Effect of Natural Pozzolan Addition on Expansions Caused by Alkali-Silica Reaction

V. RAMAKRISHNAN, DAN JOHNSTON, AND PRASAD NUNNA

The use of natural pozzolans to prevent excessive expansion of concrete caused by an alkali-silica reaction is referred to in the published literature. However, few data have been published on the use of natural pozzolans in field concrete. Results of an extensive study to determine the influence of natural pozzolans in reducing deleterious expansion due to alkali-silica reaction are presented. Twenty-six different types of natural pozzolans were collected from various locations in the Black Hills of western South Dakota and tested to determine their mineralogical content, chemical composition, and physical properties. On the basis of the strength activity index test with cement, the 10 most promising pozzolans were selected. Those were tested to determine their effectiveness in controlling the alkali-silica reaction. That was done by blending 10, 15, and 25 percent of natural pozzolans (by weight) with Type I/II cement. The blended cements then were tested according to ASTM P214, using mortar bars. Test results indicated that all the natural pozzolans tested except one were effective in reducing expansion due to alkali-silica reaction. A comparison of the effectiveness of reducing deleterious expansion by fly ash and natural pozzolan blended cements indicated that two natural pozzolan-blended cements were more effective than the Class F fly ash-blended cement in reducing expansion.

Cracks caused by the use of sands that are prone to alkali-aggregate reaction were observed in pavements in South Dakota. South Dakota Department of Transportation (SDDOT) tested some of the sands using ASTM C289. Test results indicated the possibility of the deleterious nature of the sands used in the construction of pavements. Although fly ashes and natural pozzolans such as pumice, volcanic ash, diatomaceous earth, and siliceous shales have been used to control alkali-silica reaction (ASR) (*1–12*), problems associated with homogeneity, variability in composition, and uniformity and anomalous expansion, persist, and it is difficult to maintain quality control. By producing suitable pozzolan under controlled conditions and blending it with the cement in the plant under controlled conditions, one can eliminate many of these problems. The use of a natural pozzolan blended Type IP cement is a viable solution. Therefore, the feasibility of obtaining such a natural pozzolan was investigated. Adequate supplies of natural pozzolans exist near Rapid City, South Dakota, and the state-owned South Dakota Cement Plant in Rapid City can manufacture the Type IP cement. The possibility of controlling ASR expansions in pavements by replacing part of the cement with pozzolan was studied. It was necessary to determine the amount of pozzolan to be blended to obtain the optimum effectiveness in controlling ASR.

V. Ramakrishnan and P. Nunna, South Dakota School of Mines and Technology, 501 East St. Joseph Street, Rapid City, S.D. 57701–3995. D. Johnston, South Dakota Department of Transportation, 700 Broadway Avenue East, Pierre, S.D. 57501-2506.

OBJECTIVES

- To find a natural pozzolan that is more efficient, effective, and economical than fly ash in reducing the deleterious expansion due to ASR.
- To find the optimum quantity of natural pozzolan that can be blended with cement to produce a Type IP cement for minimizing ASR.
- To ensure the selected natural pozzolan for blending does not, in any way, adversely affect the fresh and hardened properties of cement, mortar, or concrete.

MATERIALS AND TEST SPECIMENS

Cement: The cement used was ASTM Type I/II, conforming to ASTM C150 specifications. It was manufactured at the South Dakota Cement Plant. Its chemical and physical properties are given in Table 1.

Fly Ash: The fly ash used was a low-calcium ASTM Class F obtained from a source in North Dakota. The fly ash was supplied by SDDOT. Its chemical analysis and other properties are also given in Table 1.

Pozzolans: Different types of natural pozzolans collected by R. Holm of the Geology Department, South Dakota School of Mines and Technology, were used in this investigation. The designation, deposit and description of the pozzolans are given in Table 2. Table 3 contains the chemical compositions determined by and inductively coupled plasma (ICP) spectrometer. With the ICP method, samples are subjected to high temperature, which causes the sample to dissociate into individual atoms and ions. The atoms and ions emit light at wavelengths characteristic of the elements present. The spectrometer sorts the various wavelengths and measures the intensity of the specific spectral lines. The intensities are directly proportional to elemental concentrations in the sample. Table 4 gives the chemical compositions as obtained using a scanning electron microscope.

Aggregates: A highly reactive fine aggregate provided by SDDOT was used for all mixes.

Water: The water used was tap water from the Rapid City Municipal supply system.

Test Specimen: Four mortar bar specimens were prepared from each mixture for the ASTM P214 test method. For strength activity index, three cubes of size 50 mm (2 in.) were cast for each mixture.

TEST PROCEDURES

ASTM P214 is able to detect within 16 days the potential for deleterious expansion of mortar bars caused by ASR. Mixture propor-

TABLE 1 Chemical and Physical Properties of Cement and Fly Ash

	PORTLAND CEMENT	FLY ASH
CHEMICAL ANALYSIS (%)		
SiO_2	22.74	52.66
Al_2O_3	4.75	18.69
Fe_2O_3	3.40	4.65
CaO	63.91	3.12
MgO	1.20	2.79
SO_3	2.10	-
TiO_2	-	5.29
Na_2O	0.15	0.40
K_2O	0.59	2.52
MnO	-	0.28
Moisture Content		0.02
Loss on Ignition	1.50	0.02
Physical Test Results		
Fineness Blaine(m^2/kg)	387	-
Fineness Retained on #325 sieve	-	16.72
Soundness Autoclave Expansion(%)	-0.01	0.09
Bogue Potential Compounds		
C_3S	44.57	
C_2S	31.58	
C_3A	6.83	
C_4AF	10.35	

tions were selected according to ASTM P214, 1 part cement and 2.25 parts graded aggregate. The cement was replaced by the pozzolan with 10, 15, and 25 percent by weight of cement. For the fly ash, two additional percentages, 30 and 40 percent, were included. The water cementitious ratio used was 0.44 for all mixtures. The aggregate was washed, cleaned, and graded, and appropriate quantities were weighed and mixed to obtain a uniform gradation, as specified in ASTM P214.

