CONCRETE MIX DESIGN
WITH FLY ASH

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by

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ABSTRACT

The effects of substituting Class C fly ash for a portion of the portland cement in both Class S and Class S(AE) concrete were studied. The percentage of substitution ranged from 25% to 65%. Multiple samples were made and tested for compressive strength at ages of 7 days to 6 months, rapid freeze-thaw durability, and resistance to deterioration due to the action of deicing chemicals. The same tests were conducted on control specimens using the same mix designs without fly ash to provide a comparison basis. The results indicate that, for nonair-entrained concrete, up to 65% of the portland cement can be replaced with Class C fly ash as produced locally with no severe adverse effect on those characteristics examined in this study. For air-entrained concrete, replacement of up to 25% was found to have no adverse effects, and replacement of up to 65% adversely affected only the resistance to deicing chemicals.

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Chapter One

INTRODUCTION

Fly ash is being used as a partial replacement for portland cement in a number of applications; however, few tests have been conducted using locally available Class C fly ash and aggregates meeting Arkansas Highway and Transportation Department (AHTD) Standard Specifications. The AHTD has successfully used fly ash in portland cement concrete base and in pressure grouting of portland cement concrete pavement; but has not attempted such use in structural concrete. Anticipating new regulations by the Federal Highway Administration which would require the use of fly ash in structural concrete, the AHTD must develop specifications which will allow substitution of fly ash for portland cement where possible.

The primary objective of this research was to determine the effects of substitution of various amounts of fly ash for portland cement in both air-entrained (AHTD Class S(AE)) and nonair-entrained concrete (AHTD Class S). AHTD Specifications for both of these classes call for a minimum of 6.5 sacks of cement per cubic yard, a maximum of 5.5 gallons of water per sack of cement, and require a minimum compressive strength of 3500 psi at 28 days. Three characteristics of concrete were studied: compressive strength, rapid freeze-thaw durability, and resistance to deicing chemicals.

Samples were made with substitution rates of 25%, 40%, 50%, and 65% in nonair-entrained concrete (Class S) and 25%, 50%, and 65% in air-entrained concrete (Class S(AE)). The rates of substitution were calculated on an absolute volume basis. The weight of cement to be replaced was determined by multiplying the design weight by the percent replacement factor. The weight of fly ash to be used was determined by multiplying the weight of cement to be replaced by the specific gravity of the fly ash and dividing by the specific gravity of the cement. This provided a one-to-one replacement ratio. Control samples of both Class S and Class S(AE) without fly ash were made to provide a basis for comparison.

Chapter Two

LITERATURE REVIEW

Background

Fly ash is a by-product of burning pulverized coal in a furnace with the resulting heat being used to produce electricity. Coal contains clay minerals, feldspars, mica, quartz, pyrite, and other minerals in small quantities. during the combustion process, these components react to form new compounds, the major ones being silicon oxide, iron oxide, aluminum oxide, and calcium oxide. ASTM C618 distinguishes between Class F and Class C fly ash by the minimum required percentage of the sum of the silicon, iron, and aluminum oxides, and by the percent of loss on ignition. For a fly ash to be classed as Class F, the three oxides must make up at least 70% of the weight, and the loss on ignition is limited to a maximum of 12%. A Class C fly ash requires only 50% of the three oxides and limits the loss on ignition to 6%. The fly ash is collected from the smoke stack by electrostatic precipitators or by filtering through bag houses. The electrostatic precipitators are the most common method; however, some fly ashes have a high resistivity and cannot be successfully collected by this method. For these fly ashes, more commonly produced from western coal, the bag houses are used. Both methods achieve a removal efficiency of over 99%.

Historically, much of the fly ash was allowed to escape into the air; however, various efforts to protect the environment have forced power companies to collect most of the fly ash and dispose of it in some ecologically sound manner. This resulted in large quantities of fly ash being produced, creating a disposal problem. To help solve the problem of disposal, engineers and others began looking for ways to use fly ash in various types of construction.

Initially, its use as a component in concrete was restricted to mass concrete, such as in dams, or as a partial replacement for some of the fine aggregate. Most of the fly ash used in the early work was Class F, produced by the burning of bituminous and anthracite coal which is mined in the Eastern United States. This type fly ash has a low calcium oxide (CaO) content, usually in the range of 3% to 10%. The advantages when Class F fly ash is used in concrete have been well documented and the general technology is fairly well understood. Some of these advantages, as reported by Abdun-Nur[1]*, are: reduced water requirement, improved workability, lowered heat of hydration, and reduced permeability. In addition, the time of set is somewhat retarded, which can be either a disadvantage or an advantage, depending on the type of construction. These advantages, along with improved water tightness and reduced costs, are also noted by J. S. Pierce[2], citing extensive

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*Superscript numbers refer to entries in the bibliography.

research and use of both Class F and Class C fly ash by the United States Bureau of Reclamation. In the last ten years, this agency has used fly ash in amounts of up to 35% replacement in over one million cubic yards of both structural and mass concrete.

In recent years, the construction of new power generating plants and the increasing use of subbituminous and lignite coals from the Western United States has given rise to large quantities of Class C fly ash being produced. In Arkansas, there are currently five coal-burning power plants which produce approximately 450,000 tons of fly ash each year, all of which is Class C. Class C fly ash has a much higher CaO content, usually in the 20% to 30% range. This high lime content gives Class C fly ash a significant cementitious property.[3] Since Class C fly ash is a relatively new material, the technology for its use with portland cement has not been fully developed.

<u>Properties of Fly Ash</u>

The chemical composition of fly ash depends on the type of coal being used and the nature and amount of any additives which may be used. Additives are sometimes used to provide for flame stabilization, corrosion protection of the combustion chamber, and to facilitate fly ash collection. The physical properties of fly ash depend primarily on the specific combustion process and the collection techniques. Generally, fly ash particles are spherical and range in diameter from 1 to 150 microns.[4] Some of the spherical particles are hollow. It is the spherical shape which is generally accepted as providing the increased workability of fly ash concrete.

Since fly ash is a by-product, it is commonly thought of as being a highly variable, random material. However, Demirel and Pitt[5] report that the fly ash produced by three different plants in Iowa had a variability of major components similar to that of portland cement and significantly less variability of minor components. A review of mill test reports of fly ash produced by four units in Arkansas over a period of 2 years indicates that the fly ash produced by these plants has a variability of major components essentially the same as that of portland cement. This should not be surprising when viewed in terms of efficient operation of a power plant. Maximum efficiency in the operation of a power plant requires a high degree of consistency in the fuel being used, the combustion temperature, and the fly ash collection method. This leads inevitably to consistency in the waste products produced. A major change in any of these factors could certainly result in a significant change in the fly ash produced; however, such major changes are not likely to occur on a frequent basis. Constant monitoring of operational processes and timely testing of the fly ash would provide the data necessary to adjust mix designs to accommodate these changes when they occur. Such adjustment would be based on the results of comprehensive tests of the new fly ash. The percent replacement allowable and the amount of air-entraining agent required would be the main concerns. With some fly ashes, replacement with a greater ratio than one-to-one could be required to produce a satisfactory mix.

