Use of Fly Ash in Concrete Pavement Constructed in Nebraska

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Nebraska has an abundance of sand-gravel in streams and old lake beds that in many ways is an excellent aggregate for use in concrete. It provides a concrete that is highly workable in the plastic stage and durable with high strength after it hardens. However, certain materials in this aggregate often react with portland cements in such a manner that disruptive expansion is produced in the concrete and its useful life is considerably reduced.

Various methods for inhibiting this reaction and its resulting expansion have been investigated and one method that showed considerable promise in a series of laboratory tests was the use of fly ash in the concrete. Because the laboratory tests were favorable, two experimental test roads, each approximately 6 mi in length, were constructed with concrete involving the use of fly ash. One road was constructed in 1950 and the other in 1951. Results indicate that the use of fly ash in the concrete presented no special problems in construction and the fly ash concrete was durable, high in strength and did not expand because of cement-aggregate reaction.

•CONSIDERABLE QUANTITIES of sand-gravel are available over most of Nebraska. This aggregate consists of angular to rounded pebbles of granite, quartz, and feldspar, with minor amounts of accessory minerals and metamorphic and sedimentary rocks. It occurs as alluvial deposits in modern and ancient stream beds or terraces; because it originates from weathered rock that has been subjected to the washing action of water, only the hardest and most durable particles remain. This excellent aggregate, when combined with the proper proportions of cement, air-entraining agent and water, produces a concrete that is both plastic and easy to handle before it hardens, and develops high strength and durability after it hardens. However, concrete made with Nebraska sand-gravel is subject to progressive and permanent expansion caused by a cement-aggregate reaction, which in some instances seriously damages the concrete within a few years.

Through field surveys and laboratory studies it has been determined that replacing 30 percent of the sand-gravel aggregate with crushed limestone will satisfactorily inhibit this reaction, and a concrete using substitutions of limestone has been in general use by the Nebraska Department of Roads since 1947. This has proven to be a sound and durable concrete in every respect, but because sources of good quality limestone are limited within the state, the Department is constantly looking for other means of inhibiting cement-aggregate reaction.

One method that appears to be particularly promising is the use of fly ash in the concrete. Tests conducted in the laboratory indicated that if 25 or 30 percent of the cement used in sand-gravel aggregate concrete is replaced with fly ash, serious ex-

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pansion would not develop. Because the laboratory tests indicated a favorable reduction in expansion, two experimental paving test roads were constructed with concrete in which fly ash was used in varying amounts. This is a report of these field studies.

The special engineering required for these studies was furnished by the Materials and Tests Division of the Nebraska Department of Roads, in cooperation with the U. S. Bureau of Public Roads, using Highway Planning funds.

DESCRIPTION OF TEST ROADS

One of the test roads was constructed between Fremont and Arlington, Neb., on US 30 in August and September 1950. US 30 is one of the main traveled roads across Nebraska (Fig. 1). This 6.15-mi long project was chosen because it is a straight and level stretch of road with no heavily traveled intersecting highways and, therefore, should have a uniform traffic load throughout the length of the project. Bollen and Sutton have previously described the construction of this project and reported some of the early tests on the concrete (1). Throughout this report this test road is identified as the Fremont project.

Before 1947, the Nebraska Department of Roads used two different classes of concrete (Classes A and H) for most concrete construction. Both used a sand-gravel aggregate, but the aggregate for Class H concrete was coarser on the coarse fraction of the aggregate and also finer on the fine fraction than the aggregate for Class A concrete. The aggregate for Class H concrete had approximately 26 percent retained on the No. 4 sieve and 21 percent passing the No. 30 sieve, whereas the aggregate for Class A concrete had only 19 percent retained on the No. 4 sieve and 13 percent passing the No. 30 sieve.

TABLE 1

QUANTITIES OF MATERIALS PER CUBIC YARD OF CONCRETE
(Fremont Project)

Class of Concrete	Cement (sk)	Fly Ash (lb)	Total Aggregate (tons)	Air Content (%)	Aggregate
47B	6.0	None	1.45-1.55	4-7	30% Crushed limestone[a] 70% Sand-gravel[a]
A	7.0	None	1.32-1.47	5-9	100% Sand-gravel[b]
A1	6.0	94	1.32-1.46	5-9	100% Sand-gravel[b]
A2	5.0	188	1.30-1.45	5-9	100% Sand-gravel[b]
A + 2	5.5	188	1.28-1.43	5-9	100% Sand-gravel[b]
H	6.4	None	1.41-1.53	4-8	100% Sand-gravel[c]
H1	5.4	94	1.40-1.52	4-8	100% Sand-gravel[c]
H2	4.4	188	1.39-1.51	4-8	100% Sand-gravel[c]

[a]Crushed limestone—approximately 18 percent retained on $^3/_4$-in. sieve, 95 percent retained on No. 4; sand-gravel—15 percent retained on No. 4 sieve, 18 percent passing No. 30 sieve.
[b]Sand-gravel—approximately 19 percent retained on No. 4 sieve, 13 percent passing No. 30 sieve.
[c]Combined sand-gravel aggregate—approximately 26 percent retained on No. 4 sieve, 21 percent passing No. 30 sieve.

Because most sand-gravel aggregate sources in Nebraska are deficient in coarse material, the aggregate for Class H concrete was more difficult to produce. However, because it had more coarse material, only 6.4 sk of cement were used per cubic yard of concrete, whereas 7 sk per cubic yard were used in the Class A concrete.

After it was discovered that concrete made with Nebraska sand-gravel aggregates is subject to progressive expansion and that substitutions of a good quality of crushed limestone for part of the sand-gravel aggregate would inhibit this expansion, the sand-gravel types of concrete were abandoned in favor of one using crushed limestone. This concrete was identified as Class 47B, and since 1947 most of the concrete for the Nebraska Department of Roads has been of this type.

