Pozzolans in Sand-Gravel Aggregate Concrete

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Sand-gravel aggregates produced over a large area of Nebraska are reactive with cements in concrete structures and pavements, generally causing excessive expansion and "map" cracking. Some pozzolan materials will inhibit severe cement-aggregate reaction when interground with the cement or when used to replace part of the cement in a concrete mixture.

Tests were made on a series of laboratory mixes and on field experimental sections to determine the physical characteristics and durability of air-entrained concrete in which a pozzolan material was interground with the cement and also air-entrained concrete in which part of the cement was replaced with flyash.

These tests indicate that the pozzolan concrete had better workability at normal temperatures, slightly lower early strength, but usually higher strength at later ages and improved durability in freezing and thawing. The expansion of concrete beams tested in a wetting-and-drying test and of mortar bars tested in sealed containers at 100 F. was definitely less or was completely inhibited in the concretes or mortars made with these pozzolans. The concrete made with the manufactured pozzolanic cement required more mixing water for a workable mix which resulted in lower strength and higher absorption.

● INVESTIGATIONS conducted by the Nebraska Department of Roads and Irrigation indicate that sand-gravel aggregates produced over a large area of Nebraska are more or less reactive with cements in concrete structures and pavements. This reaction generally causes "map" cracking of the surface and often causes excessive expansion which may destroy the concrete (*1*). A survey made in 1943 indicated that practically all sections of sand-gravel-aggregate concrete pavement in Nebraska over 5 yr. old were map cracked to some extent. Conventional fine and coarse aggregate concrete generally did not show map cracking.

A number of corrective measures have been used by other organizations in attempts to prevent this reaction and expansion (*2–9*). The method used in Nebraska has been to replace 30 percent of the sand-gravel aggregate with crushed limestone. Because the sources of supply are limited within the state, most of the limestone has to be imported from quarries in Missiouri, Iowa, and Kansas. Although the cement factor was reduced in the concrete made with limestone-sweetened aggregate, the savings in cost of cement is less than the additional cost of limestone in areas where the limestone has to be shipped for a considerable distance.

It has been reported that some pozzolan materials will also inhibit serious cement-aggregate reaction when interground with the cement or used to replace part of the cement in a concrete mixture (*4–6*). Information obtained from an unpublished study of pozzolan materials used on an experimental pavement project in a neighboring state and from studies made by the Bureau of Reclamation indicate that flyash might be a suitable pozzolan material to use in Nebraska sand-gravel concretes (*5*). Flyash is a finely divided residue consisting predominantly of small spheres of glass collected from the flues of power plants which burn pulverized coal. Other pozzolan materials could be found that would reduce expansion in the concrete, but unlike flyash, most finely divided materials require a higher water-cement ratio and cause the surface of the concrete to be sticky and difficult to finish.

The low cost of flyash as a replacement for part of the cement and the savings resulting from the use of local sand-gravel aggregates without limestone sweetening would mean a considerable savings in cost and time where corrective or innocuous aggregates have to be shipped for a considerable distance.

TESTS OF LABORATORY MIXES

Mortar-Bar Tests

In order to determine the effectiveness of flyash to inhibit unfavorable reactions in concrete mixes made with local sand-gravels, a series of mortar-bar tests was made according to the "Tentative Method of Tests for Potential Alkali Reactivity of Cement-Aggregate Combinations," ASTM Designation C 227-50T. In this test, sets of 1- by 1- by 10-in. mortar bars made with various cement-aggregate combinations were stored above water in sealed containers at 100 F. Companion sets made with various amounts of the cement replaced with flyash were also tested. The expansion of some of these bars after one year of test is shown in Figure 1.

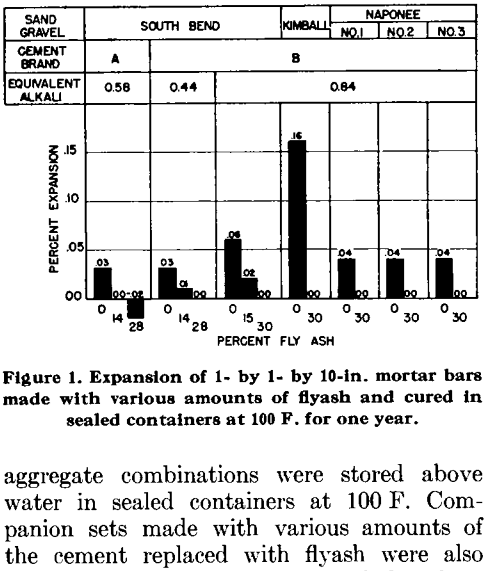

Figure 1. Expansion of 1- by 1- by 10-in. mortar bars made with various amounts of flyash and cured in sealed containers at 100 F. for one year.

The Brand B cement, with an equivalent alkali content of 0.84, was a high-alkali cement selected for these tests and is not typical of all the cement manufactured by this company.

These tests indicate that when flyash was used, the percent expansion was reduced for every combination of cement and aggregate tested, and when approximately 30 percent flyash was used as a replacement, the expansion of the mortar was completely inhibited.

Concrete Mixes

Since flyash proved satisfactory as an inhibitor of expansion in the mortar-bar test, the next step was to determine its effect on concrete mixtures.

Prior to the construction of an experimental paving project, a series of mixes was made in the laboratory to study the physical characteristics of the various classes of concrete that were to be used on the project. Two different brands of cement were used in mixes in which various amounts of the cement were replaced with flyash. A pozzolanic cement was also employed in some of the mixes. The pozzolanic cement was produced by mixing a Type I cement with a selected clay that had been heated to about 1,700 F. This cement is designated as PPZ in the figures of this report.