The specimens (mortar bars) used for the test were made according to ASTM C227. The molds were stripped after 1 day, and the bars were placed in water that was heated to 80°C. On the second day, initial measurements were taken and the bars stored in 1 N NaOH solution at 80°C. The bar expansions were measured when they were hot, within 15 sec of removal from the container. Expansions were monitored for 14 days.

Strength Activity Index with Cement

Cubes 50 mm (2 in.) were cast from the control mixture and from each of the test mixtures in accordance with ASTM C109. Mixture proportions were selected according to ASTM C311. For control mixture, 250 g of cement, 687.5 of sand and water-to-cement ratio of 0.484 were used in molding three specimens. For the test mixture, 20 percent of the cement used in the control mixture was replaced by the pozzolans and water was added to achieve adequate workability. The water-to-cement plus pozzolan ratios are given in Table 5.

Molded specimens were covered with polythene sheets and stored for 24 hr at 23°C (73°F). The cubes were removed from the molds and cured in lime-saturated water for 28 days. Compressive strength was determined for both the control and the test mixture according to ASTM C109. To study the effect of calcining, the pozzolans were calcined at different temperatures (Table 6). A strength activity index was determined for the calcined pozzolans at the age of 7 days.

Density

Density was determined according to ASTM C188.

Fineness by No. 325 Sieve

The raw pozzolan materials were crushed using different sized crushing machines and ground to fine powder in a ball mill. The fineness of each pozzolan was determined by calculating the amount of pozzolan retained when wet sieved on a No. 325 sieve in accordance with ASTM C430.

Blaine Fineness

Fineness related to the air permeability (ASTM C204) was used to determine the Blaine fineness of the pozzolans and fly ash. Because the materials are not cement, the constant *b*, necessary to the equation for determining Blaine fineness, was obtained. The procedure for calculating the constant *b* is given in ASTM C204.

TABLE 2 Designation, Deposit, and Description of Pozzolans

SAMPLE DESIGNATION	DEPOSIT	DESCRIPTION
PR1	Rockyford ash	Light gray tuff (Zeolite)
F1	Fuson shale of Dakota FM	Gray clay weathered to nodules
F2	Fuson shale of Dakota FM	Reddish (burnt color) shale yellowish coat on weathered surface
W1	Sharps FM just above Rockyford ash member	White to light gray, hard, resistant to weathering
W2	Rockyford ash member of Sharps FM	Very white Zeolitic tuff
MW1	Mowry shale	Shale, dark gray weathers medium gray
MW2	Mowry shale	Weathered sample
SM1	Upper part of Rockyford ash	Weathered, light gray volcanic tuff
SM2	Lower part of Rockyford ash	Very white, hard volcanic tuff
CB1	Rockyford ash	White ash (tuff)
CT1	Sharps FM 10-15 ft above Rockyford ash	Light gray, more like a siltstone
US1	Upper unit of Sharps FM	White to gray siltstone
ERC1	Rockyford ash	Highly weathered more like a pumice
PRC1	Probably middle of Sharps FM	Whitish gray, very hard, F.grained contained many 1 inch or smaller vugs w/chalk vugs
FE1	White river group(basal Chadron FM)	Brownish gray clay, sample is fairly weathered
FE2	Brule FM of White river group	Light brown weathered clay
FE3	Brule FM	Brown clay
VA1	Brule FM	White pure ash
BG1	Pierre shale	Yellowish, highly weathered Bentonite
AC1	Belle Fourche shale	Gray Bentonite
TH1	Tomahawk volcanic area	Yellow to light brown Rhyolitic Lithic tuff containing several Xenoliths
F3	Fuson shale	Light gray, nodular clay
F4	Fuson shale	Reddish fissile shale
MO1	Morrison FM	Greenish shale
VA2	Appears to be in Morrison FM	White volcanic ash
WW1	Clinker from coal mine	Light red in color
MOU	Late Jurassic Morrison FM	Volcanic tuff
PS1E	Upper Cretaceous	Brown shale, expanded Pierre shale by kiln heating
LK1	Early Cretaceous Lakota FM	Silicified volcanic tuff
LK2	Early Cretaceous Lakota FM	Silicified volcanic tuff

TEST RESULTS AND DISCUSSION

Density: Densities of all the pozzolans, portland cement, and Class F fly ash are given in Table 7. The densities of all pozzolans were less than that of the cement, and they varied between 2.13 gm/cm^3 and 2.84 gm/cm^3.

Fineness: The fineness obtained by wet sieving through No. 325 Sieve for all pozzolans was above 90 percent passing (Table 7). The objective of obtaining a pozzolan finer than 90 percent passing was therefore achieved. The fly ash was used as received, without further grinding. Blaine finenesses of selected pozzolans are indicated in Table 8.

Strength Activity Index with Portland Cement

The strength activity index was used as a prescreening method for selecting the pozzolans for further testing. Strength activity index results are given in Table 5. The pozzolans had a wide range of strength activity; the values varied between 19.78 and 91.72 percent. On the basis of the strength activity index test results, 10 pozzolans were selected for blending with cement and tested for their effectiveness in controlling expansion due to ASR. The pozzolans selected for further testing had a strength activity index of at least 60 percent, except for MW1. Some of the pozzolans (for example, VA1, VA2, and LK1, LK2) were from similar geological forma-

TABLE 3 Chemical Compositions of Pozzolan Samples Using Inductively Coupled Plasma

