of a high-reactivity metakaolin on compressive strength of concrete (Hooton, Gruber, and Boddy 1997). Mixtures with 8 to 12% metakaolin replacement at 0.4 to 0.3 water-cementitious materials ratio (*w/cm*) greatly improved the compressive strength at all ages. Hooton, Gruber, and Boddy (1997) showed that high-reactivity metakaolin enhanced resistance to chloride ingress.

1.6—Chemical and physical properties

When a mixture of portland cement and a pozzolan reacts, the pozzolanic reaction progresses like an acid-base reaction of lime and alkalies with oxides ($SiO_2 + A1_2 O_3 + Fe_2O_3$) of the pozzolan. Two things happen. First, there is a gradual decrease in the amount of free calcium hydroxide with time, and second, during this reaction there is an increase in formation of CSH and calcium aluminosilicates that are similar to the products of hydration of portland cement (Fig. 1.6). According to Lea (1971), the partial replacement of portland cement by pozzolan of high SiO_2/R_2O_3 ($R_2O_3 = Al_2O_3 + Fe_2O_3$) ratio has been found to increase the resistance of concrete to sulfate and seawater attack (R_2O_3 is approximately the summation of the Al_2O_3 and Fe_2O_3 contents). This is, in part, attributable to the removal of free hydroxide formed in the hydration of portland cements.

The result is that 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) indicated that pore refinement resulting from pozzolanic reaction is important for enhancing chemical durability and mechanical strength (Mehta 1987).

The shape, fineness, particle-size distribution, density, and composition of natural pozzolan particles influence the properties of freshly mixed unhardened concrete and the strength development of hardened concrete. Most natural pozzolans tend to increase the water requirement in the normal consistency test as a result of their microporous character and high surface area. Natural pozzolans can improve the performance of both fresh and hardened concrete when used as an ingredient of portland-pozzolan cement or as an admixture to portland-cement concrete.

1.7—Uses

Pozzolans of natural origin have been used in mass concrete on large projects in the United States, and where they are locally available they are used in concrete construction and manufacture of concrete products. Such uses of pozzolans of natural origin are more widespread in Europe than in the United States. Natural pozzolans are now used in concrete in a variety of ways, depending upon their reactivity. The natural pozzolans may be used as partial replacements for portland cement or in addition to portland cement. Some natural pozzolans have been used in much the same way as fly ash. Other natural pozzolans of high reactivity, such as metakaolin, have been found to perform similarly to silica fume, and are used in a similar manner.

According to Mielenz, Witte, and Glantz (1950), in 1933 the USBR undertook an intensive study on using natural pozzolans for the purpose of controlling the heat of hydration of concrete and other concrete benefits for mass concrete applications such as large dams. Several investigations revealed the effect of calcination of more than 200 prospective natural pozzolans on their properties and performance in concrete. The following properties were reported:

1. Mineralogical and chemical composition;
2. Pozzolanic activity, water requirement, and strength; and
3. Expansion due to alkali-silica reactivity.

Mielenz, Witte, and Glantz (1950) conclude 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. Many natural pozzolans were usable in the raw state. If moist, they usually required drying and grinding before use. The best natural pozzolans owed their activity to volcanic glass with 70 to 73% SiO_2 content, with 40 to 100% being in the form of rhyolitic glass. Mielenz (1983) gives the history and background on mineral admixtures along with the use of natural pozzolans (raw and calcined). Elfert (1974) describes the experiences of the USBR in the use of large quantities of fly ash and natural pozzolans in the western United States. Table 1.2 lists the types of mineral admixtures used in concrete dams, built during the time period 1915-1964.

Today, blended cements consisting of portland cement and pozzolan, as covered by ASTM C 595 and C 1157, are used in concrete construction for economic reasons to help reduce the energy consumption and to achieve specific technical benefits.

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 a specially made portland-pozzolan cement in several structures (bridges) because of its proven resistance to sulfate attack from seawater and its lower heat of hydration (Davis 1950).

Meissner (1950) reports that a portland-pozzolan cement containing 25% interground calcined Monterey shale was produced during the 1930s and 1940s. 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% interground calcined pozzolan, was used in 1935 for the construction of the Bonneville Dam spillway on the lower Columbia River. In 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 pumicite, which was batched separately at the concrete mixer at the rate of 20% by mass of cement. This pozzolan was obtained from a deposit along the San Joaquin River near Friant.

During the 1960s and early 1970s, natural pozzolan was used at the rate of 42 kg/m^3 (70 lb/yd^3) in nearly all of the concrete in the California State Water Project, including 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. Requirements on this pozzolan exceeded those of ASTM C 618.

A 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 1/3 that of portland cement (Saad , Andrade, and Paulon 1982). This natural pozzolan is produced by calcining kaolin clay and grinding it to a fineness of 700 to 900 m^2/kg (380 to 490 yd^2/lb). Because of this high fineness and activity it can be used for cement replacement up to 50% by volume, with 90-day compressive strength similar to concrete made with portland cement. At Jupia Dam, the use of this natural pozzolan, at 20 to 30% of the volume of cement, resulted in lower temperature rise, improved cohesion, and reduction of expansion due to alkali-silica reaction (Andriolo 1975). When first used for general concrete construction the pozzolan replaced 30% of the cement by volume, and when used for structural concrete construction the rate of replacement was 20%. The use of this high-reactivity pozzolan in mass concrete construction provided substantial gains in cost and improved the concrete properties. (Saad, Andrade, and Paulon 1982).

CHAPTER 2—EFFECTS OF NATURAL POZZOLAN ON CONCRETE PROPERTIES

2.1—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. Because some natural pozzolans perform better than others and project requirements differ, optimum proportions for a given combination of pozzolan and portland cement cannot be predicted. When used as a replacement for a portion of portland cement, natural pozzolan replaces an equal volume or equal mass of the cement. Because the density of natural pozzolans is typically less than the density of portland cement, mass replacement results in a greater volume of total cementitious materials than when volume replacement is used at a given percentage. The mass of natural pozzolan employed may be greater than that of the replaced cement if the concrete is proportioned for optimum properties and maximum economy.

Proportioning techniques for concrete including a finely divided mineral admixture are similar to those used in proportioning concrete that does not include such an admixture. Proportioning techniques for concrete mixtures are given in ACI 211.1. Specific procedures for proportioning mixtures containing pozzolans were developed by Lovewell and Hyland (1974). Finely divided mineral admixtures, whether natural pozzolan or other finely divided material, should usually be regarded as part of the cement paste matrix in determining the optimum percentages of fine and coarse aggregate.

The effect of the natural pozzolan on the mixing water requirement should also be determined. Some finely divided mineral admixtures cause a major increase in water requirement; others have little or no effect on water requirement, and still others typically reduce the water requirement of concrete in which they are used (Mather 1958). Natural pozzolans affect the water requirement of the concrete and therefore the cement content. A natural pozzolan should be considered as part of the cementitious material (U.S. Bureau of Reclamation 1975). The amount of natural pozzolan used varies significantly based upon the activity of the pozzolan. Some natural pozzolans are used in a range of 15 to 35% based upon the mass of the total cementitious material in the concrete. More reactive natural pozzolans can be used in lower concentrations of 5 to 15% by mass of total cementitious material; however, such low concentrations may increase expansion resulting from the altered silica reaction in the presence of some alkali-reactive aggregates (Stanton 1950). The optimal amount of natural pozzolan depends on where the concrete is used and the specifications for the work.

2.2—Properties of fresh concrete

Most natural pozzolans produce a cohesive mixture that maintains a plastic consistency, improving the workability. Typically, natural pozzolans absorb water from the mixture and hold this water in the system allowing for improved finishing.

Where the available concrete aggregates are deficient in finer particle sizes, particularly material passing the 75 μm (No. 200) sieve, the use of a finely divided mineral admixture can reduce bleeding and segregation, and increase the strength of concrete by supplying those fines missing from the aggregate (ACI 211.1). When an appropriate quantity of mineral admixture is used to correct such grading deficiencies, no increase in total water content of the concrete is required to achieve a given consistency or slump. Drying shrinkage and absorption of the hardened concrete are not greatly affected. A favorable particle shape, which is not flat or elongated, and a satisfactory fineness of the mineral admixture, however, are necessary qualities if a low water content is to be achieved without use of a water-reducing admixture. For example, coarse pozzolan of poor particle shape, such as finely divided pumicites, may require an increase in water content of the concrete for a given slump. This may contribute to increased bleeding and segregation of the fresh concrete.

The use of finely divided mineral admixtures having pozzolanic properties can provide a major economic benefit in that the use of these materials permits a reduction in the amount of portland cement in the mixture. For example, Waugh (1963) reported that the U.S. Army Corps of Engineers experienced a major economic benefit through the use of natural pozzolan; although, aside from a reduction in water requirement, other technical benefits had not been spectacular. When the ratio of surface area of solids to volume of water is low, the rate of bleeding is relatively high. Moreover, most of the bleeding does not appear at the surface. The aggregate particles settle for a short period until they establish point-to-point contacts that prevent further settlement. The watery paste continues to bleed within the pockets defined by aggregate particles, leaving water-filled spaces at the undersides of the particles. Therefore, with such mixtures, bleeding tends to reduce homogeneity of the concrete. In extreme cases, the lack of homogeneity is manifested by open fissures large enough to be easily visible to the naked eye in a cross section of the concrete under the aggregate particles. This lack of bond between paste and aggregate reduces the potential strength of concrete and increases permeability and absorption.