All three of these classes of concrete were used on the Fremont project along with three combinations of Class A and two combinations of Class H concrete in which part of the cement was replaced with fly ash. The proportions and basic quantities of materials per cubic yard are given in Table 1. Classes 47B, A and H are the standards for comparisons; A1, A2, A + 2, H1 and H2 were included to show the effect of fly ash on sand-gravel aggregate concretes.

Test sections of pavement were constructed with each class of concrete in combination with each of two brands of Type I portland cement, making a total of 16 different combinations. Four sections were repeated, making a total of 20 sections involved in this study of fly ash. Six other sections were constructed, but because they are not pertinent to this report, they are not discussed.

The contract for this project required that the length of repetitive sections be from 600 to 1,400 ft and that of other sections from 1,000 to 1,800 ft. The contractor was free to choose any sequence in the use of the different classes of concrete and brands of cement except that he was required to have at least two sections of other classes of concrete separating sections having the same composition and proportions.

The other test road is located between Laurel and Belden, Neb., on US 20 in the northeast part of the state. This road is approximately 5.9 mi in length and is referred to in this report as the Laurel project. It was constructed in September and October 1951. The terrain in this area is gently rolling with good drainage and the soil varies from loess to a sandy loam with some areas of almost pure dune sand. US 20 is a main traveled highway extending east and west across the northern part of the state. A considerable amount of farm stock is trucked over this road enroute to the market at Sioux City, Iowa. The location of this project is also shown in Figure 1.

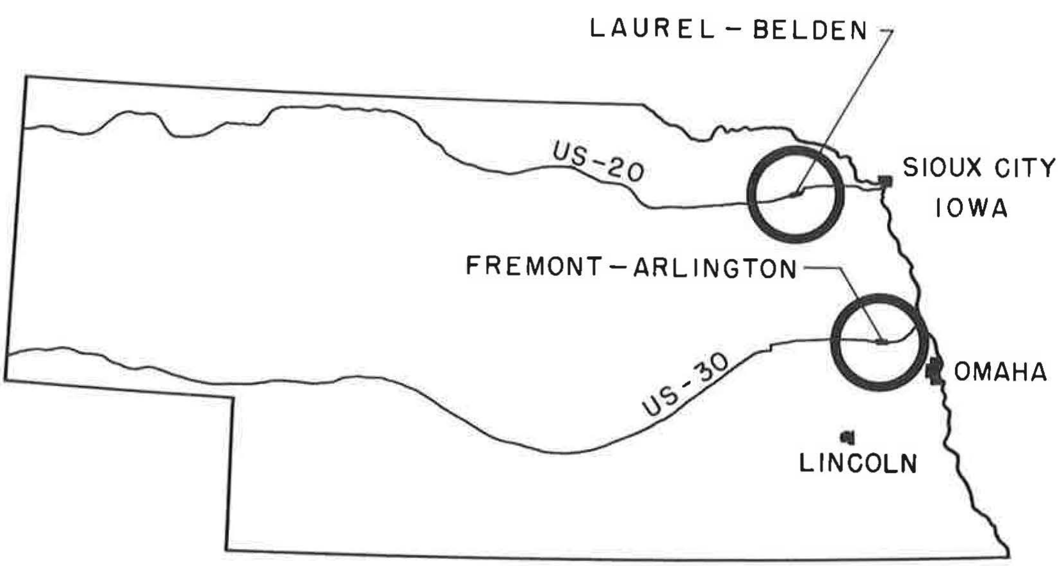

Figure 1. Location of Nebraska test roads.

The contract for construction of this project required that 10 to 15 percent of the area of the concrete pavement should be constructed with regular Class A concrete and the remaining 85 to 90 percent should be constructed with a corresponding concrete in which 25 percent of the cement had been replaced with fly ash. The contract also required that one brand of cement be used throughout the project. The mixture proportions for each class of concrete are given in Table 2.

Both projects have many things in common in their design. The concrete pavement was 22 ft wide, with a uniform thickness of 8 in., and was laid directly on 4 in. of compacted granular foundation course. Contraction joints were spaced at 16-ft 4-in. intervals throughout both projects. Expansion joints were provided only on bridge approaches and where the new pavement joined old existing concrete. Tie bars were placed across the centerline joint and load transfers were used in the few expansion joints. No load transfers were provided at the contraction joints and no reinforcing mesh was used in the slab. Both projects were approximately 6 mi in length and were constructed during the latter part of the summer.

The sand-gravel for both projects was obtained from a wet pit on the Platte River near Fremont, Neb., and the crushed limestone for the Fremont Project came from a quarry near Weeping Water, Neb. Each car of cement used on both projects was sampled and tested for physical characteristics and some samples were also tested to determine their chemical composition. The minimum and maximum values of these tests are given in Table 3 for each brand of cement. The fly ash for both projects was supplied by the Chicago Fly Ash Co. of Chicago, Ill. Each car was sampled and tested, and the results of these tests are given in Table 4.

PAVING OPERATIONS

The materials were dry batched to a 34-E paving mixer at the paving site. The paving operations were similar to those used on other projects except that a hopper was required to weigh the fly ash. However, no extra operations were required in the production of fly ash concrete because during the time that a hopper was used to weigh fly ash, a hopper for weighing crushed limestone was not required. Therefore, one simply took the place of the other.