Varying amounts of an air-entraining agent were added to the concrete mixtures to produce the desired percent of air entrainment.

Tests on Plastic Concrete

The most-outstanding characteristics of the plastic flyash concrete mixed in the laboratory were an increase in plasticity and a reduction in mixing water. Figure 2 shows the water-slump relationship of laboratory mixes containing different quantities of flyash and a mix made with pozzolanic cement. For a given slump, the mixing water was reduced as much as 0.3 gal. per sack of cement, or for a given amount of mixing water, the slump was increased as much as 4 ½ in. when flyash was used to replace part of the cement in the concrete mixtures.

More mixing water was required for a given slump when pozzolanic cement was used in the concrete than when Type I cement of the same brand was used. This difference in the slump characteristics of concrete made with pozzolanic cement and concrete made with Type I cement was less for the stiffer mixes than it was for mixes with higher slumps. For mixes with a 1½-in. slump or less, the difference in the amount of mixing water required was approximately 0.2 gal. per sack of cement.

For a given amount of air entrainment, considerably more air-entraining agent had to be used in the concrete mixes made with flyash than was required in the nonflyash mixes. It was presumed that the carbon in the flyash caused the reduction in air voids in the concrete and three series of mortar tests were made in the laboratory to determine the amount of air-entraining agent required for various amounts of entrained air. Figure 3 shows the results of these tests. No flyash was used in one series, a 0.7-percent-carbon flyash was used in another series and a 2.6-percent-carbon flyash, representing the flyash used in the concrete mixes, was used in the third series. For a given amount of air entrainment, the low-carbon flyash mortars required no more air-entraining agent than the nonflyash mortars but two to three times as much air-entraining agent was required for the 2.6-percent-carbon flyash mortars.

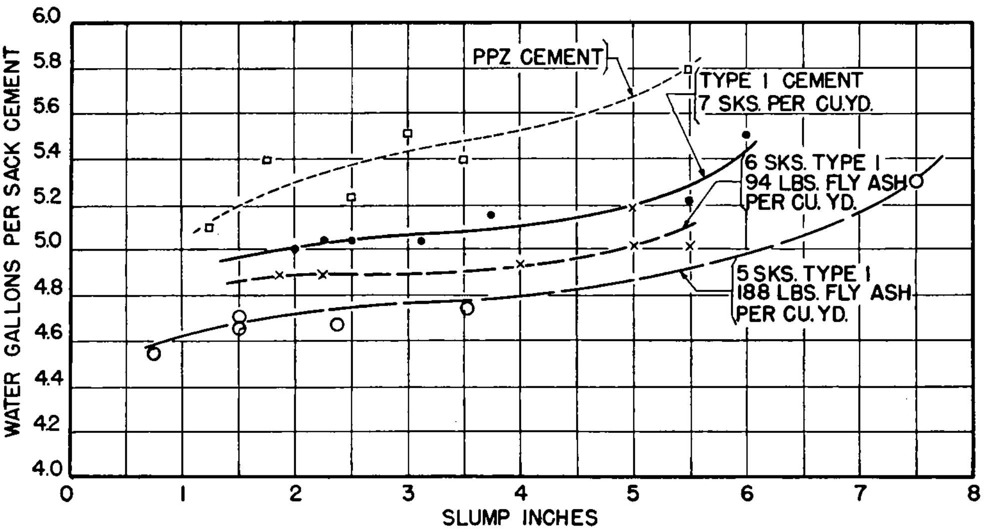

Figure 2. Water-slump relationship of concrete mixes made in the laboratory with South Bend sand-gravel, Brand B cements and various amounts of flyash.

Strength Tests

Eight 6- by 12-in. concrete cylinders were cast from most of the laboratory mixes. These specimens were cured in a moist room and two cylinders from each mix were tested in compression at 7 days, three at 28 days, and three at 90 days.

Figure 4 shows the average compressive strength of each class of concrete with a 1½-in. slump.

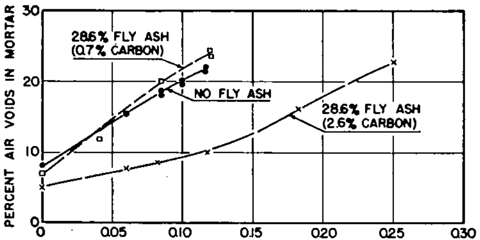

Figure 3. Percent air-entraining agent required for various amounts of entrained air in mortars made with portland cement and blends of portland cement with flyash.

Concrete mixes were made using each of two different gradations of sand-gravel. One gradation which is considered as the finer, was graded from 19 percent retained on the No. 4 sieve to 15 percent passing the No. 30 sieve. The other gradation which is considered as the coarser, was graded from 29 percent retained on the No. 4 sieve to 25 percent passing the No. 30 sieve. Although the coarser grade of aggregate had more material retained on the No. 4 sieve, it also had more material passing the No. 30 sieve than the other gradation. The amount of cementing material was reduced 0.6 of a sack per cu. yd. of concrete in the mixes made with the coarser aggregate.

The compressive strength of concrete cylinders made with a flyash-cement combination was lower at early ages but at later ages was usually higher than the compressive strengths of similar concrete made without flyash.