These undesirable effects can be reduced by increasing the ratio of surface area of solids to volume of water in the paste. This generally increases the stiffness of the paste and, at a given slump, effects a wider separation of the aggregate particles in the concrete. Increasing the amount of a suitable pozzolan usually increases the ratio of surface area of solids to volume of water.

Natural pozzolans generally increase the cohesiveness of the mixture by producing a more plastic paste that allows the concrete to consolidate readily and flow freely under vibration. The increased cohesiveness also helps to reduce segregation.

Natural pozzolans should have physical characteristics that allow the portland cement-pozzolan paste to contain a maximum proportion of solid matter and a minimum proportion of water. This requires that the mineral particles not have too high a surface area. The preferred shape would be a smooth, round particle instead of an irregular, rough-textured particle that would have a higher water demand. The high water demand of bentonite, which has a surface area considerably higher than cement, limits the use of that natural pozzolan to smaller percentages than those used in conventional concrete mixture proportions.

As is the case with other pozzolans, for example, fly ash (ACI 232.2R), the use of natural pozzolan may extend the time of setting of the concrete if the portland cement content is reduced. The setting-time characteristics of concrete 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 pozzolan; and the fineness and chemical composition of the 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. Pressures on formwork may be increased when concrete containing a natural pozzolan is used if increased workability, slower slump loss, or extended setting-time characteristics are encountered.

2.3—Properties of hardened concrete

Concrete containing a pozzolan typically provides lower permeability, reduced heat of hydration, reduced alkali-aggregate-reaction expansion, higher strengths at later ages, and increased resistance to attack from sulfates from seawater or other sources than concrete that does not contain pozzolan (Mather 1958). Mather (1982) reported that the sulfate

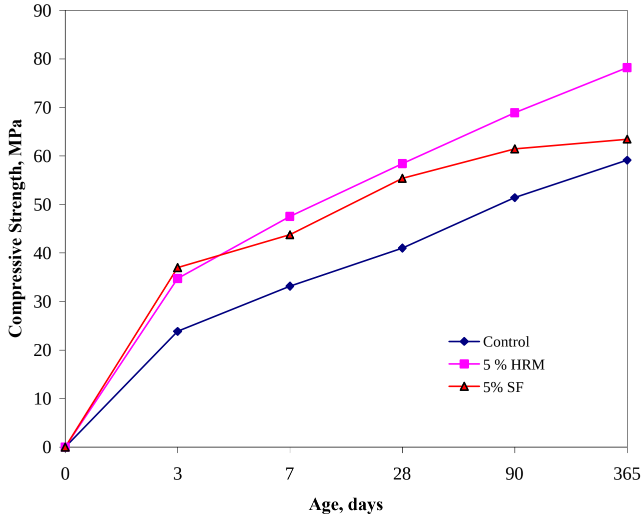

Fig. 2.1—Comparison of compressive strength of high-reactivity metakaolin and silica fume concrete at 5% cement replacement (Calarone, Gruber, and Burg 1994).

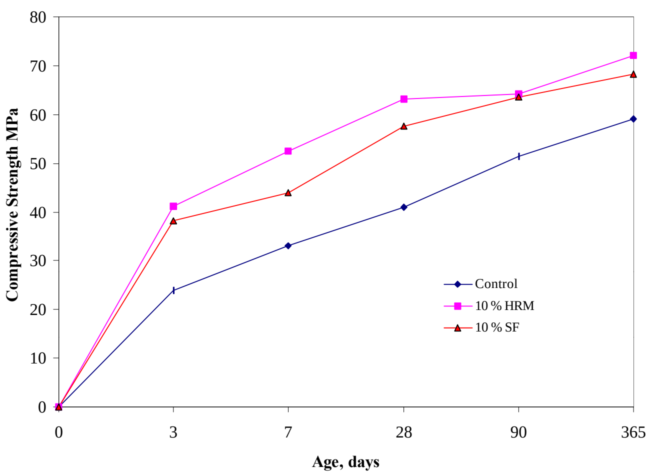

Fig. 2.2—Comparison of the compressive strength of high-reactivity metakaolin and silica fume concrete at 10% cement replacement (Calarone, Gruber, and Burg 1994).

resistance of mortar is highest when a silica fume or a highly siliceous natural pozzolan is used.

2.3.1 *Strength*—The effect of a natural pozzolan on the compressive strength of concrete varies markedly with the properties of the particular 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. For example, materials that are relatively low in chemical activity generally increase the strength of lean mixtures and decrease the strength of rich mixtures. On the other hand, cements and pozzolans contribute to strength not only because of their chemical composition but also because of their physical character in terms of particle packing (Philleo 1986). When some pozzolanic materials of low chemical activity are used to replace cement on an equal volume basis, early strengths may be reduced.

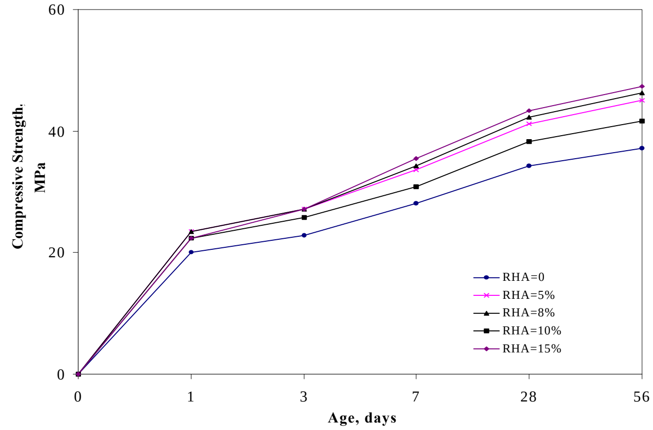

*Fig. 2.3—Development of compressive strength of concrete with different percentages of RHA as cement replacement (*w/cm *= 0.40) (Zhang and Malhotra 1996).*

These early strengths can be increased by substituting the pozzolanic material for the cement on an equal mass basis or a volumetric amount greater than one-to-one for the cement replaced, provided that the increase in the amount of pozzolanic materials does not significantly increase the *w/cm* so that the required strength of the concrete is not achieved.

A natural pozzolan of high chemical activity, such as metakaolin, can sometimes increase early-age strengths, even when used as a replacement for cement, either by an equal mass or by volume in an amount greater than one-to-one for the cement replaced. Caldarone, Gruber, and Burg (1994) compare the compressive strength of a concrete without pozzolan with concrete containing a highly reactive metakaolin at an addition level of 5 to 10% by mass of cement. Figures 2.1 and 2.2 show that at all testing ages, the concrete containing this natural pozzolan provided higher compressive strength than the control (*w/cm* = 0.38, 0.36, 0.38, and 0.36 compared with 0.41 for the control).

Zhang and Malhotra (1996) report on the physical and chemical properties of RHA, and a total of 10 air-entrained concrete mixtures were made to evaluate the effects of the use of RHA as a cement replacement. Their test results indicate that RHA is highly pozzolanic and can be used to produce high-performance concrete. The test results are shown in Fig. 2.3 through 2.5. Figure 2.3 shows the compressive strength development of concrete with different percentages of RHA. Figure 2.4 shows the increase of compressive strength of concrete containing RHA with decreasing *w/cm* from 0.50 to 0.31. Figure 2.5 shows compressive strengths of concrete with RHA and silica fume compared with that of control concrete at various ages up to 730 days.

It has been shown in Europe and the United States that the intergrinding of pozzolans with portland cement clinker in the production of blended cements improves their contribution toward strength. Results from an investigation of the effect of curing time on the compressive strength of ASTM C 109 mortar cubes, made with portland-pozzolan cements containing 10, 20, and 30% Santorin earth, are shown in Fig. 2.6 and 2.7 by Mehta (1981). It is clear from these re-

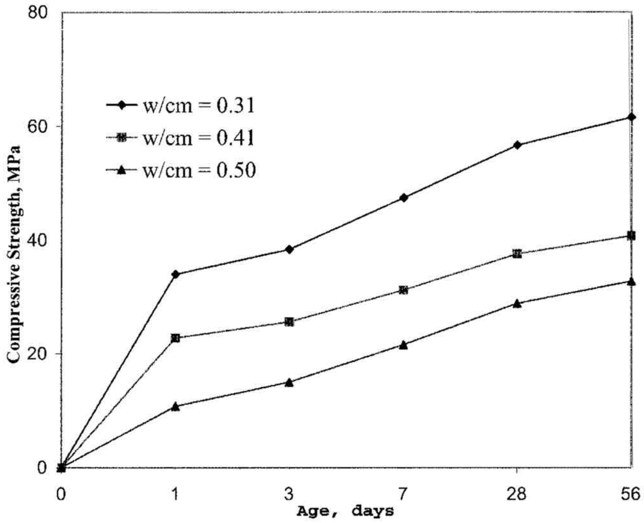

Fig. 2.4—Development of compressive strength of concrete with different w/cm *(RHA content = 10%) (Zhang and Malhotra 1996).*

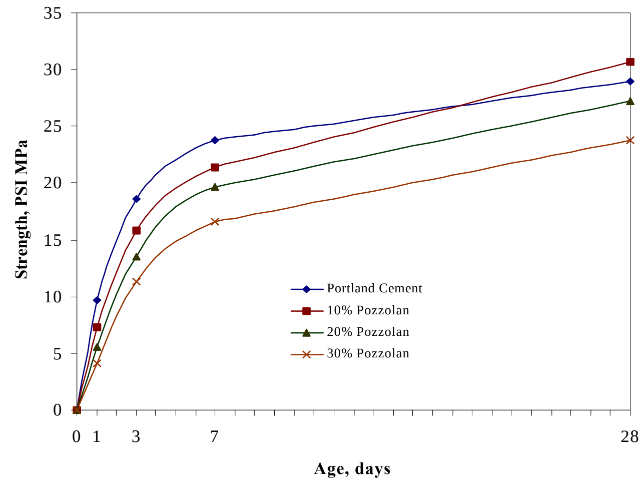

Fig. 2.6—Effect of curing time on compressive strength of mortar cubes up to 28 days made with portland-pozzolan cements containing Santorin earth (Mehta 1981).