The use of fly ash in air-entrained concrete usually causes a significant increase in the amount of air entraining agent (AEA) required to obtain a specific air content. It is generally agreed that the AEA demand is closely related to the carbon content of the fly ash, particularly when the agent is a neutralized Vinsol resin.[6-10] In addition, the fineness of the fly ash has also been found to influence the AEA demand.[11-12]

Chapter Three

TEST METHODS AND MATERIALS USED

General Test Plan

Two complete cycles of tests were conducted. The first cycle consisted of a control mix (AHTD Standard Class S Concrete) and one mix each with 25%, 40%, 50%, and 65% fly ash content. All of the first cycle mixes were nonair-entrained. The second cycle consisted of a control mix (AHTD Class S), one mix of AHTD Class S(AE), and one mix each of the Class S(AE) with 25%, 50%, and 65% fly ash content.

The percent fly ash content is the percentage of portland cement replaced with fly ash, computed on an absolute volume basis. The quantities of aggregates were held constant and the water and AEA quantities were adjusted to produce the desired slump and air content. Figures 1 and 2 show the mix designs for Class S and Class S(AE) concrete, respectively, using the AHTD standard method of absolute volume. The quantities shown for a 1.2 cubic foot batch were the quantities used to prepare the control samples without fly ash. The same quantities of aggregates were used for the fly ash concrete samples, and the appropriate percent of cement was replaced with fly ash. The water was adjusted in order to hold the slump constant for all of the samples. This reduction in water content did reduce the yield slightly, but this minor effect was ignored.

ARKANSAS STATE HIGHWAY DEPARTMENT
CONCRETE MIX DESIGN

JOB NO. Special   Date 8-24-84   Mix No. S-1

AGGREGATE DATA - BASED ON HEAT DRY CONDITION

Material	Source	Specific Gravity	Dry Rod Weight	62.4 Lbs. x Sp. Gr.	Solid Vol. per C.F.	%Absorp of Agg.
Cement	Blue Circle	3.15	94.0	196.56	0.478	-
Fine Agg.	Arkhola	2.63	109.2	(A)164.11	(C)0.665	0.38
Coarse Agg	West Fork	2.70	100.6	(B)168.48	(D)0.597	0.63
Fly ash	Chem-Ash	2.65 (Assumed)				

1. Design mix on basis of (E) 6.5 sacks cement per cubic yard.

   Yield per sack cement = 27.0 c.f. / (E) 6.5 =(F) 4.154 c.f.

2. Design mix on basis of (G) 4.5 gallons water per sack cement.

   (G) 4.5 gal. water / 7.48 = (H) 0.602 c.f. volume of water.

3. Design mix on basis of (I) 0 % entrained air.

   (I) ____% x (F) ____ = (J) ____ c.f. volume of air.

4. Cement 0.478 + (H) 0.602 + (J) 0 = (K) 1.080 c.f. mortar paste.

5. (F) 4.154 - (K) 1.080 = (L) 3.074 c.f. solid volume of coarse & fine agg.

6. Solid volume coarse agg. = (L) 3.074 x (D) 0.597 = (N) 1.835 c.f.

7. Solid volume fine agg. = (L) 3.074 - (N) 1.835 = (O) 1.239 c.f.

8. Heat dry wt. coarse agg. = (N) 1.835 x (B) 168.48 = (P) 309.16 lbs.

9. Heat dry wt. fine agg. = (O) 1.239 x (A) 164.11 = (Q) 203.33 lbs.

10. Wt. of coarse agg. for a 6.5 sack batch = 6.5 x (P) 309.16 = 2009.5 lbs.

11. Wt. of fine agg for a 6.5 sack batch = 6.5 x (Q) 203.33 = 1321.6 lbs.

MIXING WATER COMPUTATION

8.34 X (g) 4.5 gallons per sack = 37.53 lbs. water added.

0.63 % absorp. coarse agg. x (P) 309.16 = 1.95 lbs. water added.

0.38 % absorp. fine agg. x (Q) 203.33 = 0.77 lbs. water added.

Total water added = (R) = 40.24 lbs.

For 1.2 c.f. batch: Cement = ((6.5 x 94.0) / 27) x 1.2 = 27.1 lbs.

Coarse Agg. = (2009.5 / 27) x 1.2 x 1.008 = 90.0 lbs.

Fine Agg. = (1321.6 / 27) x 1.2 x 1.030 = 60.5 lbs.

Figure 1. Mix Design for Class S Concrete.

ARKANSAS STATE HIGHWAY DEPARTMENT
CONCRETE MIX DESIGN

JOB NO. Special   Date 8-24-84   Mix No. S(AE)

AGGREGATE DATA - BASED ON HEAT DRY CONDITION

Material	Source	Specific Gravity	Dry Rod Weight	62.4 Lbs. x Sp. Gr.	Solid Vol. per C.F.	%Absorp of Agg.
Cement	Blue Circle	3.15	94.0	196.56	0.478	-
Fine Agg.	Arkhola	2.63	109.2	(A)164.11	(C)0.665	0.38
Coarse Agg	West Fork	2.70	100.6	(B)168.48	(D)0.597	0.63
Fly ash	Chem-Ash	2.65 (Assumed)				

1. Design mix on basis of (E) 6.5 sacks cement per cubic yard.

   Yield per sack cement = 27.0 c.f. / (E) 6.5 =(F) 4.154 c.f.

2. Design mix on basis of (G) 4.5 gallons water per sack cement.

   (G) 4.5 gal. water / 7.48 = (H) 0.602 c.f. volume of water.

3. Design mix on basis of (I) 6.0 % entrained air.

   (I) 6.0 % x (F) 4.154 = (J) 0.249 c.f. volume of air.

4. Cement 0.478 + (H) 0.602 + (J) 0.249 = (K) 1.329 c.f. mortar paste.
5. (F) 4.154 - (K) 1.329 = (L) 2.825 c.f. solid volume of coarse & fine agg.
6. Solid volume coarse agg. = (L) 2.825 x (D) 0.597 = (N) 1.687 c.f.
7. Solid volume fine agg. = (L) 2.825 - (N) 1.687 = (O) 1.138 c.f.
8. Heat dry wt. coarse agg. = (N) 1.687 x (B) 168.48 = (P) 284.23 lbs.
9. Heat dry wt. fine agg. = (O) 1.138 x (A) 164.11 = (Q) 186.76 lbs.
10. Wt. of coarse agg. for a 6.5 sack batch = 6.5 x (P) 284.23 = 1847.5 lbs.
11. Wt. of fine agg for a 6.5 sack batch = 6.5 x (Q) 186.76 = 1213.9 lbs.

MIXING WATER COMPUTATION

8.34 X (g) 4.5 gallons per sack = 37.53 lbs. water added.

0.63 % absorp. coarse agg. x (P) 284.23 = 1.79 lbs. water added.

0.38 % absorp. fine agg. x (Q) 186.76 = 0.71 lbs. water added.

Total water added = (R) = 40.03 lbs.

For 1.2 c.f. batch : Cement = ((6.5 x 94.0) / 27) x 1.2 = 27.1 lbs.

Coarse Agg. = (1847.5 / 27) x 1.2 x 1.008 = 82.8 lbs.

Fine Agg. = (1213.9 / 27) x 1.2 x 1.030 = 55.6 lbs.