Tests of 3- by 4- by 16-in. Concrete Beams

Twenty-four 3- by 4- by 16-in. concrete beams, molded with stainless-steel measuring studs in each end, were cast from mixes representing each class of concrete and using Brand B Type I cement. All of the beams were cured 24 hr. in the molds in a moist closet and six days in the moist closet after the molds were removed. After seven days the beams were removed from the moist closet and placed for 21 days on racks in the laboratory air, which was maintained at 74 ± 3 F. and 55 to 60 percent relative humidity. The beams were then immersed in 70 F. water for two days which completed their 30-day cure.

At the end of the cure period, six beams from each set were placed in a directional freezing and uniform thawing exposure (*10*). These beams were frozen by contact of the molded 4- by 16-in. face of the beams with freezer plates until the temperature at the center of the beams was reduced to −20 F. The beams were thawed by circulating air that was kept at a temperatue of 70 F. by live steam. Four cycles of freezing and thawing were produced each day.

AVERAGE GRADATION OF SAND GRAVEL	19 PERCENT RETAINED ON NO. 4 SIEVE 15 PERCENT PASSING NO. 30 SIEVE					29% RET ON NO. 4 25% PASSING NO. 30	
SKS. CEM. PER CU. YD.	7.0	5.0	7.0	7.0	5.0	6.4	4.4
LBS. FLY ASH PER CU. YD.	NONE	188	NONE	NONE	188	NONE	188
BRAND OF CEMENT	B	B	B PPZ	A	A	B	B

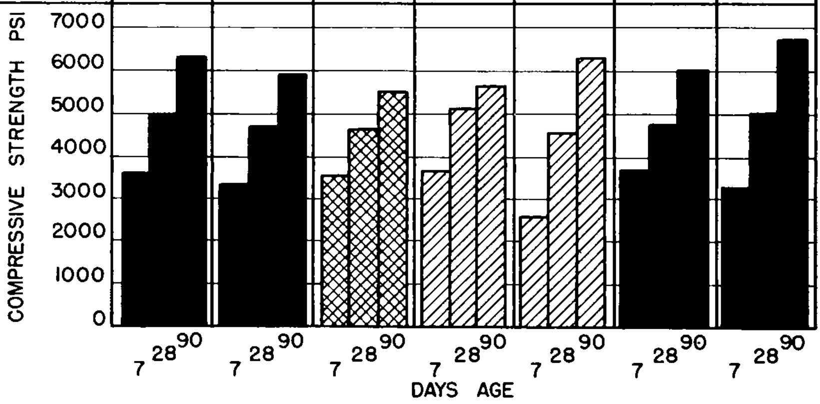

Figure 4. Compressive strength of 6- by 12-in. concrete cylinders. Mixes fabricated in the laboratory with South Bend sand-gravel aggregate, with and without flyash, and with an average slump of $1\frac{1}{2}$ in.

Figure 5 shows the percent change in length of some of the beams during the directional freezing and uniform thawing exposure. The concrete in these beams contained 7 sacks per cu. yd. of cementing materials (flyash plus portland cement) and an air content of 7.4 ± 0.2 percent. With the same air entrainment and cure, the beams containing flyash had less change in length per cycle of freezing and thawing than similar beams made without flyash.

Six 3- by 4- by 16-in. concrete beams from each mix were tested in a wetting-and-drying exposure. This test provides for repeated cycles of wetting and drying with the beams immersed in 70 F. water for 9 hr., followed by 15 hr. of drying in circulating air at 120 F. In other mixes tested previously, beams fabricated with cements and aggregates that were known to have a poor service record and that were considered reactive, expanded more than 0.05 percent and cracked in various degrees of disintegration during 1 yr. of this exposure.

Figure 6 shows the expansion of the beams tested in wetting and drying for 1 yr. None of the beams expanded to any extent or cracked while in the test. The cement used in the concrete for these beams had an equivalent alkali content of 0.44 percent. The results of the wetting-and-drying tests as shown in this figure and the results of the mortar-bar tests indicate that South Bend sand-gravel would be considered innocuous by common standards, when used with a low-alkali cement. The data shown on this figure indicates that the reduction in expansion effected by the use of flyash in a concrete mixture is not the result of a physical shrinkage of the concrete during the test. If the reduction were caused by shrinkage, a nonreactive concrete made with flyash would shrink during the test but there was no shrinkage of these beams.

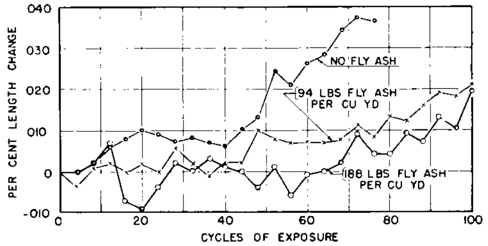

Figure 5. The effect of directional freezing and uniform thawing on 3- by 4- by 16-in. concrete beams made with various amounts of flyash. Mixes fabricated in the laboratory with South Bend sand-gravel aggregate, and Brand B cement.

AVERAGE GRADATION OF SAND GRAVEL	19% RET. ON NO. 4 15% PASSING NO. 30			29% RET. ON NO. 4 25% PASSING NO. 30		
SKS. CEM. PER CU. YD.	7	6	5	6.4	5.4	4.4
LBS. FLY ASH PER CU. YD.	0	94	188	0	94	188

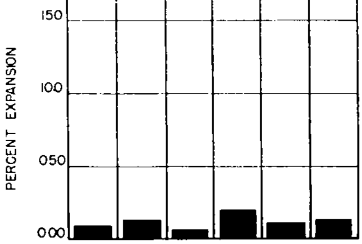

Figure 6. Expansion of 3- by 4- by 16-in. concrete beams exposed to wetting and drying for one year. Mixes fabricated in the laboratory with South Bend sand-gravel aggregate, Brand B cement, and various amounts of flyash.

