Evaluation Of Fly Ash In Portland Cement Concrete Paving In Woodbury County, Iowa

Final Report
For
Iowa Highway Research Board
Project HR-201

Highway Division
April 1980

FINAL REPORT

FOR

IOWA HIGHWAY RESEARCH BOARD

PROJECT HR-201

EVALUATION OF FLY ASH IN PORTLAND CEMENT CONCRETE PAVING IN WOODBURY COUNTY, IOWA

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TABLE OF CONTENTS

INTRODUCTION	1
OBJECTIVES	2
CONCLUSIONS	3
RECOMMENDATIONS	4
PROJECT LOCATION	5
MIX PROPORTION AND TEST SECTIONS	5
SHIPPING, STORING AND BATCHING	7
PLACING AND FINISHING	10
MATERIALS AND QUALITY CONTROL	12
PROJECT TEST RESULTS	13
TESTING AND EVALUATION	16
OBSERVATIONS	17
ACKNOWLEDGEMENTS	18
APPENDICES	19

FLY ASH IN PORTLAND CEMENT CONCRETE PAVEMENT - WOODBURY COUNTY

WOODBURY COUNTY PROJECT HR-201

TQFS-982-0(5)--30-97
TQFS-982-0(7)--30-97

FINAL REPORT

INTRODUCTION

The earliest overall comprehensive work on the use of fly ash in concrete was reported by Davis and Associates of the University of California in 1937[1]. Since that time, there have been numerous applications of the use and varying proportions of fly ash in portland cement concrete mixes.

Fly ash is a pozzolanic powdery by-product of the coal combustion process which is recovered from flue gases and is generally associated with electric power generating plants. Environmental regulations enacted in recent years have required that fly ash be removed from the flue gases to maintain clean air standards. This has resulted in an increased volume of high quality fly ash that is considered a waste product or a by-product that can be utilized in products such as portland cement concrete. There are several sources of the high quality fly ash located in Iowa (Appendix A) currently producing a combined total of 281,000 tons of material annually.

1 Highway Research Bulletin 284, Fly Ash Concrete 1961.

Due to recent cement shortages and the rapidly increasing highway construction costs, the Iowa Department of Transportation has become interested in utilizing fly ash in portland cement concrete paving mixes. A preliminary review of the Iowa Department of Transportation Materials Laboratory study indicates that a substitution of fly ash for portland cement, within limits, is not detrimental to the overall concrete quality (Appendix B). Also the use of fly ash in concrete would reduce the cement consumption as well as provide a potential cost savings in areas where high quality fly ash is available without excessive transportation costs.

The previously expressed concerns have shown the need for a research project to develop our knowledge of fly ash replacement in the Iowa Department of Transportation portland cement concrete paving mixes.

OBJECTIVES

The primary objectives of the research project are:

1. Determine and recommend solutions for problems related to shipping, storing and batching fly ash.

2. Establish a procedure for batching, mixing and placing uniform concrete with specified air content and consistency.

3. Demonstrate that concrete of comparable quality can be produced.

CONCLUSIONS

The objectives of the research project have been successfully met for the shipping and storing of the fly ash. It is desirable to have isolated storage facilities available to accommodate tested and approved material. The storage unit needs to be of sufficient capacity to insure that paving is not delayed while waiting on test results.

Manual batching of the fly ash, as was done on this project, can be integrated into the automatic batching cycle. By use of a second limit switch in the cement batching cycle, an accumulative weight of fly ash and cement can be made on a single scale dial. This would improve batching efficiency.

Occasional specification deficiencies in current fly ash production warrant additional source evaluation before developing a source certification program for fly ash acceptance.

Fly ash can be used successfully in paving mixes. All paving specifications can be met with these mixes without any observed problems being encountered. Quality control test results show that specification air content, slump and flexural strength can be achieved with normal paving operations.

Compressive strength results through 1 year verify that adequate strengths can be achieved in fly ash mixes to satisfy Iowa DOT strength requirements.

RECOMMENDATIONS

Based on results of this project, I am recommending that additional efforts be made to utilize fly ash in portland cement concrete paving. This effort should include development of the specifications using an optimum amount of fly ash as a cement replacement in the batch proportion. Future projects should then allow an option for the contractor to use standard paving mixes or a specific fly ash mix.