Because of the fineness and peculiar flowing characteristics of fly ash, small holes and cracks in the truck boxes that normally could hold cement had to be plugged. The leakage was most noticeable at the point of loading, and when a truck box was made tight enough to hold fly ash while it was being loaded, no leakage occurred enroute to the project. Close inspection of the loading and hauling of fly ash was especially necessary during the first few trips. Although the fly ash was the last material to be placed in the cement compartment of the truck and was not covered with canvas, very little blew off the truck during the trip to the project. The fly ash lost much of its flowing and dusting characteristics after it had settled in place in the truck.

TABLE 2

QUANTITIES OF MATERIALS PER CUBIC YARD OF CONCRETE
(Laurel Project)

Class of Concrete	Cement (sk)	Fly Ash (lb)	Aggregate (tons)	Air Content (%)	Aggregate[a]
A	7.0	None	1.32-1.47	5-9	100% Sand-gravel
A1.75	5.25	165	1.30-1.45	5-9	100% Sand-gravel

[a]Sand-gravel—approximately 19 percent retained on No. 4 sieve, 13 percent passing No. 30 sieve; Class A is standard 100 percent sand-gravel aggregate concrete used also on Fremont project.

TABLE 3

ANALYSIS OF CEMENT
(Fremont and Laurel Projects)

Property	Brand A, Type I		Brand B, Type I	
	Min	Max	Min	Max
Mortar air content (%)	3.4	11.9	5.0	12.1
Specific surface (sq cm/g)	1,653	1,974	1,854	2,104
Soundness:				
Steam Chest	OK	OK	OK	OK
Autoclave expansion (%)	0.091	0.224	0.054	0.154
Time of set, Gillmore (min)				
Initial	2:00	3:20	2:05	3:15
Final	3:20	4:45	3:30	4:35
Tensile strength (psi)				
At 3 days	290	368	265	373
At 7 days	370	440	368	467
At 28 days	450	523	447	543
Compressive strength (psi)				
At 3 days	1,483	2,191	1,366	2,275
At 7 days	2,516	2,800	2,125	3,350
At 28 days	4,266	5,008	3,483	4,166
Chemical composition (%)				
SiO_2	21.6	23.0	21.6	22.5
Al_2O_3	4.9	6.0	3.6	4.9
Fe_2O_3	2.6	3.1	2.7	3.3
CaO	62.6	65.2	61.8	63.2
MgO	0.4	0.7	3.5	4.8
SO_3	1.6	2.0	1.6	2.0
Loss on ignition	0.9	1.8	1.1	1.6
Insoluble residue	0.19	0.40	0.31	0.69
$3CaO \cdot SiO_2$	34	57	40	54
$2CaO \cdot SiO_2$	19	39	22	34
$3CaO \cdot Al_2O_3$	8	11	4	8
Na_2O	0.25	0.33	0.14	0.18
K_2O	0.43	0.55	0.45	0.53
Total alkali, $Na_2O + K_2O$	0.68	0.83	0.59	0.69
Equivalent alkali, $Na_2O + 0.658 \times K_2O$	0.53	0.66	0.44	0.51
Water-soluble alkali	0.04	0.07	0.18	0.25
P_2O_5	0.04	0.18	Trace	0.03
Mn_2O_3	0.15	0.18	0.06	0.09
Chloroform-soluble organic substances	Trace	0.005	Trace	0.002
CaO	0.6	2.1	0.2	0.3
Al_2O_3: Fe_2O_3	1.6	2.2	1.1	1.8

There was nothing unusual about the paving train or the paving operations. 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. All pavement was cured with kraft paper, which was left on for a minimum of 4 days.

Control of the paving operations was maintained by performing yield, slump, and air-content tests at least every 150 lin ft throughout the Fremont project and at frequent intervals on the Laurel project. A special effort was made to keep the air content of the concrete near the upper limit of the specifications. The additional control tests performed were not as a result of any difficulties encountered but merely as a means of insuring good quality concrete.

CHARACTERISTICS OF PLASTIC CONCRETE

The behavior of the fly ash concrete mixed in the field was similar to that made in the laboratory. For a given air content and slump, the use of fly ash caused a reduction in the required amount of mixing water and increased the plasticity of the mix.

All test sections (with or without fly ash) were constructed with air-entrained concrete. It was noticed that when a higher-carbon fly ash was used in the mixtures, two or three times more air-entraining agent was required for a given air content than when a lower-carbon fly ash was used.

TABLE 4

ANALYSIS OF FLY ASH
(Fremont and Laurel Projects)

Property	Min	Max
Specific gravity	2.44	2.59
Fineness:		
Retained on No. 325 sieve (%)	3.4	8.7
Specific surface:		
Wagner	1,334	2,286
Blaine	3,143	4,878
Pozzolanic activity 7 day compressive strength (psi)[a]	848	1,210
Chemical composition (%):		
SiO_2	42.8	50.5
Al_2O_3	14.4	18.5
MgO	0.4	0.7
SO_3	1.6	3.5
Ignition	0.7	3.3
Free carbon	0.6	2.6

[a]Compressive strength of 2- by 4-in. cylinder composed of 2 parts fly ash, 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 hr and 130 F for 6 days.

The rounded particles of Nebraska sand-gravels contribute to a highly workable concrete with a low water-cement ratio. This factor combined with the water-reducing characteristics of air entrainment results in concrete that requires only 31 to 35 gal of mixing water per cubic yard. Concrete with such a low water requirement may be very plastic and easy to work during periods of normal temperatures and humidity but because very little bleeding water is available, the surface of the concrete will dry rapidly and become rubbery and difficult to finish during periods of high temperature and low humidity.