TESTS OF FIELD MIXES

During August and September of 1950, an experimental concrete pavement 6.15 mi. long was constructed between Fremont and Arlington, Nebraska on US 30. This highway follows the Platte River valley across the state and is one of our most-heavily traveled highways. This location was chosen for the field investigation, because it is a straight and level stretch of highway with no heavily traveled intersecting roads and should have a uniform traffic load throughout the length of the project. Traffic surveys made at various times indicate that the annual average number of vehicles traveling between Fremont and Arlington each 24 hr. has been over 1,000 since 1941.

Experimental Sections

The major portion of this project was constructed with concrete in which flyash was used to replace various amounts of the cement. A pozzolanic cement was also used in some sections. Twenty-six sections of pavement were constructed of nine different classes of concrete. One class of concrete was used throughout the entirety of each section. Each class of concrete was produced with each of two brands of Type I portland cement, and in addition, two of the specified classes of concrete were produced with the pozzolanic cement. Six sections of pavement were repetitions of other designated sections. The proportions and composition of six of the nine classes of concrete are shown in Table 1. Three of the classes are omitted because they are not relevant to the subject of this report.

Each car of cement, used on the project, was sampled and tested for the physical characteristics of that particular cement. A chemical analysis was also made on some of the samples. Table 2 shows the maximum and minimum values of these tests for each brand and type of cement used on the project.

The flyash was also tested for its physical and chemical characteristics, and the maximum and minimum values are shown in Table 3.

Paving Operations and Procedures

The pavement was 22 ft. wide, 8 in. thick and was laid on a 4-in., compacted, granular foundation course that extended beyond the edges of the pavement slab to the face of the fill slope.

The materials were dry batched to the project from a weighing and loading plant in Fremont. The only equipment used on this project that was not used by the contractor on other paving projects was a weighing and loading bin for the flyash.

TABLE 1
COMPOSITION OF CONCRETE

Basic Quantities per Cubic Yard of Concrete				Average Gradation of Sand-Gravel Aggregate Percent by Weight Retained on Designated Sieve Sizes						
Portland Cement	Flyash	Aggregate[b]	Air	⅜	4	10	20	30	50	100
sacks	*lb.*	*tons*	%							
7.0[a]	0	1.31-1.46	6-8	5	19	48	80	87	97	99
6.0	94	1.30-1.45	6-8	5	19	49	80	87	97	99
5.0	188	1.28-1.43	6-8	5	19	48	76	87	97	99
6.4[a]	0	1.41-1.53	5.5-7	7	27	60	72	79	93	99
5.4	94	1.40-1.52	5.5-7	7	26	60	72	79	93	99
4.4	188	1.39-1.51	5.5-7	6	26	60	72	79	93	99

[a] Duplicate sections of this class of concrete were also constructed with a pozzolanic cement.
[b] Fremont sand-gravel.

TABLE 2
ANALYSIS OF CEMENT

Brand Type	A I		B I		B PPZ	
	min.	*max.*	*min.*	*max.*	*min.*	*max.*
Physical tests						
Air content in mortar, %	7.4	11.9	5.0	12.1	7.8	10.8
Specific surface, sq. cm./gm.	1687	1974	1854	2104	2166	2413
Soundness:						
Steam Chest	OK	OK	OK	OK	OK	OK
Autoclave expansion, %	0.091	0.224	0.054	0.154	0.038	0.054
Time of setting (Gillmore Test):						
Initial set, hr. min.	2:00	2:50	2:05	3:15	2:40	2:55
Final set, hr. min.	3:45	4:35	3:30	4:35	4:25	5:10
Tensile strength, psi.:						
3 days	290	368	265	373	260	340
7 days	370	440	368	467	353	442
28 days	452	523	447	543	482	547
Compressive strength, psi.:						
3 days	1483	2191	1366	2275	1500	1700
7 days	2750	2800	2125	3350	2575	2633
28 days	4325	5008	3483	4166	3675	4117
Chemical tests						
Silicon dioxide (SiO_2), %	21.6	22.7	21.6	22.5	40.8	41.6
Aluminum oxide (Al_2O_3), %	4.9	6.0	3.6	4.9	7.0	7.5
Ferric oxide (Fe_2O_3), %	2.7	3.1	2.7	3.3	1.9	2.0
Calcium oxide (CaO), %	62.6	64.8	61.8	63.2	42.1	42.5
Magnesium oxide (MgO), %	0.4	0.7	3.5	4.8	1.3	3.6
Sulfur trioxide (SO_3), %	1.7	2.0	1.6	2.0	1.3	2.2
Loss on ignition, %	0.9	1.2	1.1	1.6	1.2	1.5
Insoluble residue, %	0.19	0.40	0.31	0.69	28.9	30.9
Ratio of Al_2O_3 to Fe_2O_3	1.6	2.2	1.1	1.8	3.5	4.0
Tricalcium silicate ($3CaO \cdot SiO_2$), %	34	57	40	54		
Dicalcium silicate ($2CaO \cdot SiO_2$), %	19	39	22	34		
Tricalcium aluminate ($3CaO \cdot Al_2O_3$), %	8	11	4	8	15	17
Sodium oxide (Na_2O), %	0.25	0.33	0.14	0.18	0.10	0.11
Potassium oxide (K_2O), %	0.43	0.51	0.45	0.53	0.47	0.48
Total alkali (Na_2O) + (K_2O), %	0.68	0.82	0.59	0.69	0.58	0.59
Equivalent alkali (Na_2O) + ($0.658 \times K_2O$), %	0.53	0.66	0.44	0.51	0.42	0.43
Water-soluble alkali, %	0.04	0.07	0.18	0.25	0.16	0.18
Phosphorus pentoxide (P_2O_5), %	0.04	0.18	Trace	0.03	0.01	0.03
Manganic oxide (Mn_2O_3), %	0.17	0.18	0.06	0.09	0.06	0.06
Chloroform-soluble organic substances, %	Trace	0.004	Trace	0.002	Trace	0.003
Free lime (CaO), %	0.6	1.1	0.2	0.3	0.29	0.4
Calcium, water-soluble, %					1.7	3.72
Chloride, water-soluble, %					Trace	0.4