Figure 2. Mix Design for Class S(AE) Concrete.

Sources and Tests of Materials

The coarse aggregate was crushed limestone obtained from an AHTD-tested stockpile at the Arkhola Sand and Gravel Company's ready-mix concrete plant in Springdale, Arkansas. This material came from the McClinton-Anchor Company quarry at West Fork. The fine aggregate was obtained from an AHTD-tested stockpile at the same plant, and is Arkansas River sand produced by Arkhola at Van Buren, Arkansas.

AHTD personnel routinely test samples from these stockpiles on a regular basis for compliance with their specifications. The data for specific gravity, absorption, and dry rodded weight used in the mix designs were obtained from their test reports.

The cement (Blue Circle Type I) was obtained from AHTD certified stock at the Tune Concrete Products Company's plant in Fayetteville, Arkansas. The fly ash was obtained from Chem-Ash Corporation. Copies of the mill test reports for both cement and fly ash are included in Appendix A.

The air entraining agent used was a neutralized Vinsol resin produced by Master Builders Division of Martin Marietta Corporation, which is one of several on the AHTD approved list.

Mix Designs

The mix designs were prepared for Class S and Class S(AE) using the data for specific gravity, dry rodded weight, and percent absorption determined by AHTD personnel for the aggregates used. The required weights of fly ash for the various percentages were calculated using an assumed specific gravity for the fly ash of 2.65. This value was assumed because the mill test report on the fly ash was not made available until after both cycles of samples had been made. The actual specific gravity was 2.56, a difference of 3.5%. This minor error had the effect of increasing the absolute volume of fly ash in the mixes by less than 0.3%, which is considered negligible.

Sieve analyses were run on the aggregates shortly after they were delivered to verify compliance with AHTD standard specifications. The moisture content of the aggregates was determined and batch weights were calculated for a 1.2 cubic foot batch. The aggregates were weighed at that time for all planned batches in one-batch quantities and stored in plastic bags to maintain the moisture content.

<u>Casting of Specimens</u>

The test specimens for the first cycle were cast on September 8, 1984. Five mixes were prepared: one control mix (AHTD Standard Class S concrete), and one mix each with 25%, 40%, 50%, and 65% fly ash content. Three batches were prepared of each mix, using the pre-weighed aggregates and measuring the cement, fly ash, and water by weight for each batch. Table 1 lists the as-batched data for the first cycle and the specific specimens made from each batch.

Table 1. First cycle batches and specimens.

Batch Label	Cement Lbs.	Fly ash Lbs.	Water Lbs	Slump In.	Number of specimens Cyls.	F/T	Deicing
			No Fly ash:				
S1A	27.1	0	11.6	4	4	3	2
S1B	27.1	0	9.1	1	4	3	0
S1C	27.1	0	9.3	1	4	3	2
			25% Fly ash:				
S25A	20.3	5.7	9.1	2	4	3	2
S25B	20.3	5.7	9.1	1-3/4	4	3	0
S25C	20.3	5.7	9.3	2	4	3	2
			40% Fly ash:				
S40A	16.3	9.1	9.1	2-1/4	4	3	2
S40B	16.3	9.1	8.6	2-3/4	4	3	0
S40C	16.3	9.1	8.8	2-1/2	4	3	2
			50% Fly ash:				
S50A	13.6	11.4	9.1	2-3/4	3	3	3
S50B	13.6	11.4	8.6	2-3/4	5	3	1
S50C	13.6	11.4	7.9	2-1/2	4	3	0
			65% Fly ash:				
S65A	9.5	14.8	9.1	3-3/4	4	3	2
S65B	9.5	14.8	6.6	1	4	3	0
S65C	9.5	14.8	8.0	2-1/4	4	3	2

All batches contained 90.0 Lbs. Coarse Aggregate and 60.5 Lbs Fine Aggregate, including moisture.

Table 2. Second cycle batches and specimens.

Batch Label	Cement Lbs	Fly ash Lbs	Water Lbs	Slump In.	AEA ml.	Air content %
			No Fly ash:			
S-2	81.3	0	31.0	4	0	-
			No Fly Ash:			
SAE1	81.3	0	29.0	3-1/4	60	5.5
			25% Fly ash:			
SAE25	60.9	17.1	28.0	4	80	7.5
			50% Fly ash:			
SAE50	40.8	34.2	23.0	3-1/2	80	7.0
			65% Fly ash:			
SAE65	28.5	44.4	20.0	2	70	4.3

Aggregate weights for Batch S2 were triple those of the first cycle. All other batches contained 248.4 Lbs. of Coarse Aggregate, and 166.8 Lbs. of Fine Aggregate, including 0.8% and 3.0% moisture, respectively.

While testing proceeded on the first cycle, several small trial batches were made in an attempt to determine the quantity of air entraining agent needed to obtain the planned 6% air content.

The test specimens for the second cycle were cast on January 12, 1985. Five mixes were prepared: one control mix (AHTD Class S), one AHTD Standard Class S(AE), and one each of the Class S(AE) mix with 25%, 50%, and 65% fly ash content. For this cycle, a larger mixer was used that allowed preparation of a larger batch so that only one 4.2 c.f. batch was required for each mix. This was done in an attempt to provide better control over the slump and air content, since the results of the trial batches and the experience gained from the first cycle indicated that it was difficult to obtain consistently good results with small batches. Table 2 lists the as-batched data for the second cycle. A total of 12 cylinders, 3 freeze-thaw, and 4 deicing chemical test specimens were made from each batch.

The compressive strength test cylinders were standard 6 inch diameter by 12 inch height, cast in single-use plastic molds meeting the requirements of ASTM C470. The specimens for rapid freeze-thaw durability testing were 3" x 3" x 14" prisms, cast in shop built 3/4" plywood forms. The specimens for deicing chemical resistance testing were 6-1/2" x 11-1/2" x 3" prisms, cast in 3/4" plywood forms. The plywood was treated to be nonabsorbant and nonreactive with the concrete mixes. All specimens were prepared in accordance with ASTM C192, removed from the molds after 24 hours, and cured in a moist room meeting the requirements of ASTM C511 for the length of time required by the specific tests involved.

Curing and Testing of Specimens

Compressive strength test cylinders were removed from the curing room, capped with a sulfur compound, and tested at ages of 7 days, 28 days, 3 months, and 6 months. Three cylinders were tested in accordance with ASTM C39 at each age for each mix, with the exception of two cases where individual cylinders were damaged after casting and prior to testing. These are noted in the discussion.

The specimens for the rapid freeze-thaw testing were removed from the curing room at the age of 20 days, packed in moist sawdust, and transported to the AHTD laboratory in Little Rock. The curing period of 20 days before testing was selected instead of the 14 days recommended by ASTM C666 in order to assure a reasonable strength. Most of the literature indicated that fly ash concrete gains strength slowly for the first 28 days, and the decision to wait 20 days was made before casting began. The compressive strength tests indicated that this additional waiting may not have been needed; however, these results were not available until too late to change the procedure. They were stored in a freezer at 0^0F until testing by procedure A of ASTM C666 began. Three specimens were made and tested from each mix.

The specimens for the deicing chemical resistance testing were finished with a medium-stiff bristle brush. At the age of 14 days, they were removed from the curing room and stored in air for an additional 14 days at 73^0 +/- 3^0F and 45% to 55% relative humidity, at which time testing in accordance with ASTM C672 began.