Although the average slump was increased approximately ¾ in. for the sections using fly ash, less mixing water was used in these sections and they seemed to bleed even less than the other sections. Most of the concrete made with fly ash was more workable and finished more easily than corresponding non-fly ash concrete, but difficulty with finishing did develop in some localized areas of sections using fly ash during periods of high temperature and low humidity. The difficulties were not serious, and because of the many variables that affect finishing on a field project—variations not only in the weather but also in the construction procedures and in the materials themselves—it was impossible to trace the difficulty directly to the use of fly ash. Under similar conditions it is possible that all classes of concrete used on the project would have been difficult to finish.

SPECIAL TEST AREAS

Special test areas were chosen within the longer sections of pavement representing each class of concrete. Concrete cylinders and beams for laboratory tests were molded during placement of concrete in these areas. Usually the test specimens were fabricated from the concrete at two different locations within each section but in some instances where the sections were short, all specimens were fabricated at one location. Enough specimens were cast to provide at least two for each type of test and test period. The concrete for the specimens was loaded directly from the mixer into a truck and then hauled to a convenient site where the specimens were cast.

STRENGTH TESTS

All specimens fabricated for strength tests were cured under damp burlap for the first day, in damp sand for the next 4 days, and then in a moist closet until they were tested for strength. The unit compressive strengths of 6- by 12-in. cylinders representing each class of concrete are shown in Figure 2. With few exceptions the strength increased with age, and whatever retrogressions did occur probably resulted from variations in test methods rather than from actual variations in strength.

The concrete fabricated with 100 percent sand-gravel aggregate and no fly ash (Classes A and H) had compressive strengths from 5,800 to slightly over 7,000 psi at 540 days age. In most instances the concrete in which fly ash was used to replace part of the cement (A1, A2, A + 2, A1.75, H1 and H2) had slightly lower early compressive strengths but at later ages the strengths were higher than similar concrete without the substitution of fly ash. The strength of concrete using 188 lb of fly ash and brand B cement was approximately 15 percent higher at 540 days age than that of similar concrete without fly ash (A2 and A, H2 and H). All concretes using 188 lb of fly ash per

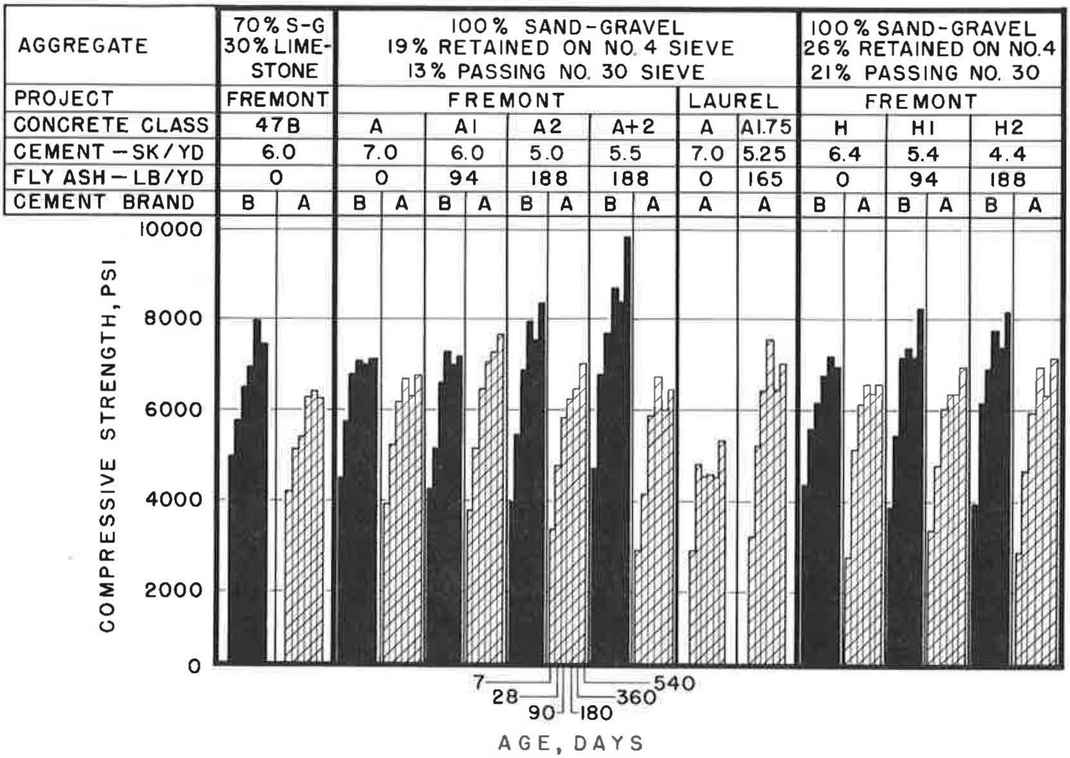

Figure 2. Compressive strength of concrete cylinders.

cubic yard had strengths at later ages that were equal to or slightly higher than the strength of Class 47B concrete made with the same brand of cement. Of all the different types of concrete, the highest compressive strength developed in concrete cylinders using 100 percent sand-gravel aggregate, 5.5 sk of brand B cement and 188 lb of fly ash per cubic yard of concrete (A + 2). At 540 days, the strengths of these cylinders averaged nearly 10,000 psi.

Concrete beams (6- by 6- by 30-in.) were cast from each class of concrete and tested for flexural strength. These tests are shown in Figure 3. The flexural strengths had the same trends as the compressive strengths except that the gain in ultimate strength when fly ash was used in concrete made with brand A cement was more pronounced. Here again the early strengths of concrete made with fly ash were slightly lower than similar concrete without fly ash, but the ultimate strengths were higher. The flexural strength of Class A + 2 concrete made with brand B cement tested higher (1,500 psi) than any concrete ever tested in this laboratory and considerably higher than the average for concrete from field projects. All classes of concrete using fly ash had higher ultimate flexural strengths than Class 47B concrete made with the same brand of cement.