Test results from the project indicate that 15% of the cement in the C-4 mix could be replaced with Iowa Public Service Port Neal #3 fly ash at a ratio of 1¼ pounds of fly ash per pound of cement reduced. According to the test results, there would be no appreciable change in anticipated concrete strength.

Fly ash should be tested and approved prior to use. This should be done on a lot or bin basis so that approved material is isolated. In the future, possibly a certification program similar to the cement program could be implemented.

I feel that it would be appropriate to evaluate the use of fly ash in the "C" structural concrete mixes. Most structural concrete is batched through a ready mix concrete plant. This project has shown that it is easy to modify a ready mix plant for fly ash batching.

PROJECT LOCATION

Fly ash research was being conducted on two Woodbury County bridge replacement projects on Iowa 982 (Old Iowa 141). Woodbury TQFS-982-0(5)--30-97, located ½ mile southeast of the Sioux City city limit, included paving two bridge approach sections 1100 and 1300 feet in length. Woodbury TQFS-982-0(7)--30-97 is located 9 miles south of Sioux City and included paving 2 bridge approach sections approximately 1300 and 500 feet in length. (Figure 1)

The contract for construction of the two projects was awarded to the Irving F. Jensen Company of Sioux City, Iowa, on March 23, 1978. The 8" standard formed portland cement concrete paving was completed between October 17, 1978 and October 26, 1978.

MIX PROPORTIONS AND TEST SECTIONS

The four bridge approaches on the two projects provided the following convenient test locations:

1. C-4 Standard C-4 mix used as the control mix was placed on the 500 foot southeast approach section of the bridge located 9 miles southeast of Sioux City.

2. C-4-10-1.5 Modified C-4 mix with 10% cement reduction and fly ash replacement at 1.5 times the weight of cement reduction was placed on the northwest approach to the bridge located 9 miles southeast of Sioux City.