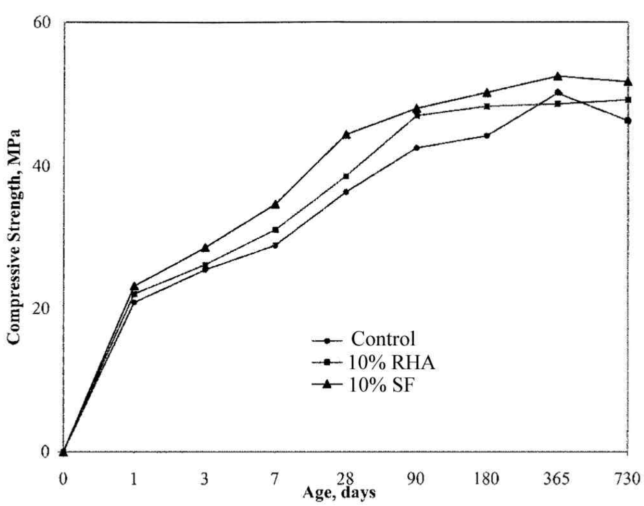

Fig. 2.5—Development of compressive strength of concrete with RHA and silica fume (w/cm *= 40) (Zhang and Malhotra 1996).*

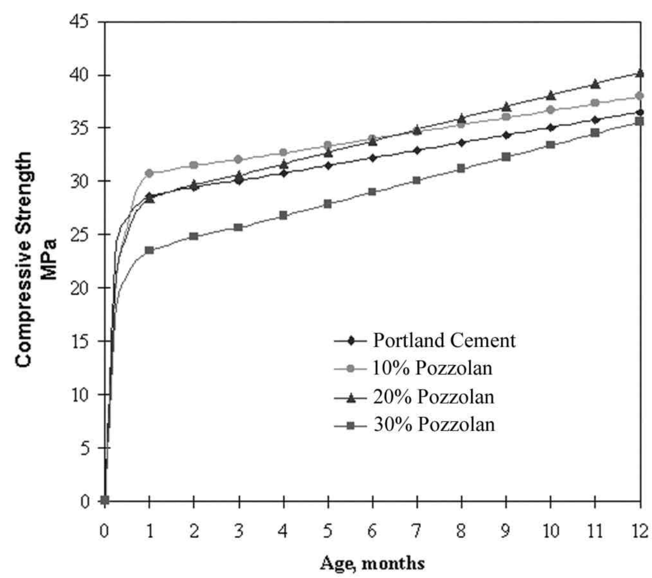

Fig. 2.7—Effect of curing time on compressive strength of mortar cubes up to 12 months made with portland-pozzolan cements containing Santorin earth (Mehta 1981).

sults that the contribution of the pozzolan to compressive strength development occurs sometime after seven days of hydration.

At 28 days, the compressive strength of a concrete with 10% Santorin earth was higher than that of the reference portland cement concrete. At 90 days, the concrete that used 10 and 20% pozzolan showed compressive strengths higher than that of the reference portland cement concrete, and at 1 year, the concrete that used 30% pozzolan was similar to that of the reference portland-cement concrete, as shown in Fig. 2.7. As shown in Fig. 2.8, Massazza and Costa (1979) reported similar results on the effect of substituting varying proportions of portland cement with an Italian natural pozzolan. Figure 2.9 compares the compressive strength development of fly ash concrete and concrete containing a calcined diatomaceous shale natural pozzolan to the compressive strength of the control concrete. (Elfert 1974).

2.3.2 *Sulfate resistance*—Use of natural pozzolans with portland cement in concrete generally increases resistance to aggressive attack by seawater, sulfate-bearing soil solutions, and natural acid waters. The relative improvement is greater for concrete with a low cement content. The use of a pozzolan with sulfate-resistant portland cements may not increase sulfate resistance and, if chemically active aluminum compounds are present in the pozzolan, a reduction in sulfate resistance of the concrete may result.

ASTM C 1012 is a suitable performance test method developed to evaluate the performance of mortars made with portland cements, blended cements, and blends of portland cements with fly ash, natural pozzolans, or slags in produc-

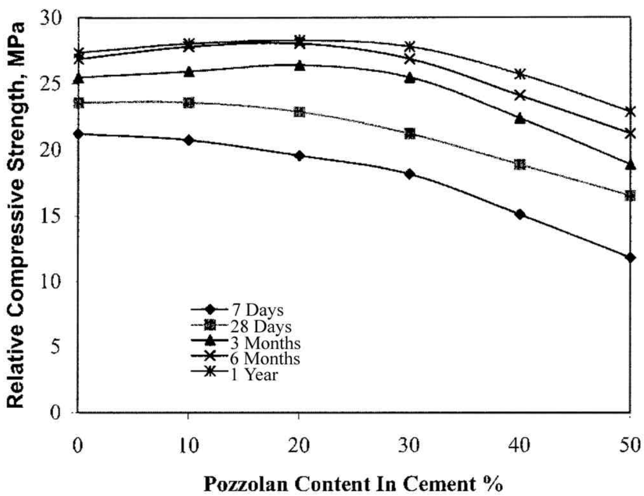

Fig. 2.8—Effect of substituting Italian natural pozzolan for portland cement on compressive strength of ISO mortar (Massazza and Costa 1979).

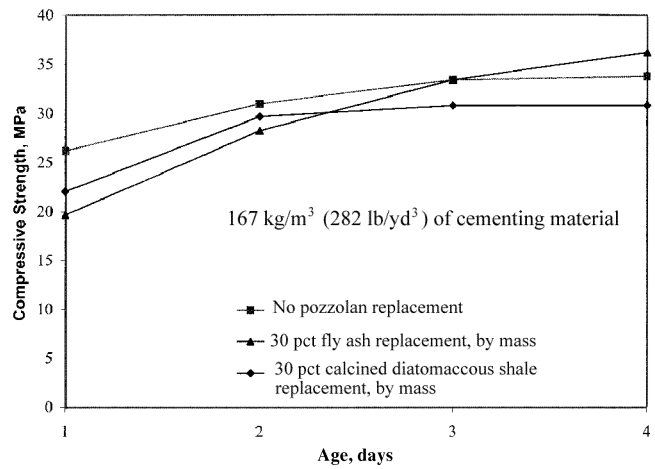

Fig. 2.9—Effect of pozzolan on compressive strength of concrete (Elfert 1974).

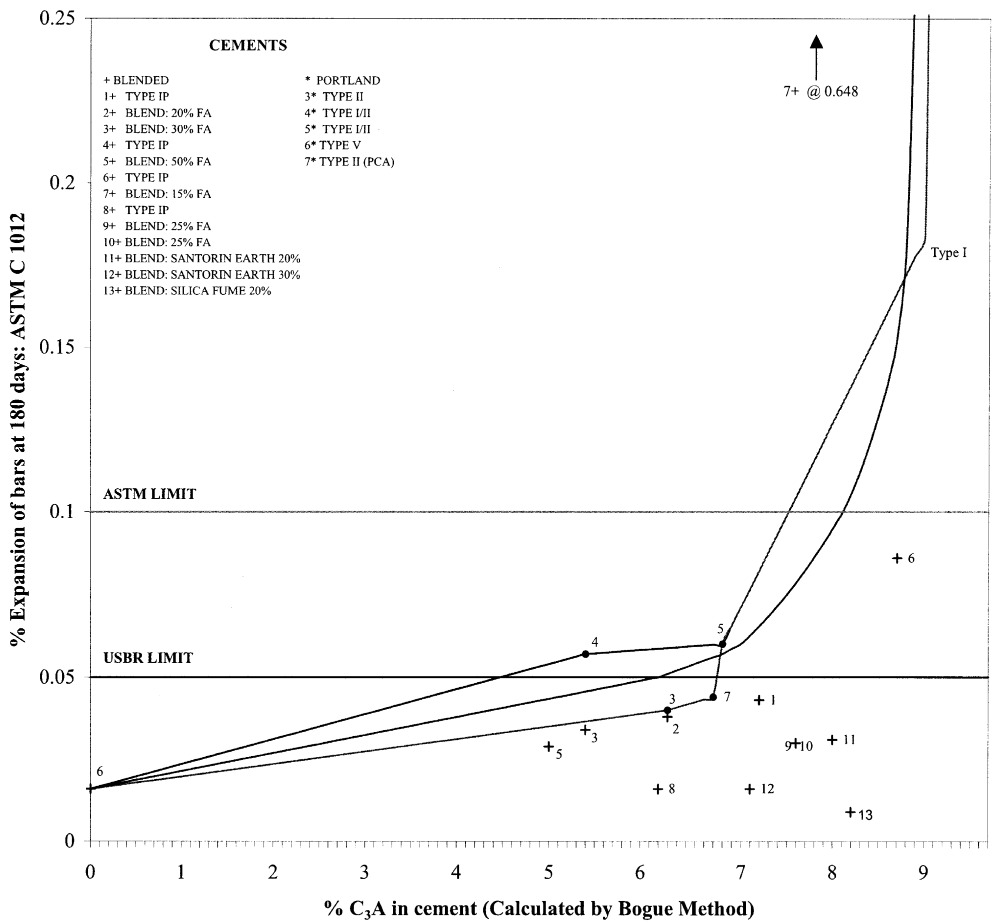

Fig. 2.10—ASTM C 1012 sulfate resistance results comparing blended cements and portland cements having same C_3A content as calculated by Bogue method (Patzias 1987).

ing a sulfate-resisting cement mortar (Patzias 1987). A series of ASTM C 1012 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, slags, or silica fume had better sulfate resistance than portland cements having the same C_3A content as calculated by the Bogue method (Fig. 2.10) (Patzias 1987).