SAMPLE	SiO_2	Al_2O_3	Fe_2O_3	CaO	MgO	Na_2O	K_2O	TiO_2	SO_3	MnO	BaO	NiO	H_2O	L I*	TOTAL
SM2	61.29	9.88	1.62	4.23	0.61	0.52	5.19	0.23	0.30	0.40	0.60	BDL	5.25	7.56	96.68
CB1	65.47	10.13	1.46	3.48	0.66	0.38	5.13	0.20	0.17	0.03	0.05	BDL	4.22	8.42	99.80
CT1	58.82	10.43	2.39	5.84	1.16	0.30	3.37	0.38	0.03	0.05	0.09	BDL	5.96	7.53	96.45
MW1	57.23	14.51	4.12	0.96	1.58	0.05	2.61	0.62	0.27	0.04	0.01	BDL	5.50	6.52	94.02
PRC1	63.76	10.96	2.89	3.98	1.19	0.34	5.16	0.45	0.20	0.04	0.05	BDL	3.75	4.45	97.22
PS1E	58.98	16.59	6.29	1.57	2.11	0.02	4.53	0.70	1.01	0.05	0.05	BDL	0.15	1.10	93.15
US1	65.24	12.09	3.12	3.24	1.61	0.39	3.52	0.50	0.09	0.04	0.04	BDL	4.90	4.21	98.99
F3	75.00	7.44	1.73	0.95	0.65	0.04	0.92	0.68	0.16	BDL	BDL	BDL	6.00	4.28	97.85
LK2	79.94	7.58	1.11	0.25	0.15	0.01	1.53	0.35	0.13	BDL	BDL	BDL	0.81	4.37	96.23
F1	-	-	-	-	-	0.01	4.12	-	-	-	-	-	-	-	-
F2	-	-	-	-	-	0.03	2.84	-	-	-	-	-	-	-	-
LK1	-	-	-	-	-	0.01	1.71	-	-	-	-	-	-	-	-
MO1	-	-	-	-	-	0.04	6.54	-	-	-	-	-	-	-	-
MOU	-	-	-	-	-	BDL	1.88	-	-	-	-	-	-	-	-
PR1	-	-	-	-	-	0.62	6.19	-	-	-	-	-	-	-	-
W1	-	-	-	-	-	0.40	4.07	-	-	-	-	-	-	-	-
W2	-	-	-	-	-	0.34	4.22	-	-	-	-	-	-	-	-
SM1	-	-	-	-	-	0.32	5.58	-	-	-	-	-	-	-	-
ERC1	-	-	-	-	-	0.58	3.93	-	-	-	-	-	-	-	-
AC1	-	-	-	-	-	0.54	1.28	-	-	-	-	-	-	-	-
BG1	-	-	-	-	-	0.34	1.01	-	-	-	-	-	-	-	-
FE2	-	-	-	-	-	0.19	2.36	-	-	-	-	-	-	-	-
VA1	-	-	-	-	-	0.34	5.98	-	-	-	-	-	-	-	-
VA2	-	-	-	-	-	BDL	2.08	-	-	-	-	-	-	-	-
WW1	-	-	-	-	-	0.27	3.58	-	-	-	-	-	-	-	-
TH1	-	-	-	-	-	0.51	3.55	-	-	-	-	-	-	-	-

L I* - Loss on Ignition
BDL - Below detection level
SiO_2 and SO_3 were determined using wet chemistry technique.

tions. In such cases, one from each geological formation was selected for testing. Pozzolan ERC1, having a strength activity index of 67.01 percent was eliminated from further testing because of unsuitable mining conditions. Fly ash used in the investigation had a strength activity index of 75.06 percent.

Effect of Calcining on the Strength Activity Index

The strength activity index for some of the pozzolans was low. Therefore, the effect of calcining the pozzolans on the strength activity index was studied. For the investigation, MW1, PS1E (expanded shale), and CT1 were selected. The strength activity index for MW1 was 45.27 percent without calcining. The pozzolan was calcined at three temperatures: 350°C, 700°C, and 1050°C. The effect of calcining was very evident for this pozzolan (Table 6). Strength increased depending on the temperature at which it was calcined. For the pozzolan CT1, the strength activity index increased from 62.00 to 88.78 percent when the pozzolan was heated at 1050°C.

The strength activity index for PS1E (Table 5) was the percentage obtained when the pozzolan was calcined at about 1050°C.

TABLE 4 Chemical Compositions of Pozzolan Samples Using Scanning Electron Microscope

SAMPLE	SiO_2	Al_2O_3	Fe_2O_3	CaO	MgO	Na_2O	K_2O	TiO_2	SO_3	MnO	Cl	P_2O_5	H_2O	L I*	TOTAL
SM2	64.28	11.84	2.06	3.85	0.78	2.03	4.04	0.25	0.10	0.00	BDL	BDL	4.05	6.72	100.0
CB1	63.95	11.46	1.54	3.08	0.99	1.44	4.53	0.29	0.08	0.00	BDL	BDL	4.22	8.42	100.0
CT1	55.52	12.75	4.36	9.70	1.84	1.05	3.20	0.82	0.17	0.29	0.07	0.39	2.31	7.53	100.0
MW1	56.21	19.29	6.26	1.47	1.68	0.48	2.80	1.15	0.86	0.00	0.00	0.35	2.93	6.52	100.0
PRC1	61.99	11.97	4.58	5.17	1.13	1.12	5.10	0.75	0.11	0.27	0.00	0.43	2.75	4.45	100.0
PS1E	56.21	19.48	9.52	2.74	2.31	0.91	3.85	1.04	1.86	0.08	0.07	0.68	0.15	1.10	100.0
US1	60.22	14.58	4.80	5.08	2.53	1.12	3.11	0.60	0.10	0.25	0.13	0.46	2.81	4.21	100.0
LK2	82.77	8.67	0.97	0.38	0.67	0.35	0.47	0.38	0.16	0.00	BDL	BDL	0.81	4.37	100.0
F3	73.62	11.60	3.44	1.38	1.03	0.19	0.22	1.02	0.17	0.00	BDL	BDL	2.88	4.28	100.0

NiO and BaO were below detection level
L I* - Loss on Ignition
BDL - Below detection level

TABLE 5 Compressive Strength and Strength Activity Index of Natural Pozzolans with Portland Cement