During the air curing period, formica strips approximately 3 inches wide were cemented to the sides of the specimens using standard contact cement, and caulked with silicone rubber sealant. The formica extended approximately 3/4 inch above the top surface of the specimens, providing the solution retention dam. This procedure, not outlined in the ASTM test method, was used in order to reduce the size of the specimen required to obtain the minimum of 72 square inches of surface. A total of four specimens were made from each mix. Two of each mix were tested using sodium chloride (NaCl) solution, and two were tested using calcium chloride (CaCl) solution.

All of the specimens were marked with an identification mark. This mark corresponded to the batch from which the samples were made, and consisted of either the letter S or the letters SAE followed by a number and another letter. The letter S was used for all nonair-entrained samples, while SAE identified the air-entrained samples. The numbers "1" and "2" marked the control samples which contained no fly ash, and the other numbers (25, 40, 50, and 65) designated the percent cement replaced with fly ash. The last letter used on the samples in the first cycle designated the specific batch from which they were made. For the second cycle, since all samples of a particular mix were made from the same batch, the final letter in the identification mark was arbitrarily assigned.

Chapter Four

TEST RESULTS AND DISCUSSION

Compressive Strength

A total of twelve standard cylinders were prepared from each mix in each cycle - three each for the four test ages. One cylinder of the 65% mix in the first cycle and one of the 50% mix of the second cycle were damaged in handling between casting and testing; therefore, the average results for these two mixes for one age reflect the average of only two cylinders instead of three. Figure 3 is a graph of the average strengths of each of the mixes.

For the first cycle, which consisted of all nonair-entrained concrete, all of the mixes showed an increase in compressive strength with time, as was expected. The lowest result was the 4100 psi at 7 days for one of the standard Class S (without fly ash) cylinders, and the highest was the 9270 psi at 6 months for one of the 50% fly ash cylinders. All of the fly ash mixes had a higher compressive strength than the non-fly ash mix at all ages except 6 months, when only the 65% mix had a higher strength.

The second cycle consisted of one standard Class S mix, without fly ash and without air-entrainment; one standard Class S(AE) mix without fly ash, but with air-entrainment; and one each of the Class S(AE) mix with 25%, 50%, and 65% fly ash content. The curing and testing of these specimens proceeded normally through the 3 month age; however, between the 3 month tests and the 6 month tests, the curing room was

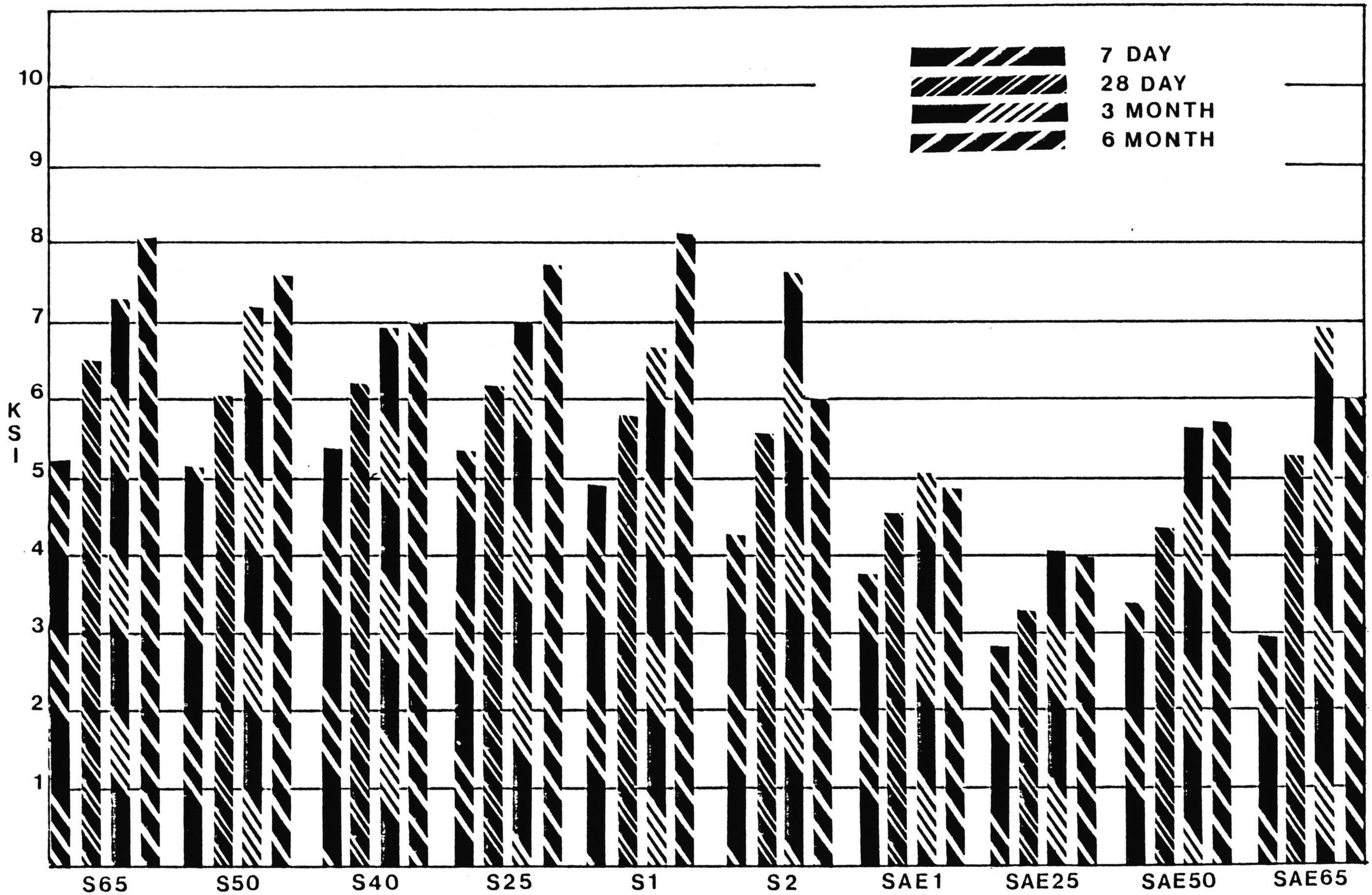

FIGURE 3. COMPRESSIVE STRENGTH.

not monitored as closely as it had been for all the previous tests, and the humidity dropped below 75% for most of this period. This is probably the cause of the unexpectedly small increase, and in some cases a decrease, in strengths between 3 and 6 months. All of the mixes did show an increase in strength with curing time up to the 3 month age. The strengths at 7 days and at 28 days were lower than expected; this is probably due to the fact that the temperature of the casting room where the cylinders were kept before they were stripped and placed in the curing room was approximately 40^{0}F. This low temperature slowed the strength gain so much that the samples had to be allowed to remain in the forms for 48 hours before they could be stripped.

The plain concrete had the highest strengths at all ages. The non-fly ash, air-entrained concrete had a higher strength at 7 and 28 days than the fly ash concretes; but was lower than all except the 25% fly ash at 3 and 6 months. The lower strength of the 25% fly ash is probably due to the much higher air content. In all cases except that of the 25% fly ash concrete, the strength at 28 days was in excess of the 3500 psi minimum required by the AHTD specifications. The compressive strengths of all the cylinders are listed in Appendix B.