An extensive research program at the USBR assessed various natural pozzolans for sulfate resistance (Elfert 1974). Figure 2.11 shows the results of accelerated tests in 2.1% sodium sulfate solution to predict the service life of var-

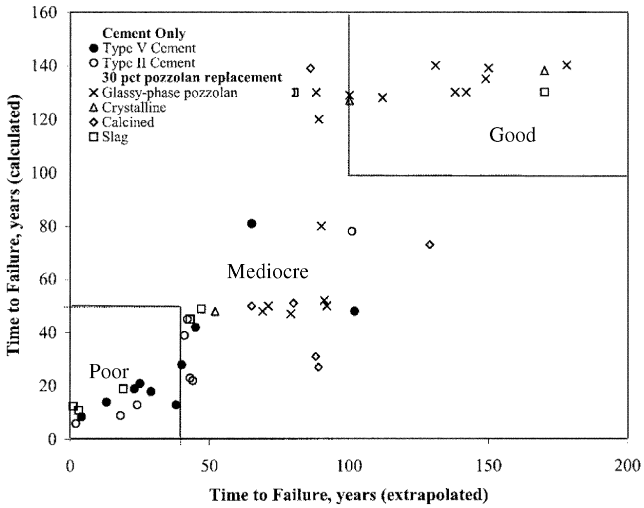

Fig. 2.11—Accelerated sulfate resistance tests to predict service life of concrete (Elfert 1974).

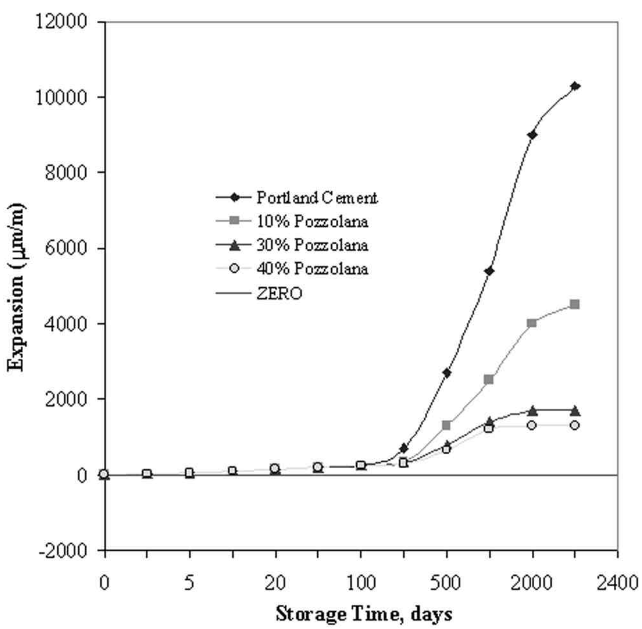

Fig. 2.12—Effect of substituting Italian natural pozzolan for portland cement on expansion of 1:3 mortar. Samples 2 x 4 x 25 cm stored in 1% $MgSo_4$ solution (Massazza and Costa 1979).

ious concretes. From early and updated tests (18 to 24 years), it was shown that 8 years of continuous service exposure is comparable to 1 year of accelerated testing using a criteria of 0.5% expansion or 40% loss of elastic modulus. These results were then plotted and categorized to determine the life expectancy of various concretes in a sulfate environment.

Massazza and Costa (1979) studied the effect of substituting portland cement with 10, 30, and 40% of an Italian pozzolan on the expansion of 1:3 mortar prisms stored for more than 5 years in 1% $MgS0_4$ solution, as shown in Fig. 2.12. The authors attribute the results to the reduced content of calcium hydroxide and to lower permeability of the concretes containing the pozzolan.

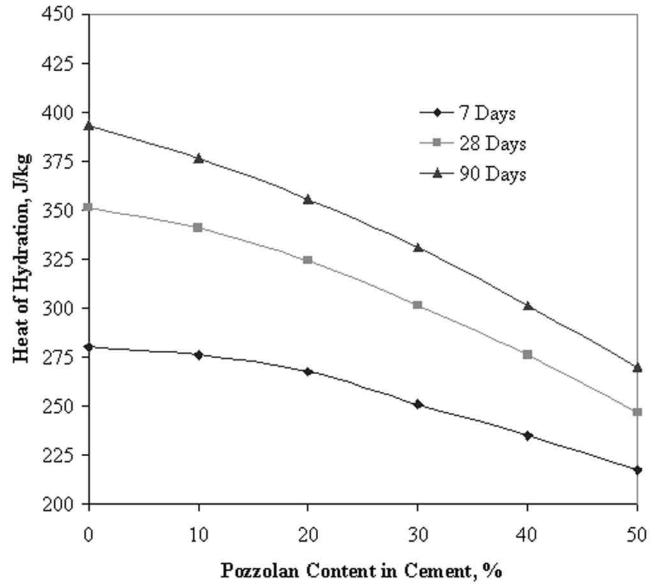

Fig. 2.13—Effect of substituting Italian natural pozzolan for portland cement on heat of hydration (Massazza and Costa 1979).

2.3.3 *Temperature rise*—At a given cement content, the addition of small amounts of chemically inert materials has little or no effect on the temperature rise during the curing of concrete in place. Pozzolans have been used in mass concrete as a partial replacement of portland cement to reduce the temperature rise, as compared to that of a comparable concrete mixture containing portland cement as the only cementing material. According to Townsend (1968), the heat of hydration that a pozzolan will contribute is approximately 50% of what would have been developed by an equal amount of portland cement.

Massazza and Costa (1979) show in Fig. 2.13 that the replacement of portland cement by the Italian pozzolan reduced the heat of hydration but by less than in proportion to the amount of portland cement replaced because of some evolution of heat during the pozzolanic reaction. Similarly, Nicolaidis (1957) found that the seven day heat of hydration of a Greek portland-pozzolan cement with 20% cement replacement by Santorin earth was reduced by 9 J/kg, compared to portland cement only.

Figure 2.14 shows the beneficial effects of using a fly ash and a natural pozzolan (calcined diatomaceous shale) in the concrete mixture to reduce temperature rise in mass concrete. The rate of heat development closely parallels the rate of compressive strength development as both are functions of the same chemical reactions. The slower rate of heat development of concrete containing pozzolans permits lowering the temperature rise at lower cost than with comparable, nonpozzolan concrete (Elfert 1974).

Figure 2.15 shows the adiabatic temperature rise of concretes containing 30% and 50% calcined-clay pozzolan by volume replacements of portland cement. Figure 2.16 shows the adiabatic temperature rise of concretes containing 15 to 25% calcined clay pozzolan as a partial replacement by volume of portland cement (Saad, Andrade, and Paulon 1982).

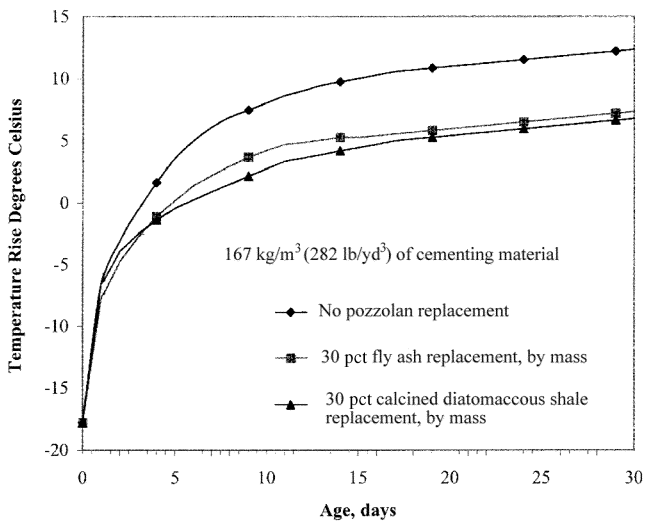

Fig. 2.14—Effect of pozzolan on temperature rise of concrete (Elfert 1974).

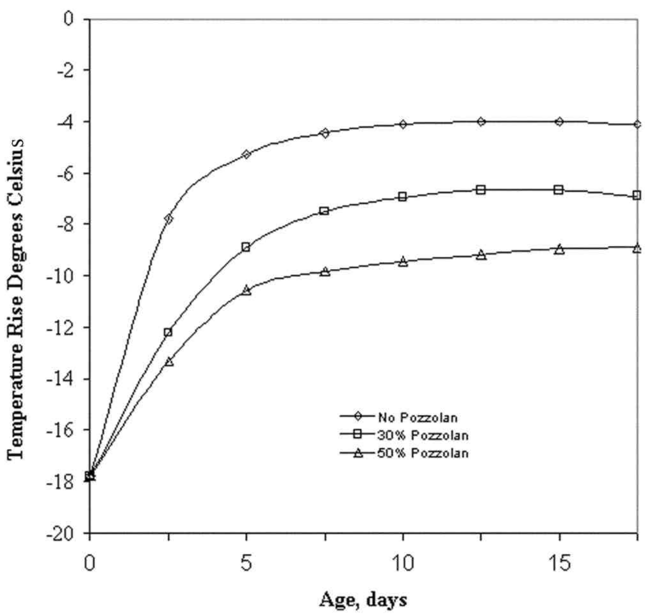

Fig. 2.15—Adiabatic temperature rise (Saad, Andrade, and Paulon 1982).