Considering all the various classes of concrete, the flexural and compressive strengths were above the average obtained on most pavement projects in Nebraska, and in some cases the ultimate strengths were considerably above average.

DURABILITY TESTS

Beams, 3- by 4- by 16-in. in size, were fabricated from each class of concrete for weathering tests. These beams were cast with a stainless steel plug in each end so that their change in length could be measured with a comparator. They were cured

7 days in a moist condition, 21 days in laboratory air and 2 days in water. After curing, the beams were distributed to various weathering exposures and tested for sonic modulus of elasticity or measured for change in length at various ages.

Wetting and Drying Exposure

Some beams respresenting each class of concrete were allocated to a wetting-and-drying exposure in which they were subjected to repeated cycles of 9-hr immersion in 65 ± 5 F water and 15 hr in circulating air at 120 F. The beams were measured periodically for change in length and sonic modulus. During 1 yr of this exposure, beams fabricated with cements and aggregates that are known to have a poor service record and are considered reactive expand 0.050 percent or more and crack in various degrees of disintegration.

The percent change in length of the beams exposed to wetting and drying are shown in Figure 4. Beams respresenting concrete made with 30 percent limestone sweetening (Class 47B) expanded only a moderate amount during this exposure. This further substantiates previous tests and pavement condition surveys indicating that sweetening with 30 percent crushed limestone will inhibit destructive cement-aggregate reaction in concrete made with Nebraska sand-gravel.

The beams representing concrete made without crushed limestone or fly ash (Classes A and H) expanded considerably more than any of the other sets of beams. Beams fabricated with Class A concrete using brand B cement and with Class H using either brand B or brand A cement expanded more than 0.050 percent during 1 yr of exposure. Beams from the Fremont project representing Class A concrete made with brand A cement expanded only 0.025 percent at 12 mo of exposure, but at 18 mo their expansion was 0.067 percent which was approximately equal to the expansion during the same amount of time of corresponding concrete made with brand B cement. Beams

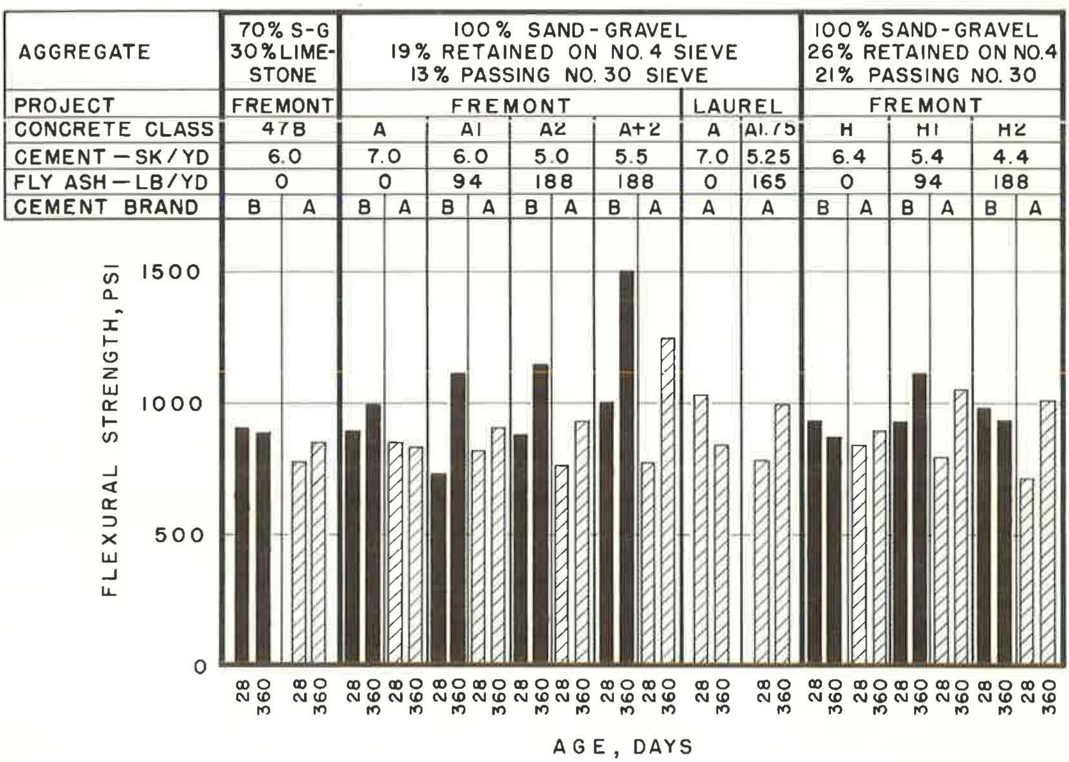

Figure 3. Flexural strength of concrete beams.