The batch trucks made three stops to load. At the first stop the trucks were charged with sand-gravel from overhead bins which were loaded by a clamshell. At the next stop the cement was loaded on the batch trucks from hopper type cement cars in the conventional manner by using a Blaw-Knox cement batcher. At the third stop the trucks were loaded with flyash. When bulk flyash was used, it was transferred from the hopper-type cars to a bin at ground level by an auger conveyor. A bucket-type conveyor raised the material to a weighing apparatus suspended above the batch truck. When bagged flyash was used, it was hand dumped into the opened bin at ground level, which caused a large amount of dust, and during windy periods the fine particles of flyash would float in the air for considerable distances before settling to the ground.

TABLE 3
ANALYSIS OF FLYASH

	Minimum	Maximum
Physical tests		
Specific gravity	2.44	2.59
Fineness:		
Retained on No. 325 sieve, %	6.1	8.7
Specific surface:		
Wagner	1334	2130
Blaine	3143	4878
Pozzolanic activity		
7 day Compressive Strength*	869	1210
Chemical tests		
Silicon dioxide (SiO_2), %	42.8	50.5
Aluminum oxide (Al_2O_3), %	14.4	16.4
Magnesium oxide (MgO), %	0.36	0.7
Sulphur trioxide (SO_3), %	1.6	3.5
Loss on ignition, %	0.7	3.3
Free carbon, %	0.6	2.6

* Compressive strength of 2- by 4-in. cylinder composed of 2 parts flyash, 1 part hydrated lime, 9 parts standard Ottawa sand and water to produce a workable mix. Cylinders cured in sealed containers at 70 F. for 24 hours and 130 F. for 6 days.

Because of the fineness and peculiar flowing characteristics of flyash, small holes and cracks in the truck boxes, that normally would hold cement, had to be plugged. The leakage was the most noticable at the point of loading, and when a truck box was made tight enough to hold flyash while it was being loaded, no leakage occurred enroute to the project. Although the flyash was the last material to be placed in the cement compartment of the truck and was not covered with canvass, very little blew off the truck on the way to the project. The flyash lost much of its flowing and dusting characteristics after it had settled in place in the truck box.

At the paving site the concrete was mixed in a 34-E single drum mixer. Each batch was mixed for a minimum time of 1 min. An air-entraining agent was added to the mix by an automatic dispenser on the mixer. Because of the fineness of the aggregate, all the concrete was easy to mix and discharge from the mixer.

Characteristics of the Plastic Concrete

The behavior of the flyash concrete and the pozzolanic-cement concrete mixed in the field was similar to that made in the laboratory. For a given amount of air entrainment and slump, the use of flyash caused a reduction in mixing water and increased the plasticity of the mix. The pozzolanic-cement concrete required more mixing water than concrete made with Type I cement of the same brand. Again it was noticed that in concrete mixes using a 2.6-percent-carbon flyash, considerably more air-entraining agent was required for a given amount of air entrainment than when a lower-carbon flyash was used.

All of the concrete was air entrained, and little bleeding was noticed in any of the sections. Bleeding was reduced to such an extent that on hot, windy days the surface of the concrete dried rapidly and became rubbery, making it difficult to finish. With these conditions, the surface of the concrete would not adhere to the surfaces of the various types of finishing equipment, and when a high spot in the concrete was floated, the surface would depress beneath the float, only to rise to its original level after the float had passed.

Although the average slump was increased approximately ¾ in. for the flyash sections, less mixing water was used in these sections, and they seemed to bleed even less than the other sections. Most of the finishing difficulties occurred in the sections made with a high percentage of flyash during periods of low humidity and high temperature. During periods of high humidity when temperatures were below 80 F., the flyash concrete was more workable and finished easier than similar non-flyash concrete.

More mixing water was used in the concrete sections made with Brand B pozzolanic cement than was used in the concrete sections made with Brand B Type I cement, with or without flyash. A considerable amount of mortar was worked to the surface of the concrete made with the pozzolanic cement and the concrete was more sticky. This caused more drag on the belt and more prominent belt marks on the surface of the concrete. This concrete was uniformly plastic and easy to finish, although there was some difficulty because of surface drying on hot, dry days.

In general, the finishing characteristics of all the concrete on the project were good. Difficulty was experienced with finishing only on days when the humidity was low and accompanied by a hot wind. Because of the inconsistencies and variations that normally occur on a field project, it was impossible to directly trace the cause of finishing difficulties. Although these difficulties may have occurred because of the use of flyash or pozzolanic cement or an air-entraining agent, under similar conditions of cure it is possible that all the different classes of concrete used on the project would have been difficult to finish. However, observations and tests on this project seem to indicate that the maximum amount of flyash and air entrainment that can be used in Nebraska sand-gravel concretes may be limited by the finishing characteristics of the concrete during periods of hot weather.