Sample	Water* / Cement + Pozzolan	Compressive Strength, MPa at age 28 days	Strength activity index with cement in %
CEMENT	0.48	47.0	-
F1	0.47	22.8	48.64
F2	0.45	20.8	44.40
W1	0.50	23.5	50.00
W2	0.50	24.9	53.11
MW1	0.50	21.3	45.27
SM1	0.50	32.2	68.50
SM2	0.50	32.7	69.60
CB1	0.50	37.6	80.15
CT1	0.45	29.1	62.00
US1	0.45	29.9	63.60
ERC1	0.50	32.4	69.01
FE2	0.45	9.3	19.78
TH1	0.47	16.2	34.43
PR1	0.48	24.9	53.11
BG1	0.55	26.8	57.14
MO1	0.48	20.8	44.32
WW1	0.48	22.9	48.71
PRC1	0.46	33.5	71.43
VA1	0.46	34.1	72.67
VA2	0.44	40.2	85.56
AC1	0.44	25.9	55.10
F3	0.46	37.0	78.75
PS1E	0.46	43.1	91.72
LK1	0.47	40.0	85.12
LK2	0.46	39.0	82.93
MOU	0.46	25.9	55.23
Fly Ash	0.44	35.3	75.06

Note:* - Water cement ratios used for strength activity index of natural pozzolans and fly ash with portland cement

TABLE 6 Compressive Strength and Strength Activity Index with Cement for Calcined and Uncalcined Pozzolans

Sample Designation	Compressive strength, MPa age 7 days	Strength activity index with cement in percent	Calcining temperature °C
Cement	32.8	-	-
MW1A	23.5	71.48	350
MW1B	27.2	82.81	700
MW1C	30.3	92.24	1050
PS1A	27.7	84.38	115
PS1B	28.5	86.79	350
PS1C	31.2	95.17	700
CT1A	29.2	88.78	950

1 psi = 0.00689 MPa

TABLE 7 Density and Fineness of Pozzolans and Fly Ash

SAMPLE	DENSITY gm/cm^3 ASTM C188	FINENESS (%) PASSING # 325 SIEVE ASTM C430	SAMPLE	DENSITY gm/cm^3 ASTM C188	FINENESS (%) PASSING # 325 SIEVE ASTM C430
CEMENT	3.13	95.26	PR1	2.27	90.71
F1	2.62	92.25	BG1	2.54	95.36
F2	2.84	91.79	MO1	2.42	96.60
W1	2.73	95.51	WW1	2.39	96.60
W2	2.32	94.89	PRC1	2.38	93.80
MW1	2.41	92.41	VA1	2.53	95.05
SM1	2.50	94.43	VA2	2.48	97.99
SM2	2.22	93.19	AC1	2.59	93.96
CB1	2.13	93.96	F3	2.34	91.79
CT1	2.30	97.05	PS1E	2.34	98.77
US1	2.36	96.90	LK1	2.30	93.65
ERC1	2.42	93.80	LK2	2.27	98.30
FE2	2.33	92.26	MOU	2.25	92.25
TH1	2.59	91.50	FLY ASH	2.67	83.80

TABLE 8 Blaine Fineness of Selected Pozzolans

SAMPLE	BULK VOLUME cm^3	DENSITY gm/cm^2	CONSTANT "b"	FINENESS cm^2/gm
Cement	1.816	3.15	0.90	3990
Fly Ash	1.777	2.67	0.92	3530
LK2	2.130	2.27	1.26	3270
PS1E	1.935	2.34	1.07	4910
SM2	2.680	2.22	1.86	4420
MW1	2.000	2.41	1.34	3500
CT1	2.016	2.30	1.14	3570

Therefore, for PS1, the strength activity index was determined when the pozzolan was treated at lower temperatures of 115°C, 350°C, and 700°C. Results indicated that there was a decrease in the strength activity index when it was treated at 115°C and 350°C. However, there was no significant difference in the strength activity index when it was treated at 700°C, compared with the pozzolan calcined at 1050°C (Table 6).

It can be concluded that calcination of pozzolans influences the strength activity index. That may be the result of removing moisture from the pozzolans by the calcining.

Effect of Pozzolans on Expansions Using ASTM P214 Test Method

According to ASTM P214, when mean expansions of test specimens exceed 0.20 percent 16 days after casting, that is indicative of potentially deleterious expansion. When expansion is between 0.10 and 0.20 percent, the results are not conclusive. If the mean expansion of the test specimens is less than 0.10 percent, it is indicative of innocuous expansion.

Expansion of mortar bars made with a reactive sand and cements without or with 10, 15, or 25 percent replacement with pozzolans by weight (LK2, PS1E, and VA2) are compared in Figures 1 through 3. The most effective pozzolans, LK2 and PS1E, and the adversely effective pozzolan VA2, are selected for discussion and comparison. The other pozzolans' effectiveness was somewhere between these extreme cases. For comparative evaluation, the influence of a Class F fly ash on ASR expansion in the mortar bars made with the same reactive sand and fly ash-blended cements is shown in Figures 4 and 8. Bar charts comparing the total expansions at 16 days for mortar bars made with and without blended cements are given in Figures 5 to 7 for pozzolans LK2, PS1E, and VA2.