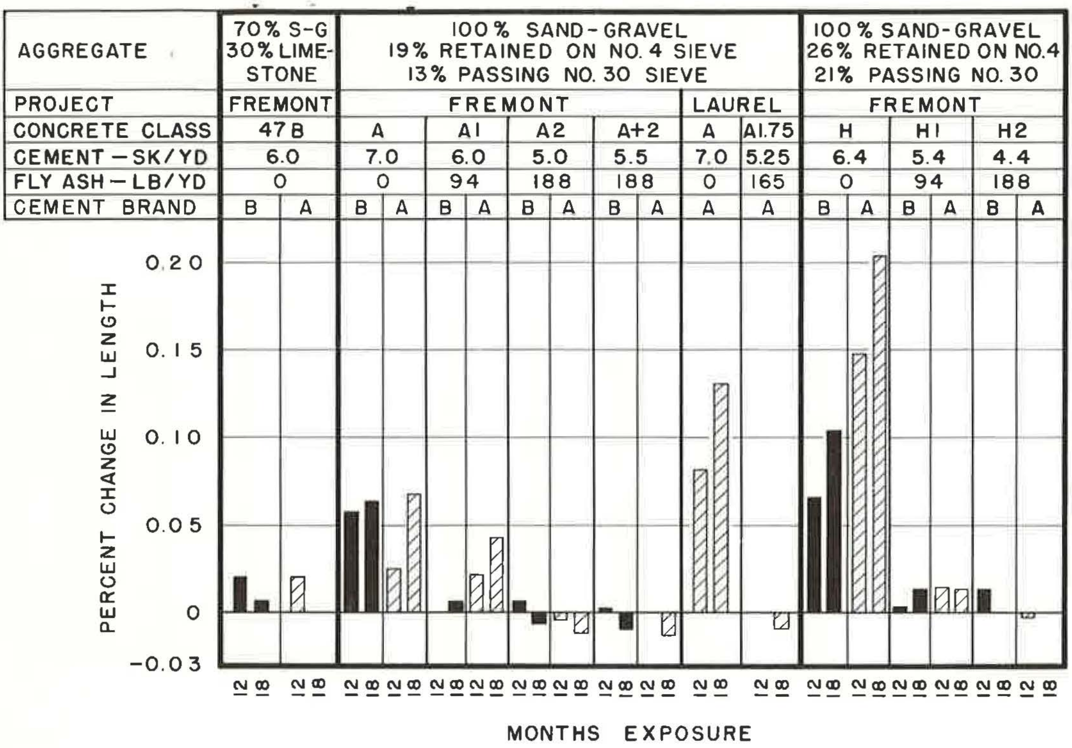

Figure 4. Length change of concrete beams in wetting and drying exposure.

representing similar concrete on the Laurel project expanded considerably more than 0.05 percent at 12 mo of exposure. This was an indication that damage could be expected in these sections because of expansion caused by cement-aggregate reaction.

In all but one instance the substitutions of 94 lb of fly ash was sufficient to inhibit the cement-aggregate reaction within a safe limit. The one exception was Class A1 concrete with brand A cement. Although the expansion of these beams was within safe limits at 12 mo, they were expanding at a rapid rate after 18 mo of treatment. Detrimental expansion was completely inhibited in all sections with a substitution greater than 94 lb of fly ash per cubic yard of concrete.

Freezing and Thawing Exposure

Beams representing each class of concrete were also allocated to a directional-freezing and uniform-thawing exposure (2). 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 then thawed by circulating air maintained at a temperature of 70 F with steam. Four cycles of freezing and thawing were produced each day.

Periodically the test beams were measured for loss in sonic modulus of elasticity (E) and change in length. All sets of beams were removed from the test when their average loss in sonic E was 30 percent or more, or after 200 cycles of freezing and thawing, whichever occurred first.

Durability factors were computed by the method described in ASTM Designation: C260-54 and are shown in Figure 5. This is a severe freezing and thawing test, and previous tests indicate that a durability factor of 40 or more is indicative of durable concrete. Based on this premise, all concretes tested were durable. However, all classes of concrete made with fly ash had a durability factor of 100, indicating that concrete made with these materials was practically unaffected by 200 cycles of freez-

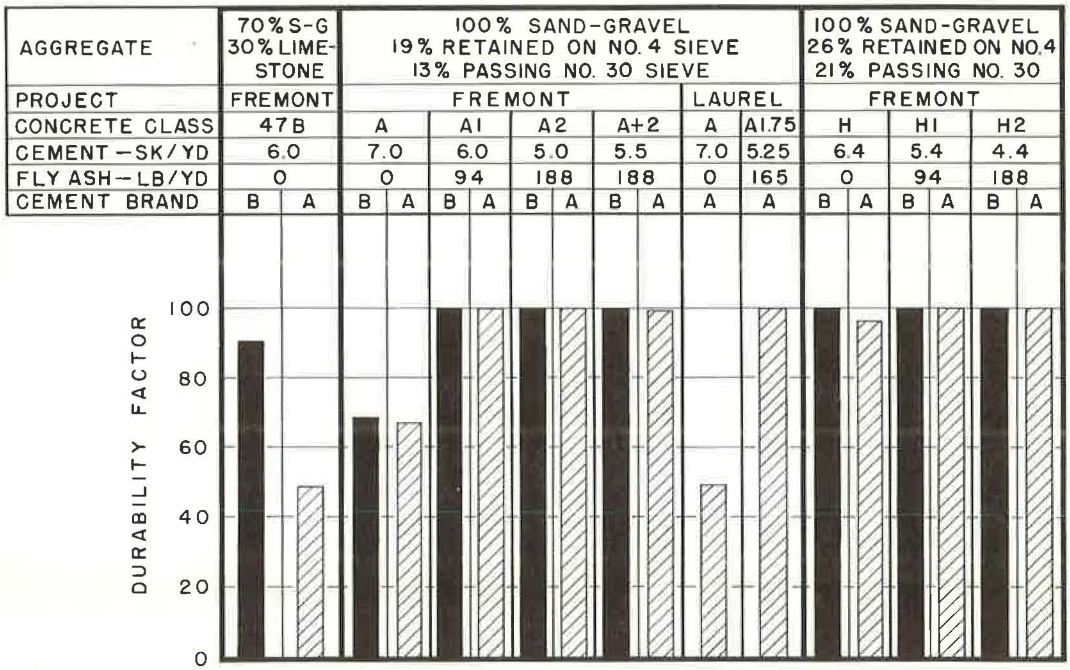

Figure 5. Durability of beams subjected to directional freezing and uniform thawing exposure.