Strength Tests

Several 6- by 12-in. concrete cylinders were fabricated at the paving site from each class of concrete for compression tests. These cylinders were cured under damp burlap for the first day, in damp sand for the next four or five days, and then in a moist closet until they were tested. Figure 7 shows the 7- and 180-day tests of those cylinders. The 7-day strengths were reduced 500 to 1,000 lb. by the replacement of two sacks of cement with flyash, but the flyash concrete usually had higher strengths at 180 days than the nonflyash concrete. The compressive strengths of concrete made with pozzolanic cement were from 10 to 20 percent less at all ages than the compressive strength of similar concrete made with Brand B Type I cement. However, the 7-day compressive strengths were above 3,500 psi., and the 180-day compressive strengths were above 5,000 psi., which are well within the range of satisfactory strengths. The 7-day strengths for all the classes of concrete were above 2,500 psi., and all of the 180-day strengths were above 5,000 psi.

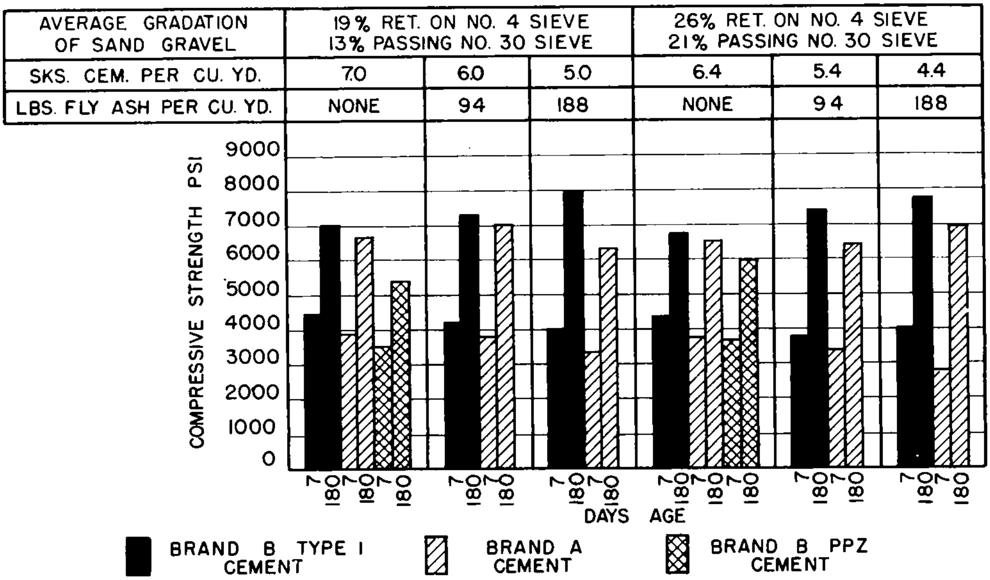

Figure 7. Compressive strength of 6- by 12-in. concrete cylinders. Concrete from experimental pavement sections made with Fremont sand-gravel aggregate.

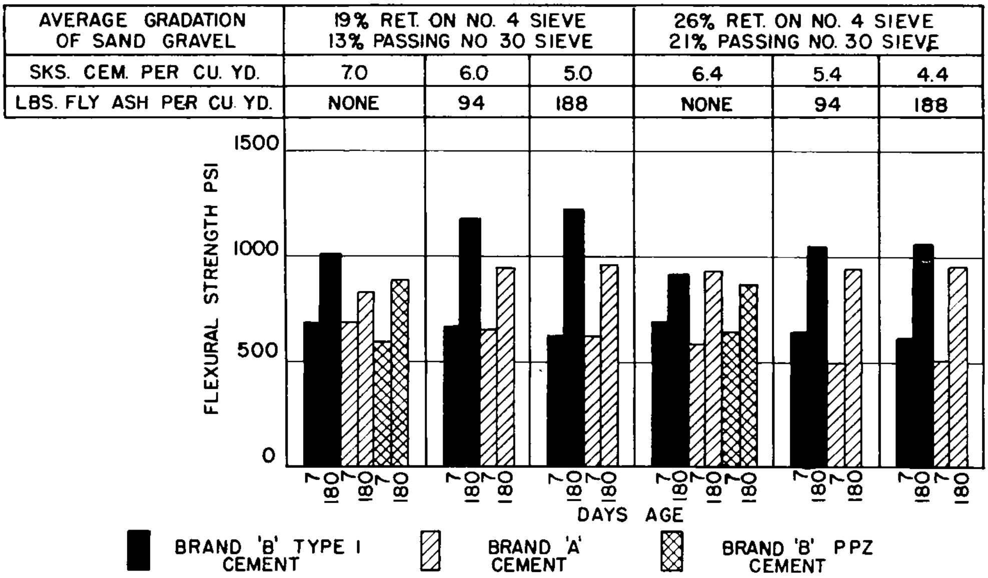

Figure 8. Flexural strength of 6- by 6- by 30-in. concrete beams. Concrete from experimental pavement sections made with Fremont sand-gravel aggregate.