Test results indicated that 10 percent replacement of cement with LK2 and PS1E pozzolans had decreased the expansions below 0.1 percent. All other pozzolans, except VA2 and PRC1, when blended with cement at 10 percent replacement level had decreased the expansions. However, the total expansions at 16 days after casting were in between 0.1 and 0.2 percent. When the cement was replaced with pozzolans at 15 percent by weight, all the pozzolans except VA2 and PRC1 had decreased the ASR expansions to an innocuous level (below 0.1 percent). When the cements were blended with pozzolan at 25 percent replacement, all the pozzolans except VA2 had decreased the total expansions below 0.1 percent. Therefore, all pozzolans, except VA2, are suitable for blending with cement to inhibit effectively ASR expansions in concrete. In the case of pozzolan VA2, it was observed that its influence on ASR expansions was entirely different from that of the other pozzolans. When pozzolan VA2 was blended with cement at 10, 15, and 25 percent replacement levels, the mortar bar expansions actually increased compared with the expansions in mortar bars made with unblended cements. That is termed the "pessimum phenomenon." A pessimum limit has been observed by other researchers *(5,7)* when certain types of fly ash were added to cement. The limit represents a percent replacement of cement below which the addition of fly ash or

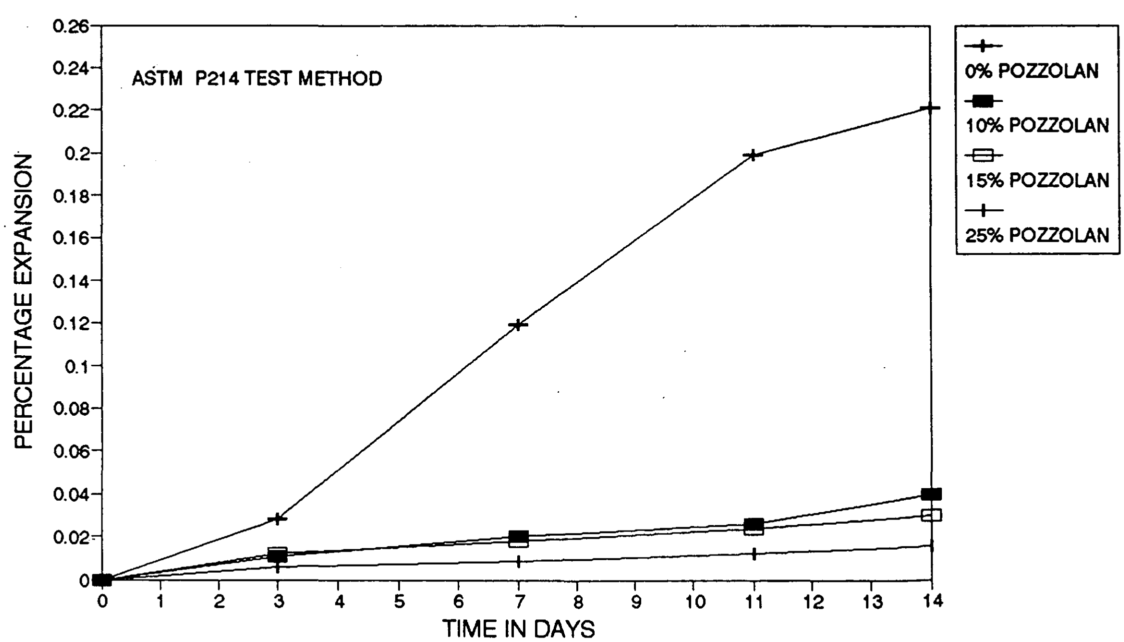

FIGURE 1 Comparison of mortar bar expansion for LK2.

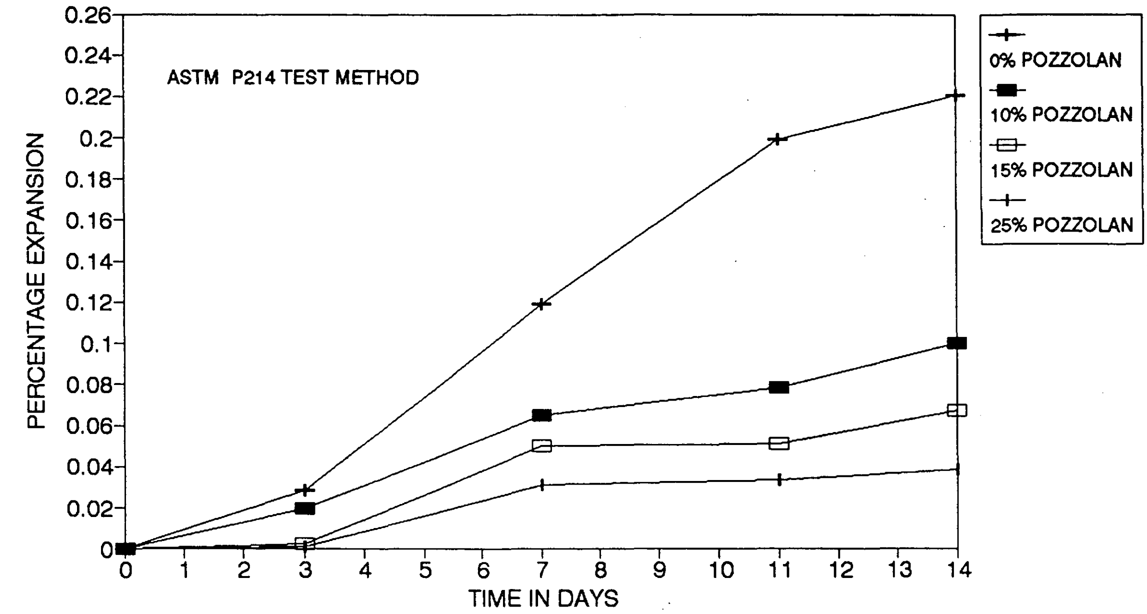

FIGURE 2 Comparison of mortar bar expansion for PS1E.

pozzolan causes equal or greater expansions in mortar bars than occurs in mortar bars without fly ash or pozzolan. When cement is blended with fly ash at a percentage above the pessimum limit, then expansions are reduced. The 10 percent replacement of cement with PRC1 pozzolan had given higher expansions than the mortar bars without pozzolan. However, at higher percentages of cement replacement with PRC1 pozzolan, the ASR expansions were reduced. Comparisons of ASR expansions in mortar bars with different types of pozzolans indicated that total expansions at 16 days after casting were below 0.1 percent in the case of mortar bars made of blended cements using all pozzolans (except VA2 and PRC1).