In summary, for nonair-entrained concrete, replacement of up to 65% of the cement with fly ash produced higher strengths at all ages except 6 months. For air-entrained concrete, replacement of cement with fly ash produced lower strengths at 7 and 28 days, but higher strengths at 3 and 6 months, except for the 25% samples, which had an excessive air content.

Deicing Chemical Resistance

Four specimens were made from each mix in each cycle for the deicing chemical resistance tests. Two were tested with a solution of sodium chloride (NaCl) and two with calcium chloride (CaCl). Both solutions were used at a strength of 4 grams per 100 milliliters. After the specified curing period, a sufficient quantity of the solution was placed on the samples to cover the surface to a depth of approximately 1/4 inch and they were then placed in a freezer at 0^{0}F for a period of 16 to 18 hours. After this period, they were removed from the freezer and stored in air at approximately 73^{0}F for 6 to 8 hours, completing one cycle. This cycle was repeated throughout the test, with solution being added as necessary to maintain the 1/4 inch depth on the surface. At the end of every fifth cycle the specimens were rinsed with clear water and the surfaces were rated in accordance with the following scale (ASTM C672):

0 - No Scaling

1 - Very Slight Scaling (1/8 inch depth, max, no coarse aggregate visible)

2 - Slight to Moderate Scaling

3 - Moderate Scaling (some coarse aggregate visible)

4 - Moderate to Severe Scaling

5 - Severe Scaling (coarse aggregate visible over entire surface)

The record of the ratings is given in Appendix C.

Figure 4 is a graph of the number of cycles to which the specimens were subjected until a rating of 5 was given, or the test was stopped due to other deterioration of the sample. Several of the nonair-entrained specimens, after several cycles, began leaking the solution through the sample and the edges began to crumble. When this deterioration reached the point at which the solution could not be maintained at 1/4 inch depth, the test was stopped.

The general results, as indicated on the graph in Figure 4, show that fly ash does have a slightly adverse effect on the resistance of nonair-entrained concrete to deicing chemicals, with this adverse effect generally increasing with increasing fly ash percentage. This decrease in deicing chemical resistance is so small that it can be considered negligible.

For air-entrained concrete, the 25% fly ash specimens showed no significant difference in deicing chemical resistance when compared to plain air-entrained concrete; however, the 50% fly ash samples deteriorated more rapidly than the 25%, and the 65% fly ash samples deteriorated approximately as rapidly as all of the nonair-entrained samples. The different amounts of entrained air in the various mixes could perhaps account for some of this effect, but not all of it.

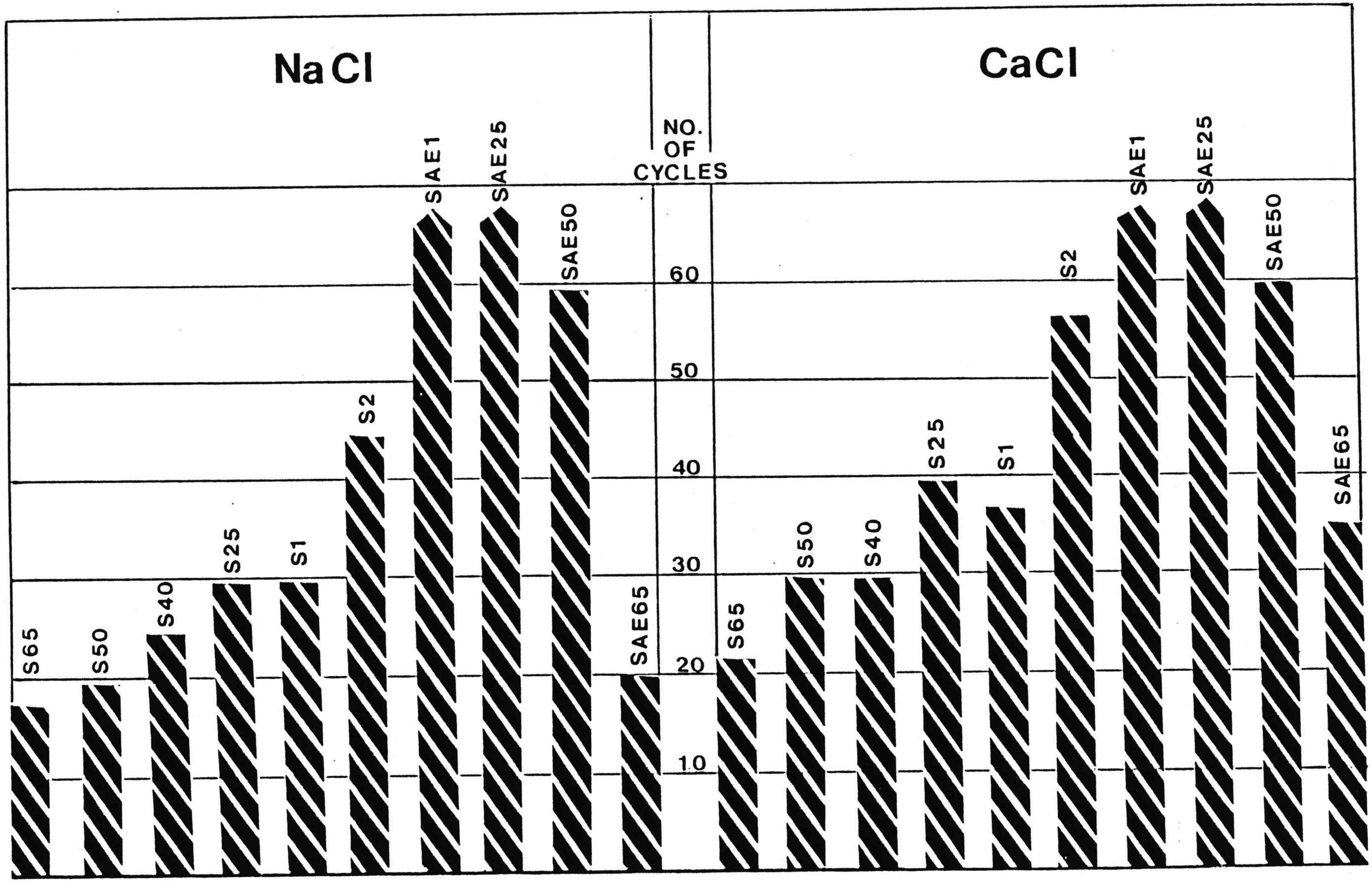

FIGURE 4. DEICING CHEMICAL RESISTANCE.

In summary, fly ash in amounts greater than 25% reduces the concrete's resistance to deicing chemicals for air-entrained concrete, but has a negligible effect on nonair-entrained concrete.

Freeze thaw durability

The resistance of the specimens to rapid freezing and thawing was tested by Procedure A of ASTM C666. This test involves surrounding the specimens with approximately 1/8 inch of water and placing them in a device that reduces their temperature to 0^0F then raises it to 40^0F in approximately three hours. At intervals of not more than 36 cycles, the fundamental transverse frequency of each specimen is determined by the procedures in ASTM C215, and compared to the frequency determined before testing began. The relative dynamic modulus of elasticity (P_C) is computed from the following formula:

$$P_C = (n_1^2 / n^2) \times 100$$

where n_1 = fundamental transverse frequency after c cycles of freezing and thawing.

and n = fundamental transverse frequency at the beginning of the test.