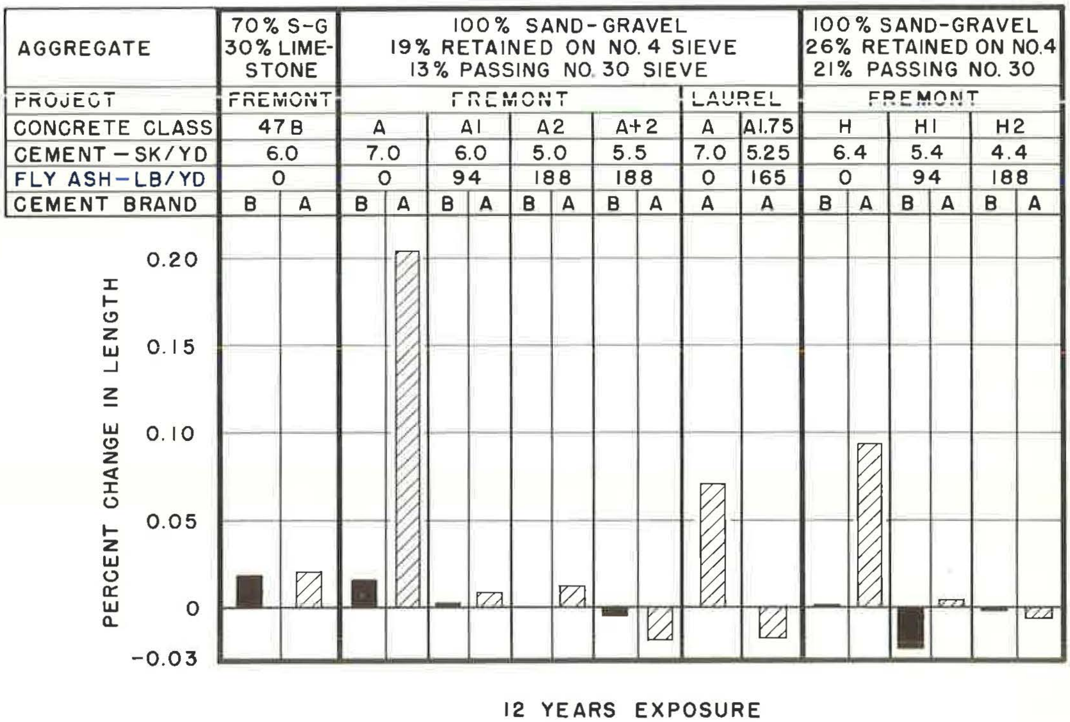

Figure 6. Length change of concrete beams in outdoor exposure yard.

ing and thawing. The inclusion of fly ash in the mixture increased the durability of the concrete when the air content was held at an adequate level.

Outdoor Exposure

Four 6- by 6- by 30-in. concrete beams representing each class of concrete were cast with measuring plugs set at 20-in. centers in their top and side faces. These beams were cured in the same manner as the small beams and then placed in an outdoor exposure yard. They were laid in parallel rows on a 4-in. sand cushion with sufficient space between them to provide maximum exposure to the sun.

The length changes of the beams after 12 yr of exposure are shown in Figure 6. These measurements indicate that the 100 percent sand-gravel concrete made with brand A cement has developed excessive expansion or is growing at a rate that will produce excessive expansion in a few years. None of the classes using fly ash or the concrete made with crushed limestone developed expansion that could be considered excessive. Also, the 100 percent sand-gravel aggregate concrete made with brand B cement did not grow excessively.

CHANGE IN LENGTH OF CONCRETE PAVEMENT

The changes in length of the pavement sections representing each class of concrete have been measured periodically since the project was constructed. For these measurements, stainless steel reference plugs were set in the plastic concrete at each special test area during construction of the pavement. The plugs were embedded in the concrete at 20-in. centers in a row that extended across the pavement perpendicular to the centerline and midway between contraction joints. Initial measurements were made at 30 days age and then periodically ever since with a 20-in. strain gage using an Invar steel bar as a standard.

Concrete pavement is constantly undergoing changes in volume because of variations in prevailing conditions. Temperature changes cause the concrete to fluctuate almost continuously day and night. Variations in moisture will also cause changes in volume which may or may not vary to a great extent each day but will certainly vary during the year. A cement-aggregate reaction will also cause a change in volume of concrete, but this change is always positive and permanent. Concrete will fluctuate in volume because of variations in temperature or moisture, but a continuous growth over a period of years is indicative of permanent damage which may be caused by a cement-aggregate reaction and/or freezing and thawing. Because no damage from freezing and thawing was apparent on either project, any permanent expansion probably resulted from a cement-aggregate reaction.

Because of fluctuations, exact values of expansions or contractions cannot be measured at any specified time, and only trends should be considered. Curves indicating these trends are plotted by the least squares method in Figure 7.

Detrimental expansion was inhibited in the concrete made with substitutions of crushed limestone and in all classes of concrete made with fly ash; in fact, most sections using fly ash had some shrinkage. Class A and Class H concrete using brand A cement without fly ash expanded considerably on the Fremont project. These sections started to map-crack about the fifth or sixth year and are in poor condition at the present time. Test sections on the Laurel project made with Class A concrete and brand A cement have not expanded an alarming amount for some unknown reason, but there are areas outside the location where the measuring plugs were set in which this class of concrete is severely map-cracked and there is considerable evidence of expansion.

Sections constructed on the Fremont project with Class A or H concrete (no fly ash) using brand B cement did not expand enough during 12 yr to cause any serious damage to the concrete. However, some areas constructed with Class H concrete are beginning to develop faint map-cracking.