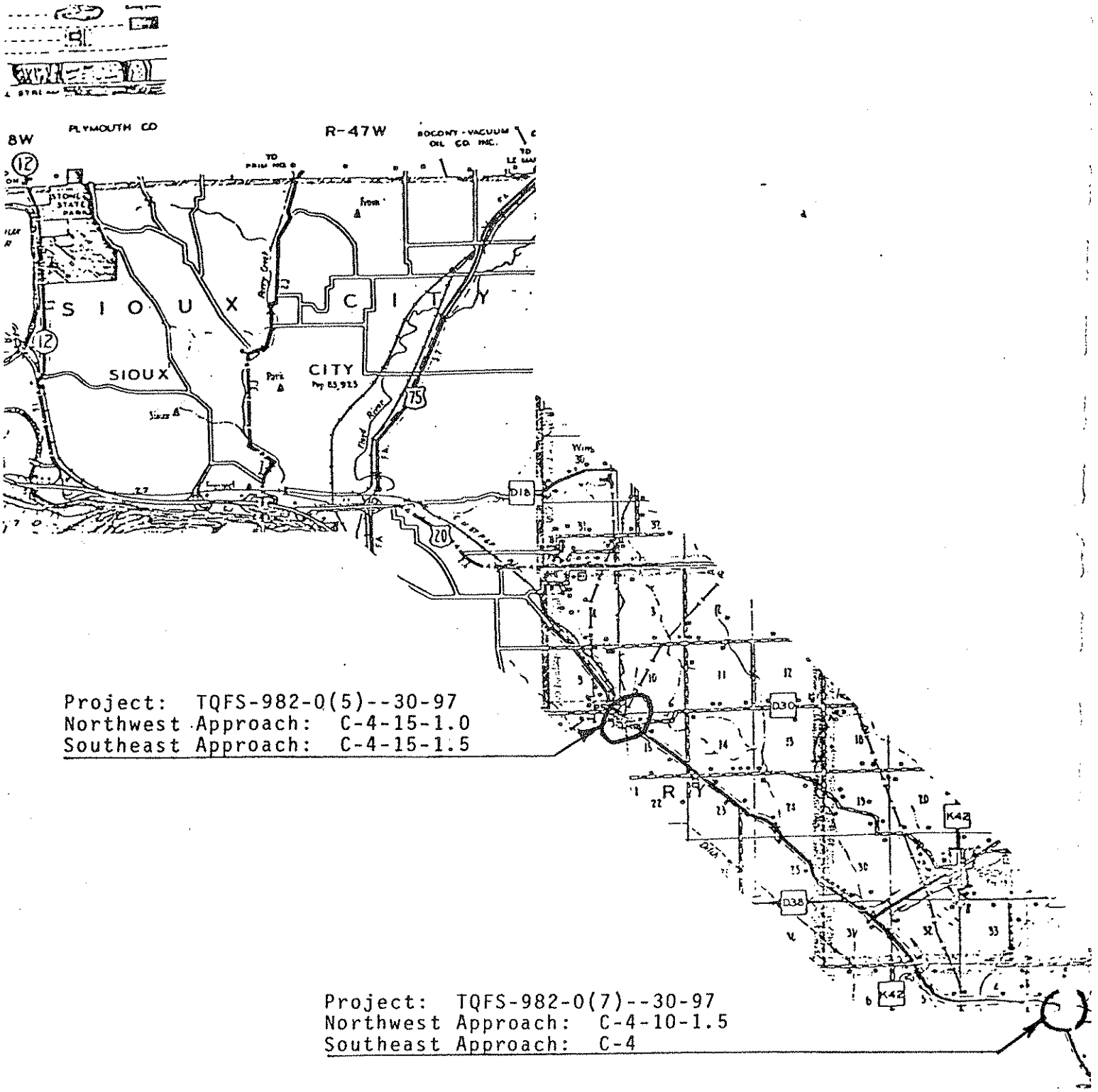


Figure 1. PROJECT LAYOUT FOR WOODBURY COUNTY HR-201

3. C-4-15-1 Modified C-4 mix with 15% cement reduction and replacement of an equal weight of fly ash was placed on the northwest approach of the bridge located ½ mile southeast of Sioux City.

4. C-4-15-1.5 Modified C-4 mix with 15% cement reduction and fly ash replacement at 1.5 times the weight of cement reduction was placed on the southeast approach to the bridge located ½ mile southeast of Sioux City.

Proportions for mix 2, 3, and 4 are part of Special Provision 212 for the project (Appendix C).

SHIPPING, STORING AND BATCHING

Fly ash for the project was obtained from Iowa Public Service Port Neal #3 Plant located near Sioux City. Weekly sampling and testing of the available fly ash was done during the summer of 1978 to monitor the quality of the material available from this source. High quality fly ash was maintained with the exception of one isolated sample obtained September 22, 1978 (Appendix D). As a result of the noncompliance, it was decided that testing for the research should be on a lot basis with a cement transport (approximately 24 tons) representing the lot. (Figure 2)

Acceptance of the individual transport loads of fly ash resulted in considerable inconvenience to the contractor as Port Neal does not have storage capacity for isolating tested