Higher values for P_C indicate greater resistance to the action of freezing and thawing for the concrete being tested.

As expected, the nonair-entrained specimens deteriorated rapidly when subjected to the rapid freeze-thaw durability testing. None of them lasted more than 100 cycles before the deterioration became so severe that further testing was impossible. In fact, all except the 65% could no longer be tested after 67 cycles. However, the use of fly ash did increase the durability of the concrete, with higher percentages of fly ash yielding greater durability, except for the 25% mix, which was only slightly lower.

The air-entrained specimens proved to be very durable when subjected to freeze-thaw testing. After 308 cycles, there was no difference in the relative dynamic modulus of elasticity (P_C) between the non-fly ash and the fly ash samples. The ASTM standard calls for ending the test at 300 cycles; however, these were continued for more than double that number in an attempt to find a significant difference between the different mixes, if one existed. After 577 cycles, the difference in the averages of P_C was less than 10 percentage points, and all had a value of 93 or greater. Even after nearly 700 cycles, the difference was still less than 10 percentage points, and all had a value of 90 or greater. The results of the tests are shown in Appendix D.

In summary, the use of Class C fly ash as a partial replacement for portland cement was found to have no significant effect on the resistance of air-entrained concrete to rapid freezing and thawing. There was, however, some increase in durability for nonair-entrained concrete with increasing percentage of fly ash content, except for the 25% samples.

Chapter Five

CONCLUSIONS

Within the limitations of the test procedures and for the materials used in this investigation, the following conclusions are made.

1. For nonair-entrained Class S concrete, Class C fly ash as produced locally can be substituted for portland cement in amounts up to 65% with no significant adverse effects, and with some significant benefits.

2. For air-entrained Class S(AE) concrete, Class C fly ash can be substituted for portland cement in amounts up to 25% with no adverse effects, and higher amounts of up to 65% can be used if resistance to deicing chemicals is not important for the specific intended use of the concrete.

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APPENDIX A

Mill tests of cement and fly ash

BLUE CIRCLE INC.

TEST DATA ON CERTIFIED CEMENT

PHYSICAL TESTS

Setting Time (Gilmore)

Initial - Hr. 2 Min. 58

Final - Hr. 5 Min. 01

Soundness Autoclave Exp. .043 %

Fineness Blaine cm^2/gm 3439

%Air - 10.6

COMPRESSIVE STRENGTH TESTS

3 days 3430 psi

7 days 4306 psi

CHEMICAL TESTS

1. Silicon Dioxide 21.2 %
2. Aluminum Oxide 5.0 %
3. Ferric Oxide 2.3 %
4. Magnesium Oxide 2.3 %
5. Sulfur Trioxide 3.0 %
6. Insoluble Residue 0.2 %
7. Loss on Ignition 1.2 %
8. Calcium Oxide 64.6 %
9. Tricalcium Silicate 57.1 %
10. Dicalcium Silicate 17.6 %
11. Tricalcium Aluminate 9.4 %

(Blue Circle Mill Analysis No. 210.)

AMERICAN INTERPLEX CORPORATION

Chemical and Physical Analyses of Fly Ash

Chemical Composition (%):

Silicon Oxide (SiO_2)	31.5	
Aluminum Oxide (Al_2O_3)	20.0	
Iron Oxide (Fe_2O_3)	6.62	
TOTAL ($SiO_2 + Al_2O_3 + Fe_2O_3$)		58.1
Sulfur Trioxide (SO_3)		1.80
Calcium Oxide (CaO)		25.2
Magnesium Oxide (MgO)		4.61
Moisture Content		0.0553
Loss on Ignition		0.263
Available Alkalies as Na_2O (28 days)		0.568
(7 days)		0.0434

PHYSICAL TEST RESULTS:

Fineness - Retained on #325 Sieve (%)	13.7
Pozzolanic Activity Index with Portland Cement @ 7 days: Ratio to control (%)	63.1
psi	2013
Pozzolanic Activity Index with Portland Cement @ 28 days: Ratio to control (%)	118.6
psi	4996
Water Requirement, % of control	83.2
Soundness - Autoclave Expansion (%)	0.113
Drying Shrinkage - Increase @ 28 days (%)	- 0.53
Specific Gravity	2.56

APPENDIX B

Compressive strength of test cylinders

COMPRESSIVE STRENGTHS - FIRST CYCLE

	No Fly Ash		25% Fly Ash		40% Fly Ash		50% Fly Ash		65% Fly Ash	
Age	Cyl No	psi	Cyl No	psi	Cyl No	psi	Cyl No	psi	Cyl No	psi
7 days	S1A	4100	S25A	5090	S40A	5230	S50A	4490	S65A	4810
"	S1B	5450	S25B	5380	S40B	5410	S50B	5590	S65B	5760
"	S1C	5060	S25C	5480	S40C	5480	S50C	5200	S65C	5130
Average - 7 days:		4870		5320		5370		5090		5230
28 days	S1A	5450	S25A	6190	S40A	5870	S50A	5910	S65A	6260
"	S1B	5620	S25B	6610	S40B	6330	S50B	6510	S65B	6970
"	S1C	6400	S25C	5730	S40C	6540	S50C	5840	S65C	6370
Average - 28 days:		5820		6180		6250		6090		6530
3 months	S1A	5910	S25A	6760	S40A	8240	S50A	6970	S65A	6470
"	S1B	6680	S25B	7220	S40B	4530	S50B	7600	S65B	8240
"	S1C	7500	S25C	7000	S40C	8170	S50C	7110	S65C	7390
Average - 3 months:		6700		6990		6980		7230		7370
6 months	S1A	7360	S25A	7850	S40A	7360	S50B1	9270	S65A	*
"	S1B	8910	S25B	7140	S40B	5730	S50B	6370	S65B	9230
"	S1C	8130	S25C	8310	S40C	8060	S50C	7250	S65C	7070
Average - 6 months:		8130		7770		7050		7630		8150

* This cylinder was damaged - not tested.

COMPRESSIVE STRENGTHS - SECOND CYCLE

Age	(no Air) No Fly Ash Cyl No	(no Air) No Fly Ash psi	No Fly Ash Cyl No	No Fly Ash psi	25% Fly Ash Cyl No	25% Fly Ash psi	50% Fly Ash Cyl No	50% Fly Ash psi	65% Fly Ash Cyl No	65% Fly Ash psi
		4030		3960		2760		3220		2860
7 days	S2	4170	SAE1	3610	SAE25	2690	SAE50	3220	SAE65	2760
		4530		3820		2900		3290		3080
Average - 7 days		4240		3800		2780		3240		2900
		4670		4740		3500		*		5200
28 days	S2	6010	SAE1	4070	SAE25	3180	SAE50	3890	SAE65	5520
		6190		4670		3110		4740		5130
Average - 28 days		5620		4490		3260		4320		5280
		7750		5090		4070		5270		7110
3 months	S2	7710	SAE1	5520	SAE25	3890	SAE50	5980	SAE65	6720
		7600		4240		4240		5730		6900
Average - 3 months		7690		4950		4070		5660		6910
		5870		4350		4000		5620		5980
6 months	S2	6010	SAE1	5090	SAE25	4070	SAE50	5620	SAE65	7110
		6120		5060		4000		5800		5060
Average - 6 months		6000		4830		4020		5680		6050

* This cylinder was damaged - not tested.