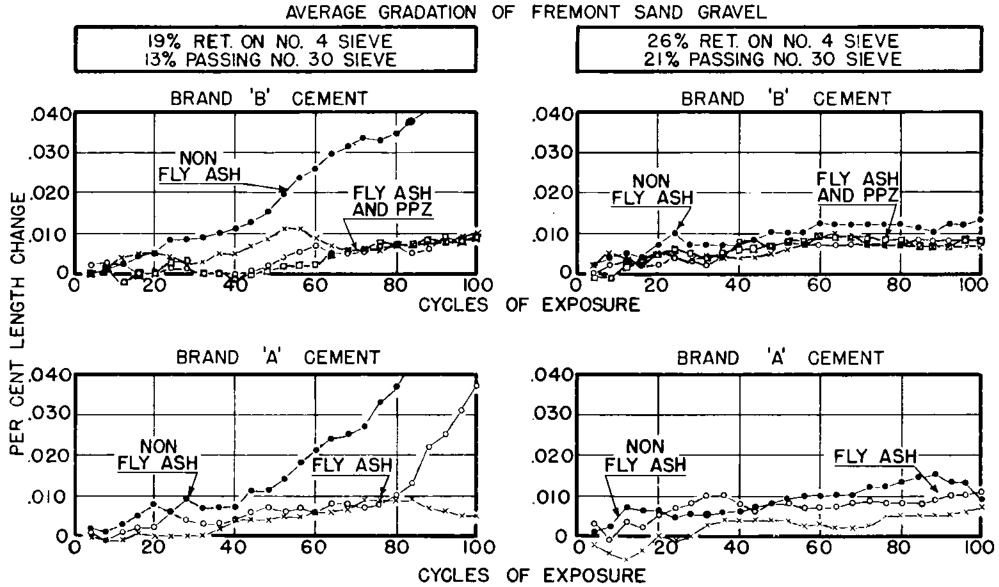

Figure 9. The effect of directional freezing and uniform thawing on 3- by 4- by 16-in. concrete beams. Concrete from experimental pavement sections.

Several 6- by 6- by 30-in. concrete beams were fabricated from each class of concrete on the experimental project for flexural tests. These beams were cured in the same manner as the cylinders. Figure 8 shows the flexural strengths of the concrete at 7 and 180 days.

The flexural strength relationships were similar to the compressive strength relationships: The use of flyash caused a reduction in early strengths but an increase in the strengths at later ages. Without exception the flexural strength of flyash concrete at the later age was higher than the flexural strength of similar nonflyash concrete. Although the flexural strength of concrete made with Brand B pozzolanic was slightly lower than similar concrete made with Brand B Type I cement, its early strengths were above the limits estab-

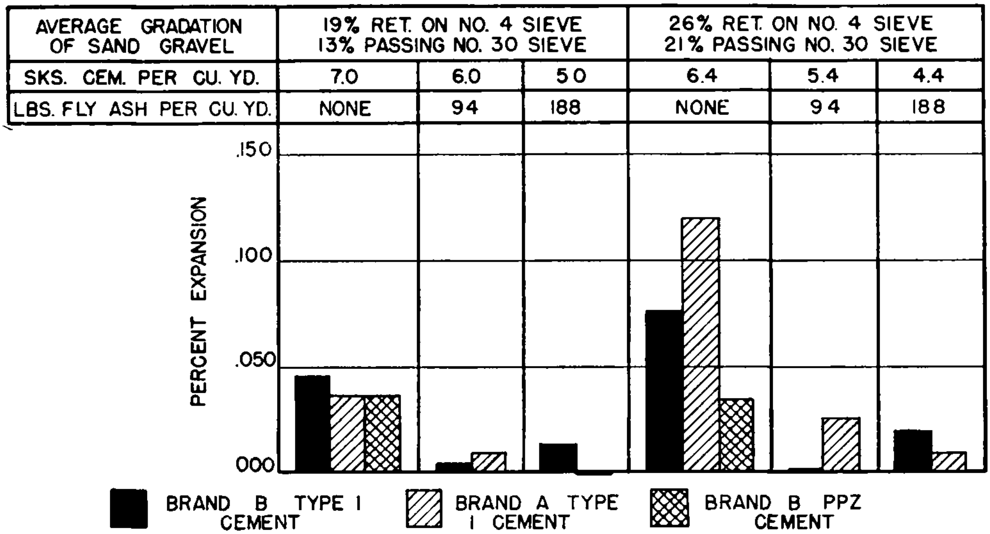

Figure 10. Expansion of 3- by 4- by 16-in. concrete beams exposed to wetting and drying for 9 mo. Concrete from experimental pavement sections made with Fremont sand-gravel aggregate.

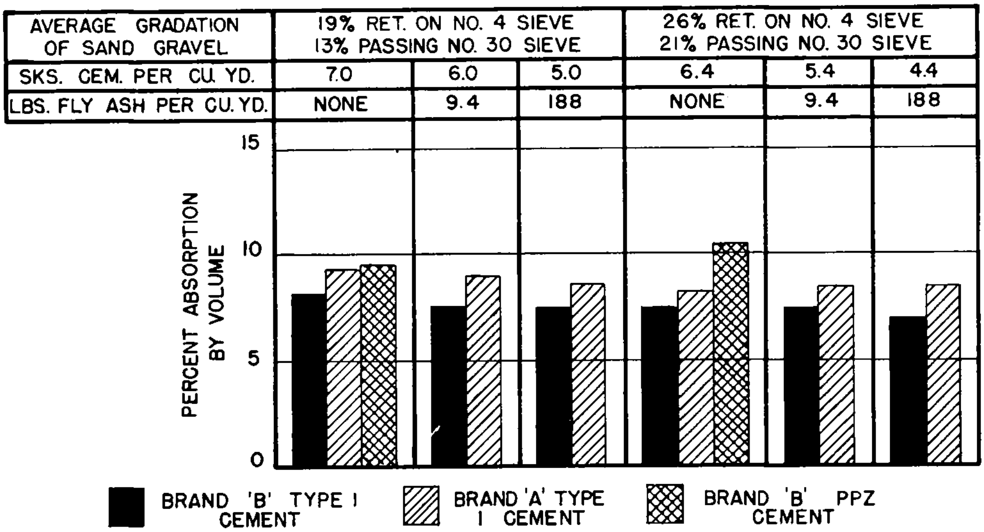

Figure 11. Percent absorption of 4- by 8-in. concrete cores cut from experimental pavement sections. Concrete from experimental pavement sections made with Fremont sand-gravel aggregate.

lished by the Nebraska Highway Department for opening pavement to traffic, and its strength at later ages compared favorably with the strength of nonflyash concrete.