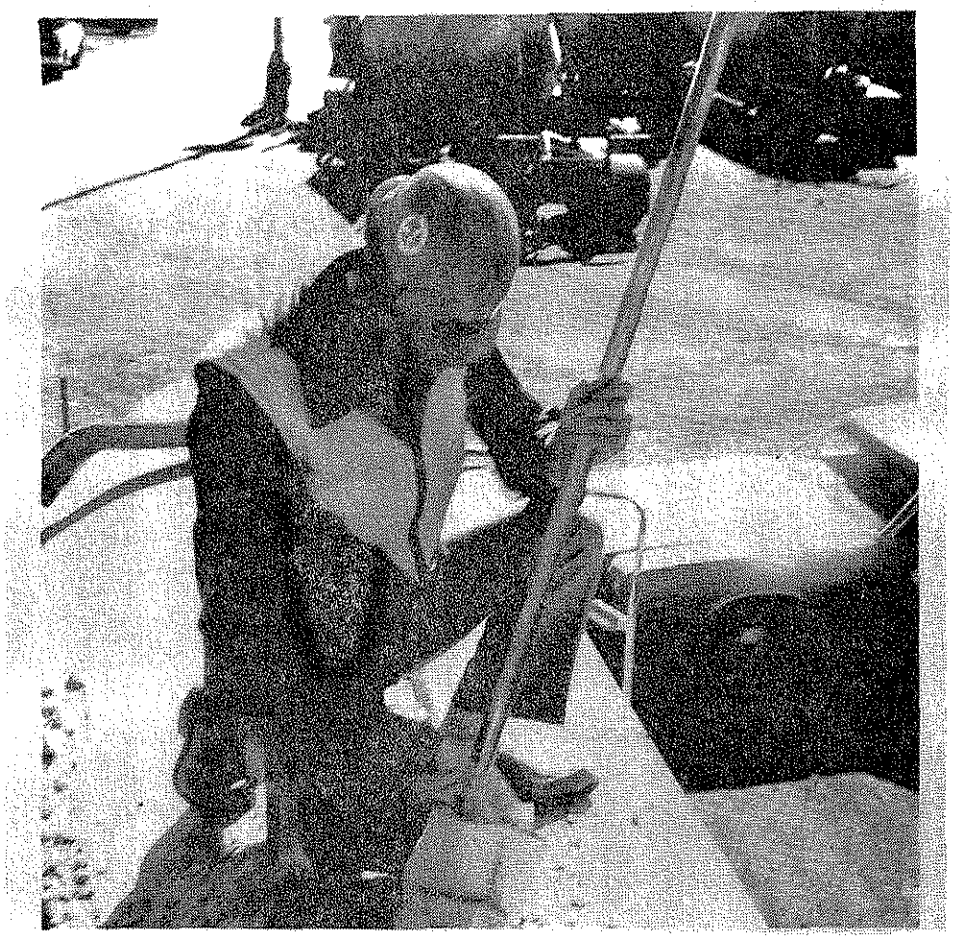


Figure 2: Sampling the individual transport load of fly ash.

and approved fly ash. Portable storage tankers (Figure 3) were moved in to assure that an adequate volume of approved material would be available to sustain the concrete production.

The contractor elected to batch the concrete at a permanent ready mix plant in Sioux City that routinely uses fly ash in certain commercial mixes. The plant is equipped with Johnson-Detecto scales and automatic batching equipment. Initial mixing

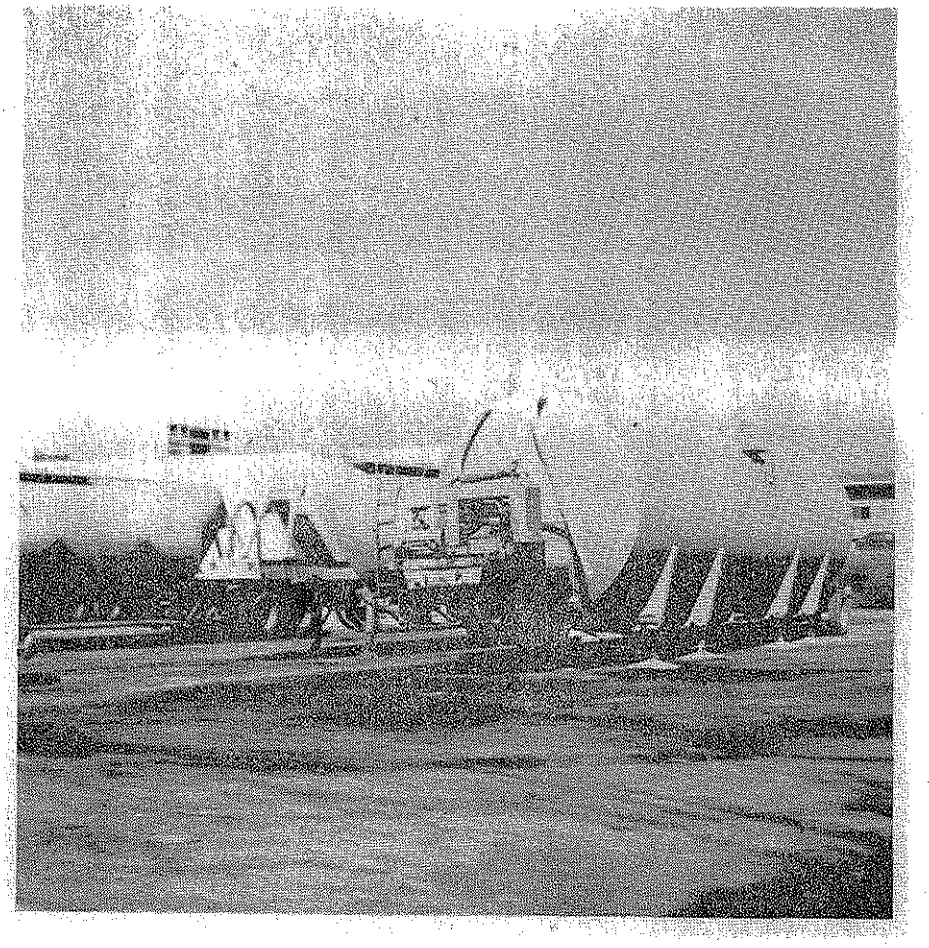


Figure 3: Portable storage tankers used to store approved fly ash.