APPENDIX C

Deicing Chemical Resistance Test Results

DEICING CHEMICAL RESISTANCE TEST RESULTS - FIRST CYCLE

No. Cycles	S1A	S1C	S25A	S25C	S40A	S40C	S50A	S50A2	S65A	S65C	Remarks
Sodium Chloride (NaCl) Solution											
0	0	0	0	0	0	0	0	0	0	0	Began test October 6, 1984.
5	0	0	0	0	0	0	0	0	0	0	
10	3	1	0	0	1	1	2	1	4	2	
15	4	1	2	2	3	3	4	4	5	3	
20	4	1	3	2	4	4	5	5	-	5	
25	5	2	4	4	5	5	-	-	-	-	
30	-	3	5	5	-	-	-	-	-	-	
35	-	4	-	-	-	-	-	-	-	-	
40	-	4	-	-	-	-	-	-	-	-	Ended test November 17, 1984.
Calcium Chloride CaCl) Solution											
0	0	0	0	0	0	0	0	0	0	0	Began test October 6, 1984.
5	0	0	0	0	0	0	0	0	0	0	
10	1	1	1	0	2	1	1	1	3	3	
15	3	2	2	2	3	1	3	2	4	4	
20	3	2	2	2	4	2	4	2	5	4	
25	3	2	2	2	5	3	5	2	-	5	
30	4	3	2	3	-	3	-	3	-	-	
35	5	3	3	4	-	4	-	4	-	-	
40	-	3	4	5	-	5	-	5	-	-	Ended test November 17, 1984.

The test was halted on November 17, 1984, after 40 cycles because the solution was seeping through the remaining samples to such an extent that the 1/4 inch depth could not be maintained.

DEICING CHEMICAL RESISTANCE TEST RESULTS - SECOND CYCLE

	S-2		SAE 1		SAE25		SAE50		SAE65		
No. Cycles	A	B	A	B	A	B	A	B	A	B	Remarks
					Sodium Chloride (NaCl) Solution						
0	0	0	0	0	0	0	0	0	0	0	Began test February 9, 1985.
5	0	0	0	0	0	0	0	0	0	0	
10	1	0	0	0	0	0	0	0	1	1	
15	3	2	1	1	0	0	0	0	4	4	
20	3	2	1	1	0	0	0	1	5	5	
25	4	2	1	1	0	0	1	1	-	-	
30	4	2	1	1	0	0	2	2	-	-	
35	5	3	1	1	0	0	3	3	-	-	
40	-	3	1	1	0	0	3	3	-	-	
45	-	4	2	1	0	0	3	3	-	-	
50	-	4	2	1	1	1	4	4	-	-	
55	-	5	2	1	1	2	4	4	-	-	
60	-	-	2	2	2	2	5	5	-	-	
65	-	-	3	2	3	3	-	-	-	-	
70	-	-	3	2	4	3	-	-	-	-	Ended test April 27, 1985.

DEICING CHEMICAL RESISTANCE TEST RESULTS - SECOND CYCLE

	S-2		SAE 1		SAE25		SAE50		SAE65		
No. Cycles	A	B	A	B	A	B	A	B	A	B	Remarks
					Calcium Chloride (CaCl) Solution						
0	0	0	0	0	0	0	0	0	0	0	Began test February 9, 1985.
5	0	0	0	0	0	0	0	0	0	0	
10	1	1	1	0	0	0	0	0	0	1	
15	2	2	1	1	0	0	1	1	2	3	
20	2	2	1	1	0	0	1	1	3	3	
25	3	2	1	1	0	0	1	1	4	4	
30	3	2	1	1	0	0	1	1	4	4	
35	3	3	1	1	0	0	2	2	5	5	
40	4	3	1	1	1	1	3	3	-	-	
45	4	3	1	1	1	1	3	3	-	-	
50	4	3	1	1	1	1	4	4	-	-	
55	5	4	1	1	1	1	4	4	-	-	
60	-	5	2	2	2	2	5	5	-	-	
65	-	-	2	2	3	3	-	-	-	-	
70	-	-	2	2	3	3	-	-	-	-	Ended test April 27, 1985.

APPENDIX D

Rapid Freeze-Thaw Test Results

RAPID FREEZE-THAW TEST RESULTS - FIRST CYCLE

No. Cycles	Freq. (hz)	Pc* %	Freq. (hz)	Pc %	Freq. (hz)	Pc %	Remarks
	Sample	S1A	Sample	S1B	Sample	S1C	
0	2500	100	2530	100	2447	100	Began test October 3, 1984.
35	1339	29	1861	54	1658	46	
67	383	2	1189	22	919	14	All samples cracking.
92	D**	-	719	8	1182	23	
109	D	-	D	-	D	-	Ended test October 22, 1984.
	Sample	S25A	Sample	S25B	Sample	S25C	
0	2375	100	2487	100	2618	100	Began test October 3, 1984.
35	1064	20	1281	27	1404	29	
67	484	4	434	3	864	11	All samples cracking.
92	D	-	D	-	D	-	Ended test October 19, 1984.
	Sample	S40A	Sample	S40B	Sample	S40C	
0	2411	100	2580	100	2523	100	Began test October 3, 1984.
35	1584	43	1832	50	1742	48	
67	775	10	928	13	799	10	All samples cracking.
92	D	-	D	-	D	-	Ended test October 19, 1984.

*Pc = Relative dynamic modulus of elasticity.
**D = Sample disintegrated; no test possible.

RAPID FREEZE-THAW TEST RESULTS - FIRST CYCLE

No. Cycles	Freq. (hz)	Pc %	Freq. (hz)	Pc %	Freq. (hz)	Pc %	Remarks
	Sample S50A		Sample S50B		Sample S50C		
0	2467	100	2470	100	2451	100	Began test October 3, 1984.
35	1815	54	2077	71	2058	71	
67	777	10	855	12	890	13	All samples cracking.
92	D	-	D	-	D	-	Ended test October 19, 1984.
	Sample S65A		Sample S65B		Sample S65C		
0	2313	100	2432	100	2463	100	Began test October 3, 1984.
35	2330	101	2299	89	2360	92	
67	2252	95	1882	60	1832	55	
92	2255	95	1483	37	902	13	All samples cracking.
109	D	-	D	-	D	-	Ended test October 22, 1984.

RAPID FREEZE-THAW TEST RESULTS - SECOND CYCLE

No. Cycles	Sample S2A Freq. (hz)	Sample S2A Pc* %	Sample S2B Freq. (hz)	Sample S2B Pc %	Sample S2C (No Air, No Fly Ash) Freq. (hz)	Sample S2C (No Air, No Fly Ash) Pc %	Remarks
0	2345	100	2394	100	2309	100	Began test February 12, 1985.
22	2296	96	2460	106	2191	90	
49	2265	93	2279	91	2163	88	
68	2268	94	2084	76	1924	69	
88	1727	54	1942	66	1137	24	
114	1353	33	1356	32	1164	25	
134	818	12	776	11	776	11	
159	D	-	D	-	D	-	Ended test March 8, 1985.