Figure 2.17 shows the autogenous temperature rise of concrete mixtures containing metakaolin and silica fume as partial replacements by volume of cement. The maximum temperature of the metakaolin concrete was somewhat higher than that of the silica fume concrete and the control concrete (Zhang and Malhotra 1995).

2.3.4 *Expansion due to alkali-silica reaction*—The committee has not found any data on the use of natural pozzolans to prevent excessive expansion resulting from alkali-silica reaction in which it is indicated that damage can be done by using too much pozzolan. An insufficient proportion of pozzolan, however, may actually increase detrimental effects of the alkali-silica reaction (Mather 1993). Trial batching and laboratory testing for compliance to ASTM C 441 should

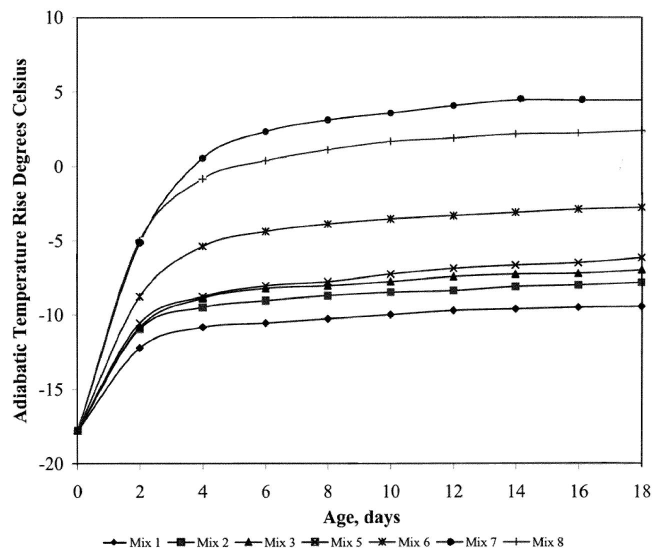

Fig. 2.16—Adibatic temperature rise (1 kg/m^3 = 1.7 lb/yd^3) (Saad et al. 1982).

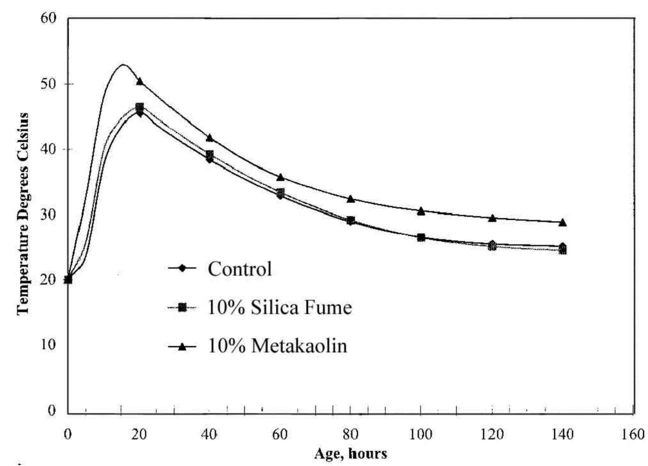

Fig. 2.17—Autogenous temperature rise in 152 x 305 mm concrete cylinders (Zhang and Malhotra 1995).

determine the appropriate amount of pozzolan required. The alkali-silica reaction involves the interaction of hydroxyl ions associated with alkalies 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 phases present in cement, in relatively small proportions expressed as sodium oxide equivalent, sum of the percentage of Na_2O, and 0.658 times the percentage of K_2O. When this particular type of distress of concrete was first described by Stanton (1940), the only apparent remedies were the use of portland cement of low-alkali content (0.60% or less computed as Na_2O) or the avoidance of reactive aggregates. The evaluation of long-term performance of test pavements indicates that pozzolans can be beneficial in reducing or eliminating map cracking and expansion resulting from this reaction.

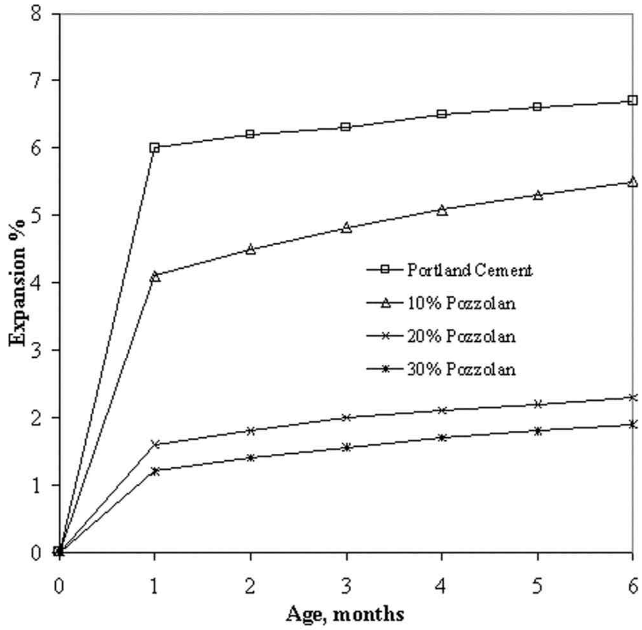

Fig. 2.18—Control of alkali-silica expansion by Santorin earth (Mehta 1981).

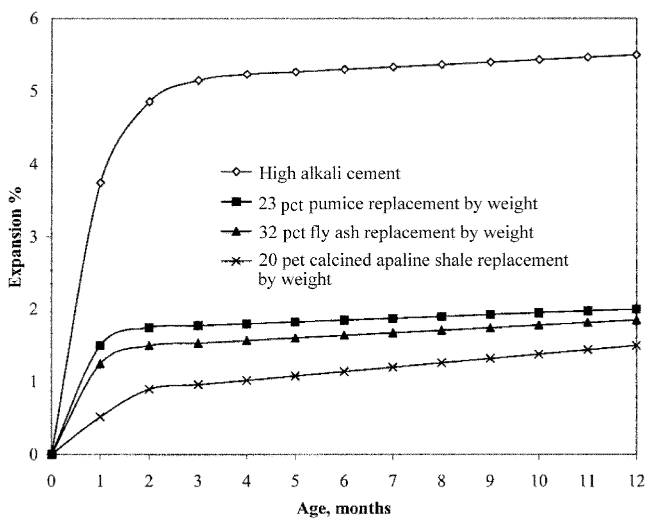

Fig. 2.19—Effect of pozzolan on reactive expansion of mortar made with alkali cement and crushed Pyrex glass sand (Elfert 1974).

Many investigators have observed that natural pozzolans are usually more efficient than fly ash in controlling the alkali-silica reaction. Pepper and Mather (1959) found that the percentage by solid volume of the pozzolan needed to replace portland cement for adequate reduction of expansion varied from 20% with diatomite, and 20 to 30% with calcined shale. In the case of a volcanic glass, 30 to 35% cement replacement was needed to meet the requirements of ASTM C 441. Similarly, the results of an investigation by Mehta (1981) show that a portland cement with 1.0% equivalent Na_2O blended with 20 or 30% Santorin earth was quite satisfactory to control the alkali-silica expansion as shown in Fig. 2.18.

Figures 2.19 and 2.20 show the effectiveness of several types of pozzolans in reducing the expansion due to the alkali-silica reaction. Although low-alkali cement is satisfactory for use with most reactive aggregates, some aggregates require the additional control provided by pozzolans or slag.

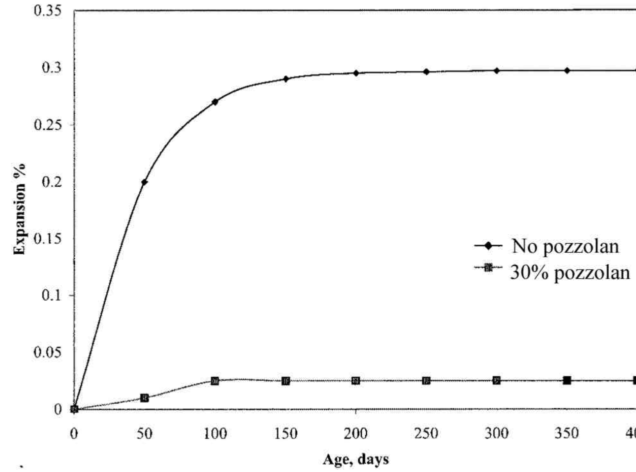

Fig. 2.20—Effectiveness of pozzolan in reducing expansion due to alkali-silica reaction (Saad et al. 1982).

2.3.5 *Permeability*—Certain pozzolans are more effective than others in reducing permeability of concrete at early ages. Under most conditions of service, however, the permeability of concrete containing any pozzolan is markedly reduced at later ages. Davis (1950) concludes 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. Depending on particle shape, particle-size distribution, and particle surface texture of the cement, aggregates, and pozzolan used, a pozzolan may increase or decrease the water requirement for given workability. Mehta (1981) made a pore-size distribution analysis with mercury intrusion porosimetry on 28-day, 90-day, and 1-year-old 0.60 *w/cm* pastes containing Santorin earth and portland cement. Table 2.1 shows the effects of age on hydration and amount of pozzolan present in the cement paste using a test for permeability that measures the depth of penetration of water containing a few drops of phenolphthalein solution after 3 h into cylindrical specimens at 70 C (Mehta 1987).