When a Class F fly ash was blended with cement at a replacement level of 10 to 40 percent by weight, it effectively reduced ASR expansion. However, when the quantity of fly ash blended was less than 20 percent by weight, the total expansion at 16 days was still higher than the innocuous level (0.1 percent). The expansions were reduced below the innocuous level only when the fly ash blended was higher than 25 percent by weight.

Mechanism by which Pozzolans Effectively Control Expansions Caused by ASR

Although the mechanism by which the pozzolans reduce ASR expansions is not clearly understood, it is clear that the physical and chemical properties of a pozzolan affect its effectiveness in

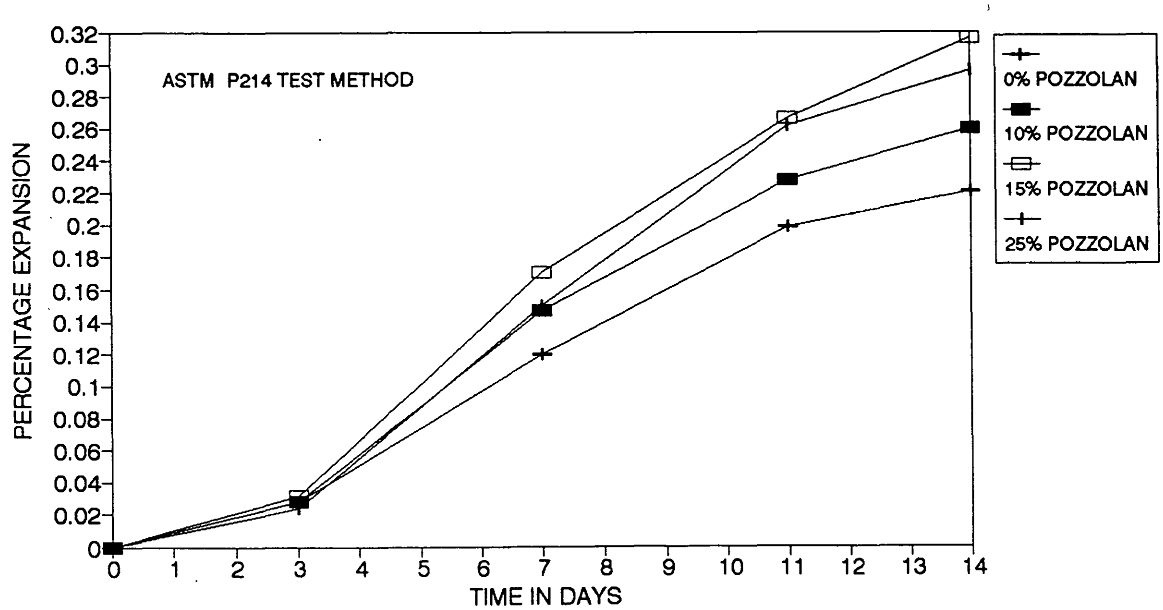

FIGURE 3 Comparison of mortar bar expansion for VA2.

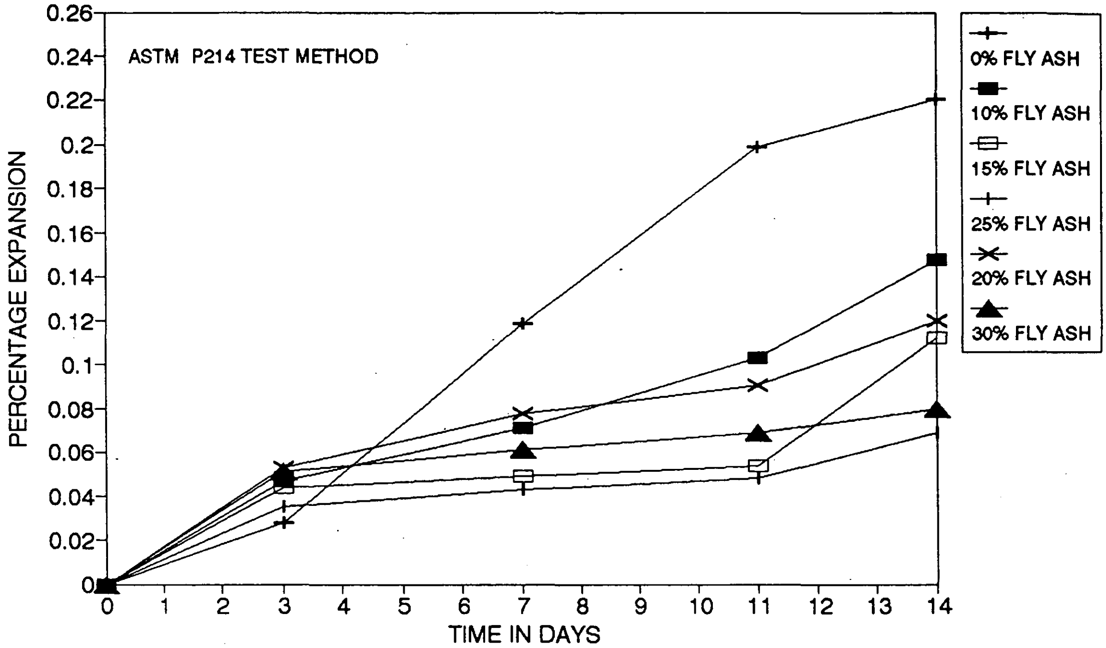

FIGURE 4 Comparison of mortar bar expansion for fly ash.

reducing ASR expansion in concrete. Because it is known that the presence of moisture increases ASR, it is possible that pozzolans are able to reduce permeability and therefore reduce ASR expansions.

In a study conducted by Larbi and Bijen (*12*) on the effect of mineral admixtures on cement paste-aggregate interface (*12*), adding fly ash or similar mineral admixtures reduced the migration of the hydroxyl ions because densification and thinning of the interfacial region prevented or reduced penetration of ions into the reactive grain and reduced ASR in concrete.