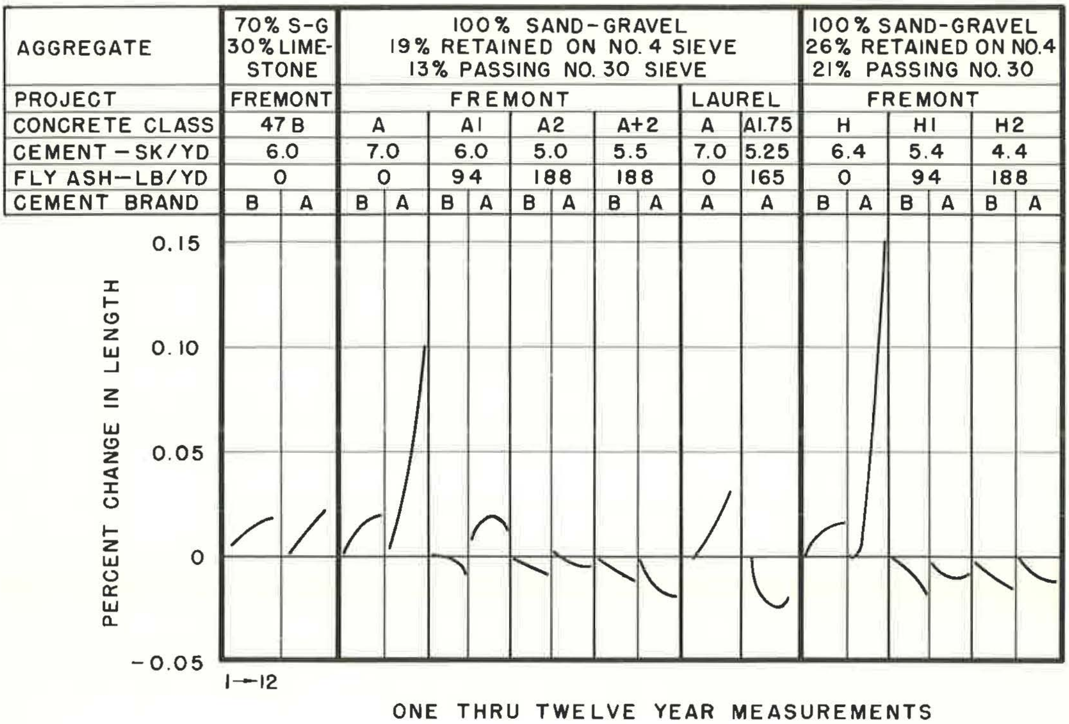

Figure 7. Linear change of concrete pavement.

PAVEMENT CONDITION

The pavement on both projects has been inspected at various intervals for the development of cracks and to determine the general condition of the concrete. At the time of the last survey (April 1962), map-cracking and evidence of expansion was observed on all sections constructed with sand-gravel aggregate concrete and portland cement A. Most areas in these sections were damaged to the extent that a protective covering or some other type of repair was needed. Similar sections constructed with cement B are in much better condition, and only a few localized ones show signs that map-cracking may be developing.

There was no evidence of map-cracking or expansion in the sections constructed with concrete containing 165 lb or more of fly ash. Some of the sections on the Fremont project made with concrete containing fly ash developed transverse cracks at an early age, but at the present time there are more transverse cracks per unit length in the sand-gravel aggregate concrete made without fly ash than there are in corresponding sections made with fly ash. Some of the 1, 800-ft sections on the Fremont project constructed with fly ash are entirely free of cracks of any kind and appear to be in perfect condition.

Rebound hammer tests taken on the pavement at the time of the last survey indicated that the strength of the sand-gravel aggregate concrete containing fly ash was higher than the strength of similar concrete made without fly ash.

The condition of the concrete sections at the present time confirms most of the laboratory tests made previously. Some sections constructed with brand B cement did not develop as much growth as was anticipated, but all concrete made with brand A cement that expanded a considerable amount in the wetting and drying test also expanded considerably during service. In all cases, the use of fly ash in the concrete reduced expansion and increased compressive strength both in the laboratory tests and in the concrete pavement. The laboratory tests also indicated that all types of concrete were durable in freezing and thawing, and there was no evidence of damage from freezing and thawing on either project. The condition of the concrete sections at the present time is also proof that sound and durable concrete pavement can be constructed with Nebraska sand-gravel and portland cement if the proper amount of a good-quality fly ash is used in the mix.

SUMMARY

Observations and tests on the Laurel and Fremont test projects during construction and during a subsequent service period of 12 to 13 yr may be summarized as follows:

1. The addition of fly ash to a sand-gravel aggregate concrete presented no special problems in batching and placing the concrete, and the additions made the concrete more workable except during periods of excessively high temperature and low humidity.
2. Although concrete made with fly ash had slightly lower early strengths than corresponding concrete without fly ash, its strengths, both flexural and compressive, were higher at later ages.
3. The use of fly ash in sand-gravel aggregate concrete increased its durability in freezing and thawing when the air content was held at an adequate level.
4. Expansion and map-cracking because of cement-aggregate reaction was satisfactorily inhibited with the use of sufficient quantities (over 94 lb/cu yd) of fly ash in sand-gravel aggregate concrete.
5. Expansion because of cement-aggregate reaction was also inhibited by using 30 percent crushed limestone in the sand-gravel aggregate concrete.
6. All sections of concrete constructed with 165 lb or more of fly ash per cubic yard of concrete are in better condition than sections constructed with corresponding concrete without fly ash. Some of the sections constructed with concrete using fly ash are still free of cracks and apparently in perfect condition after 13 yr of service.

REFERENCES

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