Reduced permeability, as it relates to resistance to chloride-ion penetration, is important for corrosion protection of reinforcing steel embedded in concrete. Hooton, Gruber, and Boddy (1997) showed that both increasing concentrations of natural pozzolan (high-reactivity metakaloin) and decreasing *w/cm* decreased diffusion, permeability, and conductivity.

Hooton, Gruber, and Boddy (1997) showed that 8 and 12% by mass of highly reactive metakaolin improved the chloride penetration resistance of both 0.30 and 0.40 *w/cm* concretes. Chloride diffusion tests, AASHTO T259 chloride ponding tests, and ASTM C 1202 resistivity tests all ranked concretes in the same order. They showed that 12% metakaolin improved chloride penetration resistance more than reducing *w/cm* of the concrete mixture containing no metakaolin from 0.40 to

Table 2.1—Depth of penetration of water into hydrated cement pastes

	Depth of penetration, mm			
Age	Portland cement	10% Santorin earth	20%	30%
28 days	25	23	23	22
90 days	25	23	23	22
1 year	25	23	18	15

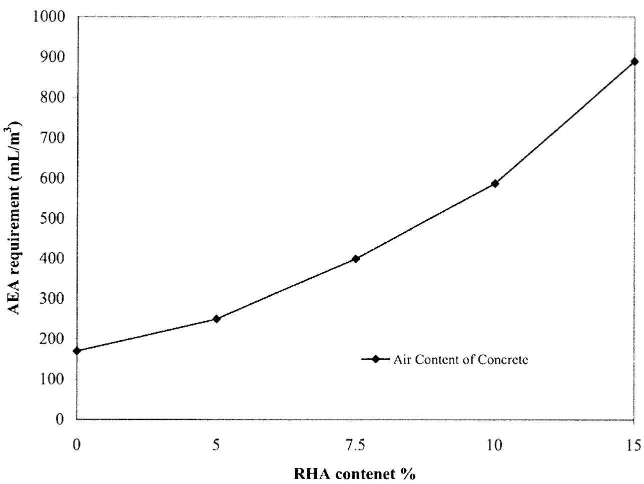

Fig. 2.21—Relationship between requirement of air-entraining admixture and RHA content (Zhang and Malhotra 1996).

0.30. Significantly reduced rapid chloride permeability values (ASTM C 1202) were also found with 10% metakaolin in concrete at $w/cm = 0.36$ compared to a concrete at a $w/c = 0.40$ (Caldarone, Gruber, and Burg 1994). Metakaolin was found to increase the chloride-binding capacity of pastes (Coleman and Page 1997), which further reduces chloride penetration. Opponents of the use of pozzolans have speculated that such use, involving conversion of calcium hydroxide to CSH, would be harmful by reducing the reserve basicity and permitting carbonation that causes decreased passivity of reinforcing steel. Others who favor the use of pozzolans have suggested that a major benefit of such use is the binding into useful, nonleaching CSH of the otherwise soluble $Ca(OH)_2$ with consequent reduction of permeability and reduced tendency for efflorescence. The committee has found no evidence that either of these phenomena are of wide occurrence or significant in degree.

2.3.7 *Freezing-and-thawing resistance*—Of the finely divided mineral admixtures, pozzolans have received the most attention regarding their effect on the freezing-and-thawing resistance of concrete. The effect of pozzolans on concrete resistance to freezing and thawing, and to the action of deicing chemicals during freezing depends on the proportioning, compressive strength, and moisture condition of the concrete, and adequacy of the air-void system at the time of exposure (Lovewell 1971).

Sometimes, the use of a pozzolan requires a higher dosage of air-entraining admixture to produce a given air content than that required by comparable concrete not containing a pozzolan. The proportion of air-entraining admixture required might vary considerably among different sources and types of pozzolans. Finely ground pozzolan containing carbon residue tends to reduce the amount of entrained air in a concrete mixture, and therefore, may require a higher dosage of air-entraining admixture to obtain a given amount of entrained air or the desired air-void spacing factor. 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; however, RHA concrete required relatively high air-entraining admixture dosage and the dosage increased with an increase of the percentage of RHA used as cement replacement as seen in Fig. 2.21.

It is clear from the research of the USBR on the effect of pozzolan on resistance of concrete to freezing and thawing that curing conditions have a very important role, as shown in Fig. 2.22. (Elfert 1974).

2.3.8 *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% Santorin earth was not significantly different from that of the concrete containing the reference portland cement, as shown in Fig. 2.23. Research by Zhang and Malhotra (1995) in Fig. 2.24 shows the drying shrinkage strain of a control mixture and concretes containing 10% replacement by silica fume and metakaolin.

CHAPTER 3—SPECIFICATIONS, TEST METHODS, QUALITY CONTROL, AND QUALITY ASSURANCE

3.1—Introduction

The ASTM specification for fly ash and natural pozzolan is ASTM C 618, and the standard test methods are in ASTM C 311. ASTM C 618 was originally published in 1968 to combine and replace ASTM C 350 on fly ash and ASTM C 402 on other pozzolans for use as mineral admixtures. ASTM C 311 for sampling and testing was published originally in 1953. In Canada, natural pozzolans are covered in CSA A23.5 on Supplementary Cementing Materials.

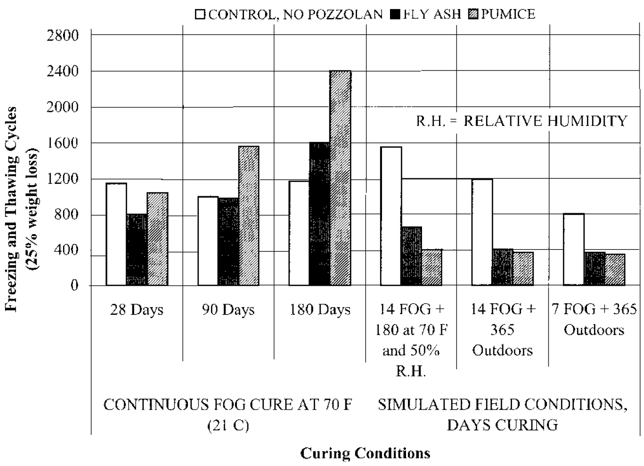

Fig. 2.22—Effect of pozzolans on freezing-and-thawing resistance of cement is greatly influenced by curing conditions (Elfert 1974).

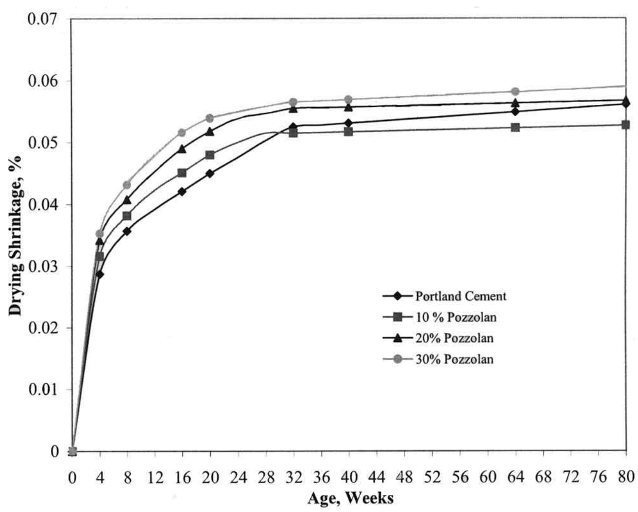

Fig. 2.23—Drying shrinkage of concrete prisms made with cements containing various amounts of Santorin earth (Mehta 1981).

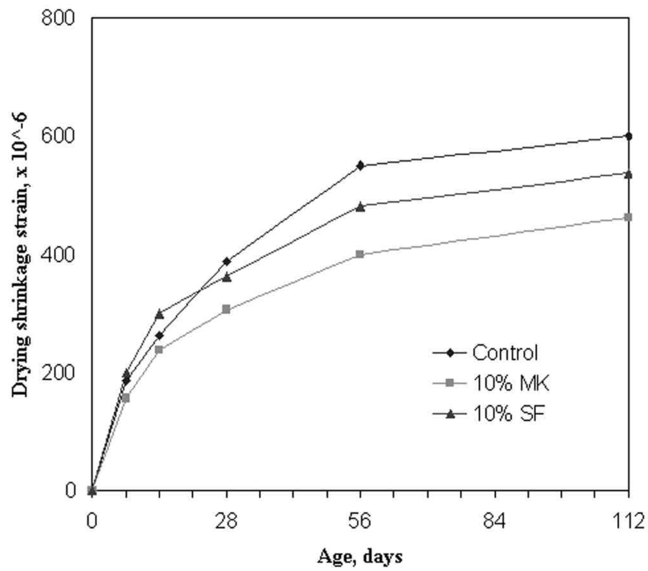

Fig. 2.24—Drying shrinkage strain of concrete (Zhang and Malhotra 1995).

3.2—Chemical requirements

Early studies sought to relate pozzolan performance with chemical analysis for silica, alumina, or iron oxide but had little success. Today, many, but not all, specifications have a minimum requirement for the sum of the oxides SiO_2 + Al_2O_3 + Fe_2O_3. The intent is to ensure that sufficient potentially reactive constituents are present. ASTM C 618 requires a minimum of 70% for the sum of these oxides for Class N pozzolans, 10.0% maximum loss on ignition, 4.0% maximum SO_3, and 3.0% maximum moisture content.