Some 3- by 4- by 16-in. concrete beams were fabricated from each class of concrete on the experimental project. These beams were moist cured for 7 days, cured in an open rack in an air-conditioned laboratory for the next 21 days and then immersed in 70 F. water for two days. After the 30-day cure, a number of beams, representing each class of concrete, were placed in the directional-freezing-and-uniform-thawing treatment and the wetting-and-drying treatment described previously in this report.

Four 3- by 4- by 16-in. concrete beams from each section of concrete were tested in a directional-freezing-and-uniform-thawing exposure. The expansion of these beams while in this exposure is shown in Figure 9. The durability of these beams was similar to the durability of the beams fabricated in the laboratory. The beams representing flyash concrete were more durable than similar nonflyash-concrete beams.

Six 3- by 4- by 16-in. concrete beams were placed in the wetting-and-drying exposure. The percent expansion for the beams representing each class of concrete is shown in Figure 10. When flyash was used in the concrete beams, the expansion was reduced in every instance and practically eliminated in most of the beams. The expansion of the beams made with pozzolanic cement was also within reasonable and safe limits.

Within a few weeks after the completion of the project, eight concrete cores 4 in. in diameter were cut from the slab at the location of each class of concrete. One of the tests performed on these cores was a 96-hr. absorption test. The cores were dried in an oven at 220 F. until their rate of loss in weight for a 2-hr. period was less than 0.1 percent of the core weight. The dry cores were weighed in air and immersed in water for 96 hr. and then weighed in air and water. The absorptions were computed as a percent by volume of the total volume of the core. The percent absorption for each class of concrete is shown in Figure 11. In almost every instance the cores from sections made with flyash were less absorptive than companion cores made without flyash. The highest absorptions were in the cores made with pozzolanic cement.

CONCLUSIONS

Based on our observations and tests the following conclusions may be made:

1. The expansion of 1- by 1- by 10-in. mortar bars made with reactive aggregates and stored in sealed containers at 100 F. was completely inhibited when 30 percent of the cement was replaced with flyash.
2. When flyash was used to replace part of the cement in a sand-gravel concrete, the characteristics of the mixture were: better workability at normal temperatures; slightly lower early strengths but higher strengths at later ages; improved durability in freezing and thawing; less expansion in a wetting-and-drying exposure; and less absorption in water than similar concrete made without flyash.
3. The sand-gravel concrete made with pozzolanic cement had characteristics similar to the flyash concrete but required more mixing water for a workable mix, which resulted in lower strengths and higher absorptions.

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Effect of Substitutions of Flyash for Portions of Cement in Air-Entrained Concrete

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It was indicated earlier that substitutions of flyash for up to 25 or 30 percent of the cement in air-entrained concrete resulted in: (1) increase in water-cement ratio, (2) decrease in air content, (3) increase in strength of moist cured concrete at ages beyond 28 days, and (4) decrease in resistance of the concrete to freezing and thawing. The effect of restoring the air content of the concrete containing the flyash substitution by adding an air-entraining agent, not included in the original program, is described in this report.

Materials and procedures in the second series of tests were the same as in the first, except that the aggregates were from a different source and the maximum size was reduced to ¾ in. and the size of the test beams was reduced to 3 by 4 by 16 in.

The results substantiate those of the first series of tests and indicate that in mixes with proportions approximating those in this test, restoring the air content of the concrete has the following effects: (1) reduces the strengths at 7 and 28 days to approximately the same extent as the cement was reduced at 1 yr. and later; however, the strength is equal to or greater than that of the standard concrete; (2) improves the resistance of the concrete to freezing and thawing to a great extent but does not bring it up to that of the standard concrete; and (3) requires considerably more air-entraining agent than normally must be used to develop a like amount of air in regular concrete made with non-air-entraining cement.

● In our first program of tests in this investigation[1] it was indicated that substitutions of flyash for up to 25 or 30 percent of the cement in air-entrained concrete resulted in: (1) an increase in water-cement ratio, (2) a decrease in air content, (3) an increase in strength of moist cured concrete at ages beyond 28 days, and (4) a decrease in resistance of the concrete to freezing and thawing.

The effect of restoring the air content of the concrete containing the flyash substitution by adding an air-entraining agent, not included in the original program, is described in this report.

MATERIALS AND PROCEDURE

The cement and flyash used in this test were from the same sources as those used in the original test. The sand and gravel were from a different source, the Hartland-Verona Sand & Gravel Company, Verona, Wisconsin, and the maximum size of gravel was ¾ in. instead of 1½ in. The gravel was composed of approximately 74 percent dolomitic material, 10 percent igneous material, 7 percent sandstone, and a total of 9 percent chert with 4

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[1] Reported in Highway Research Board Proceedings, Vol. 29, 1949.