*Pc = Relative dynamic modulus of elasticity.

**D = Sample disintegrated; no test possible.

RAPID FREEZE-THAW TEST RESULTS - SECOND CYCLE

No. Cycles	Sample SAE1A Freq. (hz)	Sample SAE1A Pc %	Sample SAE1B Freq. (hz)	Sample SAE1B Pc %	Sample SAE1C (Air entrained, No Fly Ash) Freq. (hz)	Sample SAE1C Pc %	Remarks
0	2412	100	2297	100	2307	100	Began test February 12, 1985.
22	2049	72	2335	103	2310	100	
49	2226	85	2341	104	2354	104	
68	2352	95	2457	114	2363	105	
88	2414	100	2459	115	2506	118	
114	2292	90	2393	109	2344	103	
134	2390	98	2397	109	2463	114	
159	2290	90	2383	108	2444	112	
179	2333	94	2362	106	2375	106	Slight scaling on all samples.
207	2255	87	2355	105	2277	97	
227	2298	91	2360	106	2395	108	
257	2248	87	2326	103	2349	104	
279	2264	88	2385	108	2328	102	
308	2280	89	2350	105	2305	100	Average after 308 cycles = 98.
328	2274	89	2340	104	2314	101	
355	2241	86	2360	106	2315	101	
375	2272	89	2329	103	2354	104	
402	2274	89	2332	103	2349	104	
422	2230	85	2322	102	2341	103	
446	2127	78	2388	108	2292	99	
465	2230	85	2332	103	2296	99	
488	2283	90	2368	106	2307	100	
506	2287	90	2417	111	2340	103	
526	2259	88	2398	109	2284	98	
551	2233	86	2348	104	2320	101	
577	2303	91	2343	104	2308	100	
699	2250	87	2495	118	2309	100	5/31/85; Avg. after 699 cycles = 98.

RAPID FREEZE-THAW TEST RESULTS - SECOND CYCLE

No. Cycles	Sample SAE25A Freq. (hz)	Sample SAE25A Pc %	Sample SAE25B Freq. (hz)	Sample SAE25B Pc %	Sample SAE25C (Air Entrained; 25% Fly Ash) Freq. (hz)	Sample SAE25C Pc %	Remarks
0	2217	100	2178	100	2122	100	Began test February 12, 1985.
22	2342	112	2173	100	2175	105	
49	2136	93	2185	101	1859	77	
68	1931	76	2155	98	1859	77	
88	2230	101	2178	100	2116	99	
114	2138	93	2169	99	2101	98	
134	2177	96	2175	100	2220	109	
159	2183	97	2182	100	2106	98	Slight scaling on all samples.
179	2154	94	2145	97	2140	102	
207	2110	91	2133	96	2170	105	
227	2170	96	2158	98	2159	104	
257	2137	93	2180	100	2129	101	
279	2217	100	2127	95	2160	104	
308	2170	96	2132	96	2125	100	Average after 308 cycles = 97.
328	2177	96	2128	95	2130	101	
355	2129	92	2112	94	2153	103	
375	2110	91	2121	95	2106	98	
402	2086	89	2182	100	2115	99	
422	2079	88	2147	97	2096	98	
446	2087	89	2088	92	2086	97	
465	2098	90	2099	93	2129	101	
488	2094	89	2109	94	2139	102	
506	2106	90	2165	99	2132	101	
526	2105	90	2170	99	2082	96	
551	2127	92	2128	95	2136	101	
577	2085	88	2116	94	2080	96	
699	1973	79	2145	97	2068	95	5/31/85; Avg. after 699 cycles = 90.

RAPID FREEZE-THAW TEST RESULTS - SECOND CYCLE

	Sample SAE50A		Sample SAE50B		Sample SAE50C	(Air Entrained; 50% Fly Ash)
No. Cycles	Freq. (hz)	Pc %	Freq. (hz)	Pc %	Freq. (hz)	Pc %	Remarks
0	2227	100	2233	100	2324	100	Began test February 12, 1985.
22	2217	99	2216	98	2271	95	
49	2323	109	2300	106	2426	109	
68	2379	114	2289	105	2553	121	
88	2070	86	2225	99	2372	104	
114	2264	103	2211	98	2275	96	
134	2257	103	2234	100	2298	98	
159	2265	103	2236	100	2366	104	
179	2330	109	2223	99	2355	103	Slight scaling on all samples.
207	2290	106	2217	99	2339	101	
227	2372	113	2274	104	2365	104	
257	2325	109	2333	109	2363	103	
279	2409	117	2218	99	2323	100	
308	2272	104	2220	99	2274	96	Average after 308 cycles = 100.
328	2241	101	2201	97	2260	95	
355	2227	100	2167	94	2246	93	
375	2233	101	2180	95	2260	95	
402	2229	100	2220	99	2152	86	
422	2230	100	2188	96	2284	97	
446	2207	98	2183	96	2264	95	
465	2227	100	2166	94	2275	96	
488	2227	100	2180	95	2255	94	
506	2282	105	2040	83	2275	96	
526	2173	95	2067	86	2295	98	
551	2183	96	2173	95	2250	94	
577	2208	98	2176	95	2248	94	
699	2199	98	2040	83	2293	97	5/31/85; Avg. after 699 cycles = 90.

RAPID FREEZE-THAW TEST RESULTS - SECOND CYCLE

No. Cycles	Sample SAE65A Freq. (hz)	Sample SAE65A Pc %	Sample SAE65B Freq. (hz)	Sample SAE65B Pc %	Sample SAE65C (Air Entrained; 65% Fly Ash) Freq. (hz)	Sample SAE65C Pc %	Remarks
0	2413	100	2422	100	2359	100	Began test February 12, 1985.
22	2481	106	2498	106	2360	100	
49	2462	104	2211	83	2448	108	
68	2456	104	2263	87	2353	99	
88	2458	104	2286	89	2412	105	
114	2409	100	2486	105	2361	100	
134	2436	102	2477	105	2359	100	
159	2445	103	2435	101	2387	102	
179	2440	102	2285	89	2385	102	Slight scaling on all samples.
207	2430	101	2444	102	2339	98	
227	2395	99	2433	101	2317	96	
257	2412	100	2478	105	2380	102	
279	2400	99	2437	101	2342	99	
308	2375	97	2405	99	2330	98	Average after 308 cycles = 98.
328	2388	98	2452	102	2308	96	
355	2378	97	2418	100	2298	95	
375	2419	100	2450	102	2320	97	
402	2397	99	2459	103	2327	97	
422	2393	98	2411	99	2312	96	
446	2356	95	2372	96	2296	95	
465	2363	96	2382	97	2304	95	
488	2375	97	2387	97	2316	96	
506	2386	98	2377	96	2356	100	
526	2355	95	2398	98	2280	93	
551	2341	94	2364	95	2286	94	
577	2369	96	2368	96	2278	93	
699	2363	96	2345	94	2251	91	5/31/85; Avg. after 699 cycles = 94.

2015