3.3—Physical requirements

Pozzolan fineness is controlled in most cases by limiting the amount retained on the 45 µm (No. 325) sieve by wet sieving. 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. ASTM C 618 limits the amount retained to 34% for natural pozzolans. Some specifications use specific surface by air-permeability fineness methods to control fineness, ASTM C 618 does not.

The strength activity index with portland cement measures strength of 50 mm (2 in.) cubes made using 80% portland cement and 20% pozzolan mixed to constant flow and tested at 7 and 28 days, and is considered only as an indicator of reactivity and does not measure the compressive strength of concrete containing the pozzolan. It provides no information on the optimum proportion of pozzolan for use in concrete. Other specified and optional requirements relating to physical properties include the following:

1. *Water requirement of the mortar*—ASTM C 618 requires the water demand not to exceed 115% of the control mixture based on the amount of water required to achieve a flow equal to within ± 5% of the control mixture in the strength activity index test for mortar;

2. *Soundness*—Determine soundness by measuring autoclave expansion or contraction of a paste made with 25 parts by mass of the pozzolan and 100 parts by mass of portland cement. A length change of 0.8% is the maximum allowed by ASTM C 618. It is specified that if the pozzolan will constitute more than 20% of the cementitious material in the proposed concrete; the paste used for autoclave testing shall contain the anticipated percentage of pozzolan. The test protects against the delayed expansion that could occur if sufficient amounts of MgO are present in the concrete as periclase or CaO is present as hard-burned free lime;

3. *Uniformity limits*—These limits are given in ASTM C 618. Limits are specified for a pozzolan to keep the variation of density and fineness within practical limits for shipments over a period of time. Also, for pozzolan used in air-entrained concrete, there is an optional limit on the permitted variation of air-entraining admixture demand caused by the pozzolan;

4. *Increase in drying shrinkage of mortar bars dried 28 days*—This limit is applied only at the request of the purchaser to indicate whether the pozzolan will cause a substantial increase in drying-shrinkage in mortar bars;

5. *Reactivity with cement alkalies*—Optional mortar-bar expansion tests (ASTM C 441) can be requested if a pozzolan is to be used with an aggregate regarded as deleteriously reactive with cement alkalies and high-alkali cement; and

6. *Sulfate expansion*—Optional test for sulfate deterioration (ASTM C 1012) can be requested when the concrete will be exposed to sulfate environments.

3.4—General specification provisions

ASTM C 618 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."

3.5—Methods of sampling and testing

ASTM C 311 outlines the procedures for testing samples of pozzolan to determine compliance with requirements of ASTM C 618. The three main divisions of the standard are sampling methods, chemical analysis methods, and physical test procedures. For a number of test procedures, reference is made to other cement, mortar, or concrete tests for the body of the test procedure with ASTM C 311, indicating the modifications in proportions, preparation procedures, or test parameters. Many of these procedures use arbitrary proportions not necessarily those to be used on a project.

3.5.1 *Sampling methods*—Either individual grab samples or composite samples may be used depending on the circumstances. This method, as described in ASTM C 311, provides detailed procedures for sampling 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.

3.5.2 *Chemical analysis methods*—Chemical analysis procedures involve determining moisture content by drying to constant mass and then the loss on ignition. The latter requires igniting the dried sample to constant mass in a muffle furnace at 750 ± 50 C (1382 F ± 122 F) using an uncovered porcelain crucible (not a platinum crucible, as used for cement testing). Many of the required chemical determinations are then made using procedures that are the same as, or very similar to, those used in testing portland cement.

3.5.3 *Physical test procedures*—Physical tests include determining the density and the amount retained on the 45 µm (No. 325) sieve using the test methods developed for portland cement. Soundness and strength testing procedures are included in ASTM C 311 with reference to cement testing procedures where appropriate.

3.6—Quality control and quality assurance

The first recommended step in starting a pozzolan quality-control program is to establish the quality history for each source of pozzolan. This quality history should include ASTM C 618 certification as well as at least 40 individual test results for loss on ignition, amount retained on the 45 µm (No. 325) sieve, density, and SO_3 content. The purpose of the quality history is to demonstrate whether the pozzolan consistently conforms to specification and uniformity requirements. Statistical analysis of these data helps to determine whether the source of pozzolan is suitable for the intended use.

A company selling natural pozzolan intended to be in conformance with ASTM C 618 should have a quality-control program that is technically and statistically sound. After the quality history is established, the source should be tested periodically at the frequencies listed below to ensure continued conformance to ASTM C 618.

The important characteristics of the particular source of a pozzolan should be determined and a quality-control program established for that source, taking into account those characteristics and the requirements of specifications for its use in concrete. Samples may also be taken periodically and stored in the event that future testing and evaluation is desirable.

ASTM C 311 provides for test methods on test procedures for moisture content, loss on ignition, and fineness to be conducted on natural pozzolan samples representing not more than 90 Mg (100 tons) from a new source or 360 Mg (400 tons) from an established source and on test procedures for density and other tests in specification ASTM C 618. Table 1 in ASTM C 311 should be conducted on samples representing not more than 1800 Mg (2000 tons) from a new source or 2900 Mg (3200 tons) from an established source. Sampling and testing on a time schedule basis, in addition to the tonnage basis prescribed by ASTM C 311, may be a useful part of the program. An effective quality-control program allows the supplier to maintain test reports for demonstration of product compliance with regard to the physical, chemical, and uniformity requirements of ASTM or other special project performance requirements, as well as to monitor variability of critical characteristics. Statistical evaluations of the test data provide the supplier with information on long-term variations.

In addition to the producer's quality-control program, some users have extensive quality-assurance programs, for example, that of the U.S. Army Corps of Engineers for United States government projects.

CHAPTER 4—CONCRETE PRODUCTION USING NATURAL POZZOLANS

4.1—Storage

Because natural pozzolans are normally of lower density than portland cement, bulk density should be considered when ordering or taking inventory. The bulk density in bins or silos is generally assumed to be between 880 and 1280 kg/m^3 (55 and 80 lb/ft^3), whereas cement in bins and silos is generally assumed to be between 960 and 1500 kg/m^3 (60 and 94 lb/ft^3). Both pozzolan and cement may have lower bulk density immediately after conveying. Bulk pneumatic tank trucks that typically carry cement and pozzolan are usually large enough in volume to receive a full, legal load for over-highway delivery. Pozzolan of very low bulk density will reduce the load that can be carried.

Bins and silos intended for cement storage may also be used to store pozzolan. They should be large enough to receive at least two deliveries. Due to the similar appearance of pozzolan and 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 pozzolan and to establish proper materials management procedures (Gaynor 1978). Bins should be completely cleaned out when they are being switched over to handle a different type of material. As with cement from different mills, pozzolan from different sources should not be mixed in the same bin.

Pozzolan flows readily when aerated. This characteristic increases the possibility of leakage from bins and silos. When cement and pozzolan must be stored in different compartments of the same bin or silo and are separated by a dividing partition, the partition should be inspected frequently. A double wall with an intervening air space is highly recommended; otherwise, pozzolan may move from one bin to the other through faulty welded connections or through holes caused by wear. Because it is virtually impossible to detect contamination of a cement storage compartment by visually examining the cement as batches of the concrete are mixed, care in avoiding intermingling of cement and pozzolan is of great importance. A separate silo for pozzolan is preferred. Each storage bin and silo should be equipped with a positive shutoff valve to control the flow of the pozzolan in the weigh batcher. Rotary valves, rotary valve feeders, and butterfly valves are generally suitable for this purpose. A conventional scissors-gate may be used if it is well maintained. Independent dust collectors on cement and pozzolan bins are recommended.

4.2—Batching

When batching natural pozzolan and cement at a concrete plant, it is not necessary to install separate weigh batchers. Pozzolan and cement may be batched cumulatively in the same weigh batcher. Cement normally should be batched first so that accidental overbatching of pozzolan will not cause underbatching of cement (Gaynor 1978).

To transport natural pozzolan from bin to batcher, methods such as gravity flow, pneumatic or screw conveyors, or air slides are most often used. The method depends on the location of the pozzolan bin relative to the batch hopper. Pozzolan from overhead storage is normally conveyed by gravity flow or air slide. If the pozzolan storage is close to the same level as the weigh batcher, an air slide or a screw conveyor can be used. Because pozzolan flows very easily, a positive shut-off valve should be installed to ensure that pozzolan does not flow through the air slide or screw when the conveying device is stopped. Pozzolan can be conveyed from lower level storage by pneumatic conveyor.

CHAPTER 5—CONCRETE APPLICATIONS FOR NATURAL POZZOLANS

5.1—Concrete masonry units

Some manufacturers of concrete masonry units use as much as 35% pozzolan in the cementitious material for the manufacture of units cured using high-pressure steam. Others use from 15 to 35% in the cementitious material for the manufacture of units cured using low-pressure steam. Pozzolan reportedly gives added plasticity to the relatively harsh mixtures used in concrete masonry units (Belot 1967). Autoclave curing is not as common as in the past, and some of the newer curing systems with short preset times can present early strength problems when some pozzolans of lower activity are used.