As for the chemical properties, it has been suggested that the pozzolans reduce or eliminate ASR expansion by pozzolanic reaction

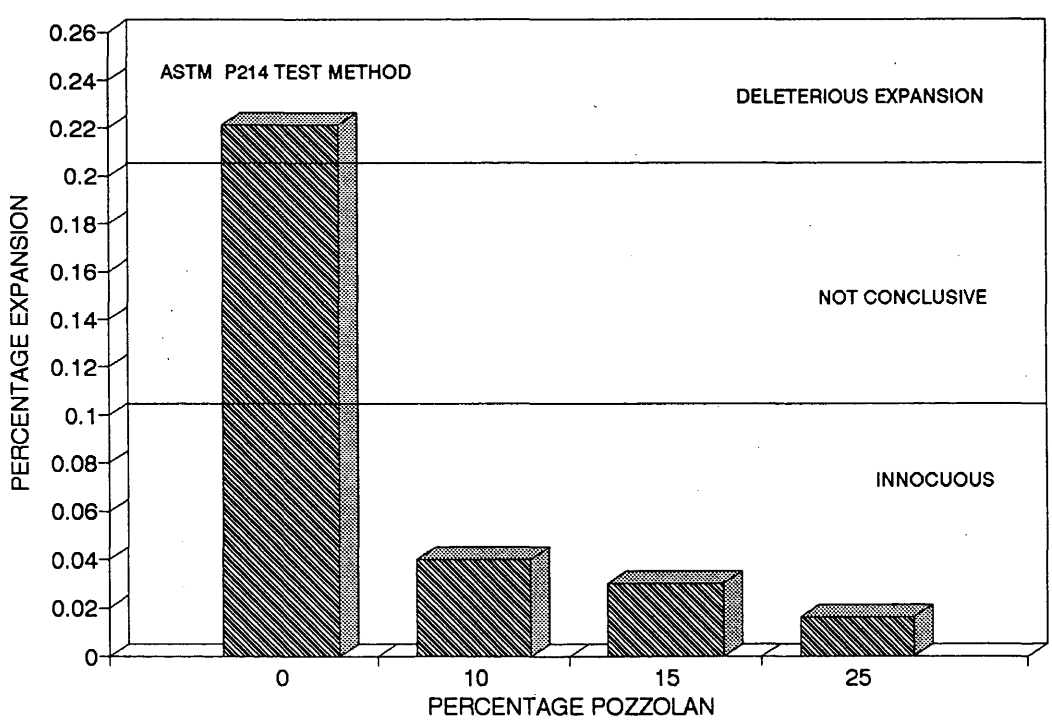

FIGURE 5 Comparison of expansions for pozzolan sample LK2.