When natural pozzolan is used in concrete products cured in an autoclave at temperatures of 135 to 190 C (275 to 374 F) and pressures of 0.5 to 1.2 MPa (75 to 170 psi), the cement content may be reduced by 30 to 35%. Particular care should be taken to ensure that the pozzolan meets the soundness requirement of ASTM C 618. The average cement replacement in low-pressure steam-curing applications is about 20% pozzolan.

Tests for resistance to freezing and thawing of concrete masonry units containing pozzolans indicate that such units can be expected to perform well in vertical construction, such as walls. For the more severe conditions of horizontal exposure, a minimum compressive strength of 21 MPa (3045 psi) based on the net area of the unit is recommended when normal-density aggregates are used. Air entrainment is not practical at the extremely low or zero slumps used for concrete masonry units. It could, however, 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 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). Pozzolan can be used to reduce moisture absorption of masonry units.

5.2—Concrete pipes

Pozzolans may provide significant benefits in the manufacture of concrete pipes. Properly proportioned mixtures containing pozzolans lessen the permeability of concrete, and therefore, make pipe more resistant to weak acids and sulfates (Davis 1954; Mather 1982). The increase in sulfate resistance achieved depends on the type of cement, type of pozzolan, bedding and backfill used, groundwater, and sulfate concentration. Many concrete pipe producers use cement contents higher than needed for strength to obtain the required workability. Replacing some of the cement with pozzolan can reduce the cement content. 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. Equipment used in pipe production may last longer because of the lubrication effect. Use of a natural pozzolan can increase the cohesiveness of the no-slump, freshly placed concrete, facilitating early form stripping. A reduction in the heat of hydration of concrete mixtures containing pozzolan can reduce the amount of hairline cracks on the inside surface of stored pipe sections (Cain 1979) and concrete mixtures containing pozzolan tend to bleed less.

5.3—Prestressed concrete products

Each form used in the production of prestressed concrete products requires a large capital investment. For this reason, prestressed concrete products generally achieve their competitive position in the marketplace by using a limited number of forms and a short production cycle. Production cycles of 24 h are common. Compressive strengths of 24 to 28 MPa (3480 to 4060 psi) are 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. These early concrete strengths are generally achieved with high cement contents of 355 to 445 kg/m^3 (600 to 750 lb/yd^3), conventional or high-range water-reducing admixtures, or both, and curing methods employing elevated temperatures. A nonchloride accelerating admixture is sometimes used. With the exception of highly reactive natural pozzolans, such as metakaolin, that do not reduce early strength, natural pozzolans are generally neither used for prestressed concrete structural members, nor for prestressed concrete pipe.

When pozzolans are used, better surfaces with fewer air voids are usually achieved. This is attributed to the improved workability of the concrete.

5.4—Mass concrete

Natural pozzolans have been used extensively in the United States in mass concrete structures where the risk of thermal cracking can be a major problem. Natural pozzolans were used in the construction of the Los Angeles Aqueduct, the San Francisco Bay and Golden Gate bridges, and in 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 in which natural pozzolans were used in the United States (ACI 207.1R). Davis (1950) gives extensive evaluations and experience in the use of pozzolans. 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), Kokubu (1963), and Tuthill, Adams, and Mitchell (1963). Elfert (1974) gives an extensive report on USBR experience with fly ash and other pozzolans over the period of 1942-1973, with reference also to use of finely divided mineral admixtures in mass concrete in the period of 1915-1916. Today, practically all mass-concrete dams contain natural pozzolans, fly ash, or ground slag.

By using natural pozzolan concrete in massive dam construction, it is possible to achieve a 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 to increased permeability (Price 1982). In addition, use of pozzolan can reduce thermal stresses by the reduction of the heat of hydration in mass concrete structures (Blanks, Meissner, and Rawhauser 1938; Carlson, Houghton, and Polivka 1979). Improved sulfate resistance and reduction of alkali-silica reaction provided by proper incorporation of pozzolan into concrete mixtures are other important considerations in the construction of massive concrete dams.

The committee found no case histories of the use of natural pozzolan in structural concrete.

CHAPTER 6—OTHER USES OF NATURAL POZZOLANS

6.1—Grouts and mortars

According to ACI 116R, grout is "a mixture of cementitious material and water, with or without aggregate, proportioned to produce a pourable consistency without segregation of the constituents." Its primary purpose is to fill spaces or voids. Mortar contains the same basic ingredients but with a less fluid consistency. It is used in masonry construction and is specified by ASTM C 270. This specification permits the use of natural pozzolans as a blended cement. The effects of using natural pozzolans in mortars have not been fully investigated; however, 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:

- In preplaced aggregate concrete, where grout is injected into the voids of previously placed coarse aggregate to produce concrete (ACI 304.1R);
- 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;
- To provide support for deep mine applications;
- In curtain grouting, where very fluid mixtures (often with the aggregate omitted) are used to fill cracks or fissures in rock;
- In 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;
- In slab jacking, to raise and realign concrete slabs or structures that have settled; and
- In 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.

6.2—Controlled low-strength materials

Formulations containing pozzolan, cement, water, and fine aggregate have been used as controlled low-strength fills in place of compacted soil. These formulations, delivered by truck mixers, can be proportioned to flow like a liquid, but they are capable of supporting normal loads after hardening. No tamping or compaction is necessary after hardening to achieve the required density and strength. Such materials can be used for trench backfilling, pipe bedding, foundation subbase, paving subbase, 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 settlement could cause problems. Compressive strengths ranging from approximately 0.35 to 8.28 MPa (50 to 1200 psi) can be achieved, which provides the necessary rigidity for volume stability. At compressive strength levels less than 1 MPa (145 psi), such formulations can be excavated readily. Economy is achieved because no backfill labor crews and equipment are necessary. The material can be self-leveling and can 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, must be considered in some applications. Pozzolan can also be used by itself as a fill material. The necessary moisture requirements and packing densities can be determined through the use of laboratory and field tests. Work on this class of products is the responsibility of ACI Committee 229 (ACI 229R). Blended hydraulic cements, which may contain natural pozzolans, are the responsibility of ACI Committee 225 (ACI 225R).

CHAPTER 7—REFERENCES

7.1—Referenced standards and reports

The standards and reports listed below were the latest editions at the time this document was prepared. Because these documents are revised frequently, the reader is advised to contact the proper sponsoring group if it is desired to refer to the latest version.

American Concrete Institute (ACI)

116R Cement and Concrete Terminology
201.2R Guide to Durable Concrete
207.1R Mass Concrete
211.1 Standard Practice for Selecting Proportions for Normal, Heavyweight, and Mass Concrete
212.3R Chemical Admixtures for Concrete
212.2R Guide for Use of Admixtures in Concrete
225R Guide to the Selection and Use of Hydraulic Cements
229R Controlled Low-Strength Materials (CLSM)
232.2R Use of Fly Ash in Concrete
234R Guide for the Use of Silica Fume in Concrete
304.1R Guide for the Use of Preplaced Aggregate Concrete for Structural and Mass Concrete Applications
308 Standard Practice for Curing Concrete
318 Building Code Requirements for Structural Concrete

American Society for Testing and Materials (ASTM)

C 109 Test Method for Compressive Strength of Hydraulic Cement Mortars (Using 2-in. or [50-mm] Cube Specimens).
C 150 Specification for Portland Cement
C 151 Test Method for Autoclave Expansion of Portland Cement
C 185 Test method for Air Content of Hydraulic Cement Mortar
C 227 Test Method for Potential Alkali Reactivity of Cement-Aggregate
C 270 Specification for Mortar for Unit Masonry
C 311 Methods of Sampling and Testing Fly Ash or Natural Pozzolans for Use as a Mineral Admixture in Portland Cement Concrete
C 441 Test Method for Effectiveness of Mineral Admixtures in Preventing Excessive Expansion of Concrete due to the Alkali-Aggregate Reaction
C 595 Specification for Blended Hydraulic Cements
C 618 Specification for Coal Fly Ash and Raw or Calcined Natural Pozzolan for Use as a Mineral Admixture in Portland Cement Concrete
C 1012 Test Method for Length Change of Hydraulic Cement Mortars Exposed to a Sulfate Solution
C 1157 Performance Specification for Hydraulic Cement

American Association of State Highway and Transportation Officials (AASHTO)

AASHTO M 295 Standard Specification for Coal Fly Ash and Raw or Calcined Natural Pozzolan for Use as Mineral Admixture in Portland Cement Concrete
AASHTO T 259 Method of Test for Resistance of Concrete to Chloride Ion Penetration

Canadian Standards Association

A 23.5 Supplemental Cementing Materials and their Use in Concrete Construction

Addresses of the following organizations are:

American Association of State Highway and Transportation Officials
444 N Capital Street NW
Suite 249
Washington, D.C. 20001

American Concrete Institute
P.O. Box 9094
Farmington Hills, Mich. 48333-9094

American Concrete Pipe Association
222 Las Colinas Blvd W
Irving, Tex. 75039

American Society of Civil Engineers
345 East 47th St #18
New York, NY 10017

ASTM
100 Barr Harbor Dr
West Conshohocken, Pa. 19428

Canadian Standards Association
178 Rexdale Blvd
Etobicoke (Toronto), ON
Canada
M9W 1R3

CANMET
405 Rochester Street
Ottawa, ON
Canada K1A 0G1

National Concrete Masonry Association
2302 Horse Pen Rd
Herndon, Va. 2207

Transportation Research Board
2101 Construction Ave NW
Washington, D.C. 20418

United States Bureau of Mines
810 7th Street NW
Washington, D.C. 20001

United States Bureau of Reclamation
11056 W County Road 18 E
Loveland, Colo. 80537

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