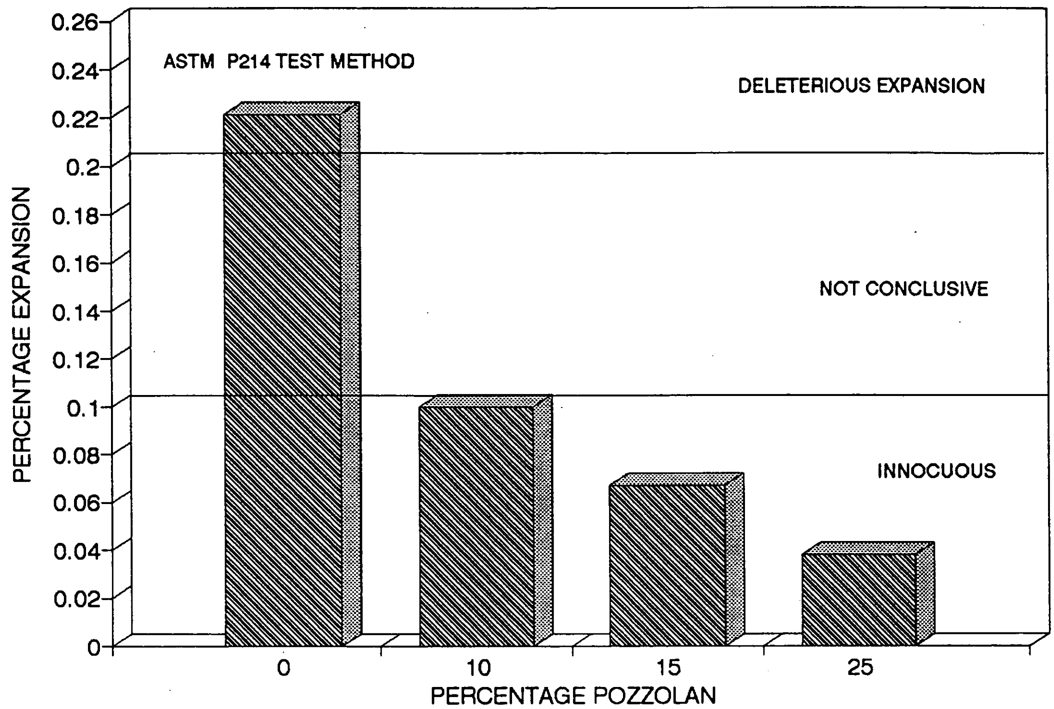

FIGURE 6 **Comparison of expansions for pozzolan sample PS1E.**

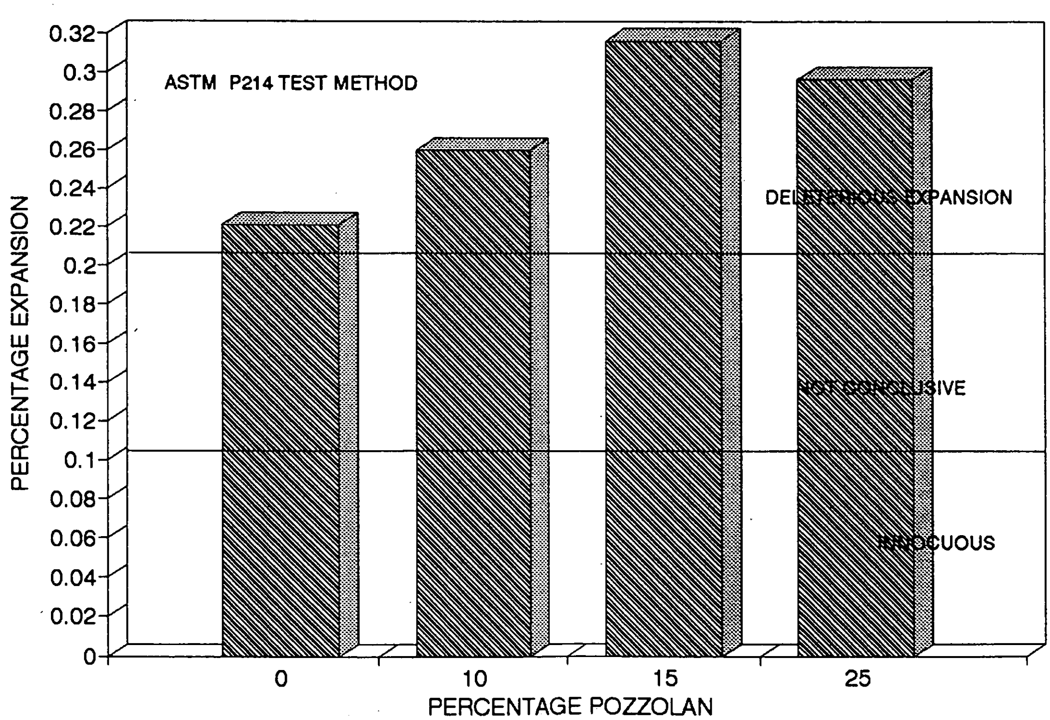

FIGURE 7 **Comparison of expansions for pozzolan sample VA2.**

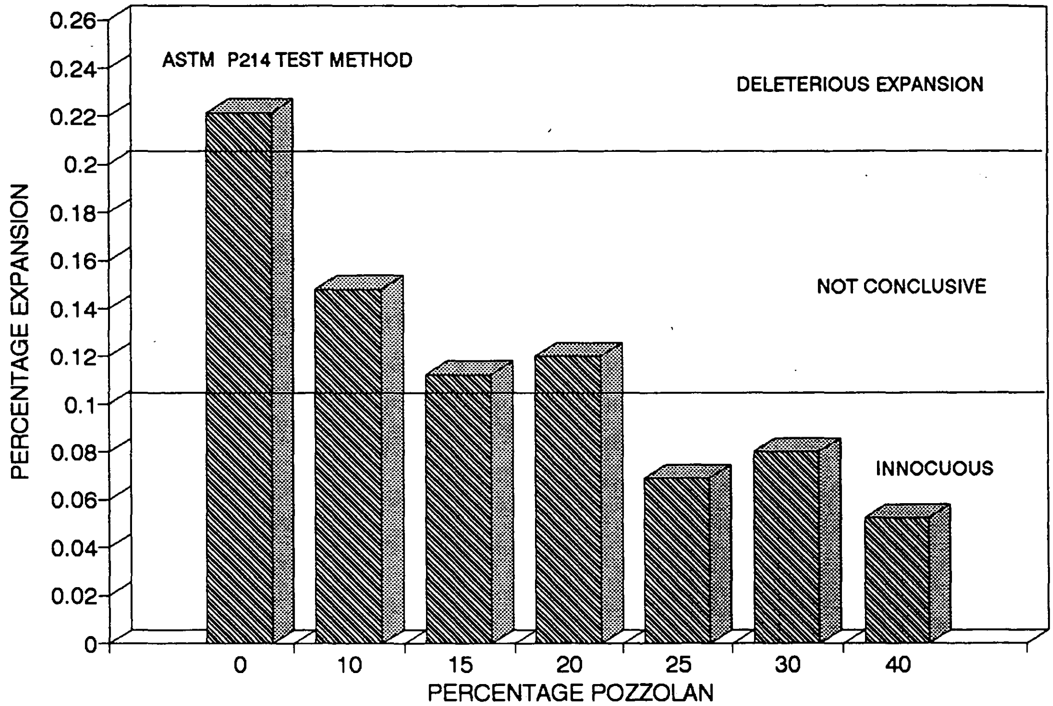

FIGURE 8 Comparison of expansions for fly ash.

and producing lower C/S mole ratio calcium silicate hydrates by reacting with the higher C/S mole ratio hydrates. The new hydrates can absorb large amounts of alkali into their structure and retain them, thereby reducing their availability for reaction with the silica in the aggregate.

CONCLUSIONS

- Two pozzolans—a gray, highly siliceous "fireclay" from the Lakota formation (LK2), and Pierre shale, which is a dark brown to black noncalcareous shale that was expanded (calcined) at about 1050°C (PS1E)—are most effective for controlling ASR. Only one pozzolan, a white volcanic ash (VA2), is unsuitable for use in controlling ASR expansion. Higher percentage replacement (15 or 25 percent) was more effective in reducing the ASR than was 10 percent replacement. Pozzolans LK2 and PS1E were more effective in controlling expansions than was the Class F fly ash investigated.
- With conventional crushing and grinding operations it is possible to produce pozzolans up to the required fineness, that is, above 90 percent passing through Sieve No. 325.
- The strength activity index of the pozzolans investigated in portland cement had a wide range of values between 19.78 and 91.72 percent. When blended with the cement, some pozzolans affected the strength of concrete adversely. Such pozzolans, even when they effectively inhibit ASR expansions, should not be used for blending with cement.
- The study on the effect of calcination of pozzolans on the strength of mortar cubes made with calcined pozzolan blended cements indicated that the strength activity index increases with an increase in the temperature of calcination.
- The Class F fly ash investigated effectively reduced ASR expansion of mortar bars made with reactive sand below the innocuous level (0.10 percent) when 25 percent of the cement was replaced with fly ash.

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