of the concrete is accomplished with an 11 cubic yard Johnson central mixer. One compartment, of their three compartment cement silo, was utilized to handle the fly ash in the batching process.

The automatic batching cycle was used to batch the cement and aggregates. This batch, along with a portion of the mixing water, was then charged into the mixer. Fly ash was then

batched manually using the cement hopper and scale and then charged into the mixer along with the remaining mixing water to complete the batch cycle. Transit mixers were used to transport the concrete to the grade.

PLACING AND FINISHING

The concrete for the fixed form paving was spread, vibrated, and finished with a Pave-Saver finishing machine Model #16-22. (Figure 4)

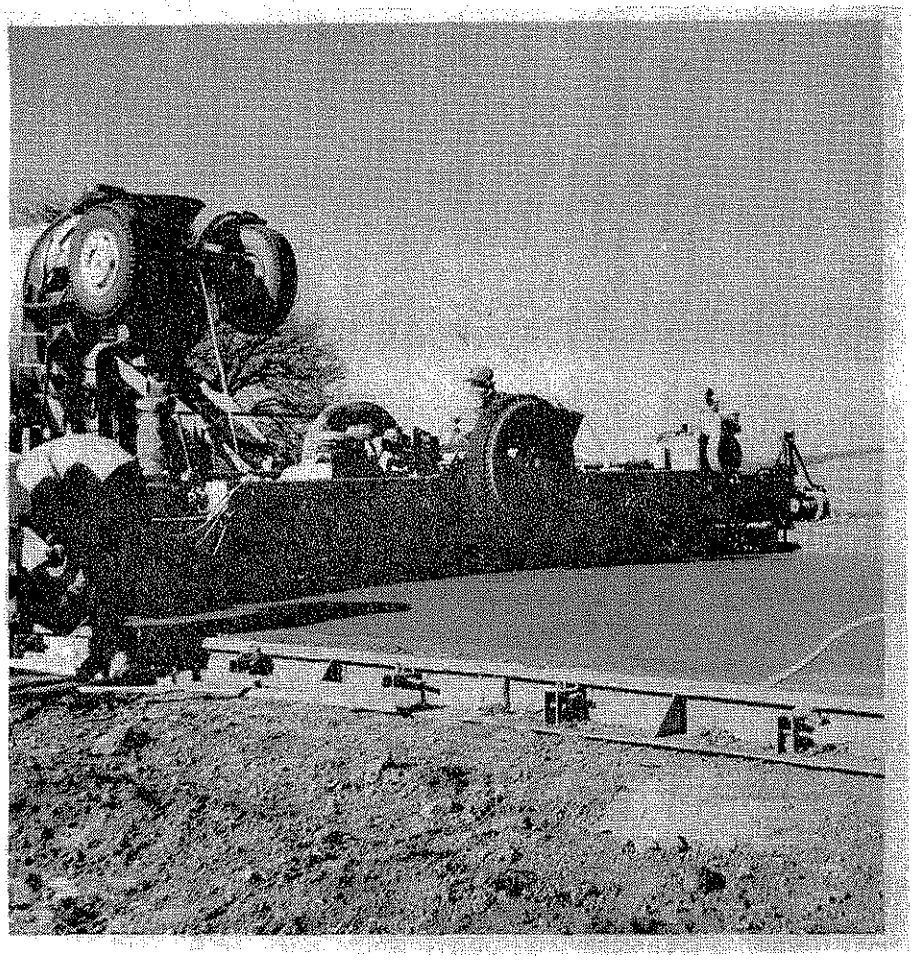


Figure 4: Pave-Saver finish machine in operation

Minor hand finishing near the side forms was done prior to the final straightedge operation. (Figure 5) Astro grass texturing, followed by a hand applied cure, completed the concrete placing sequence. No special equipment was required in the operation.

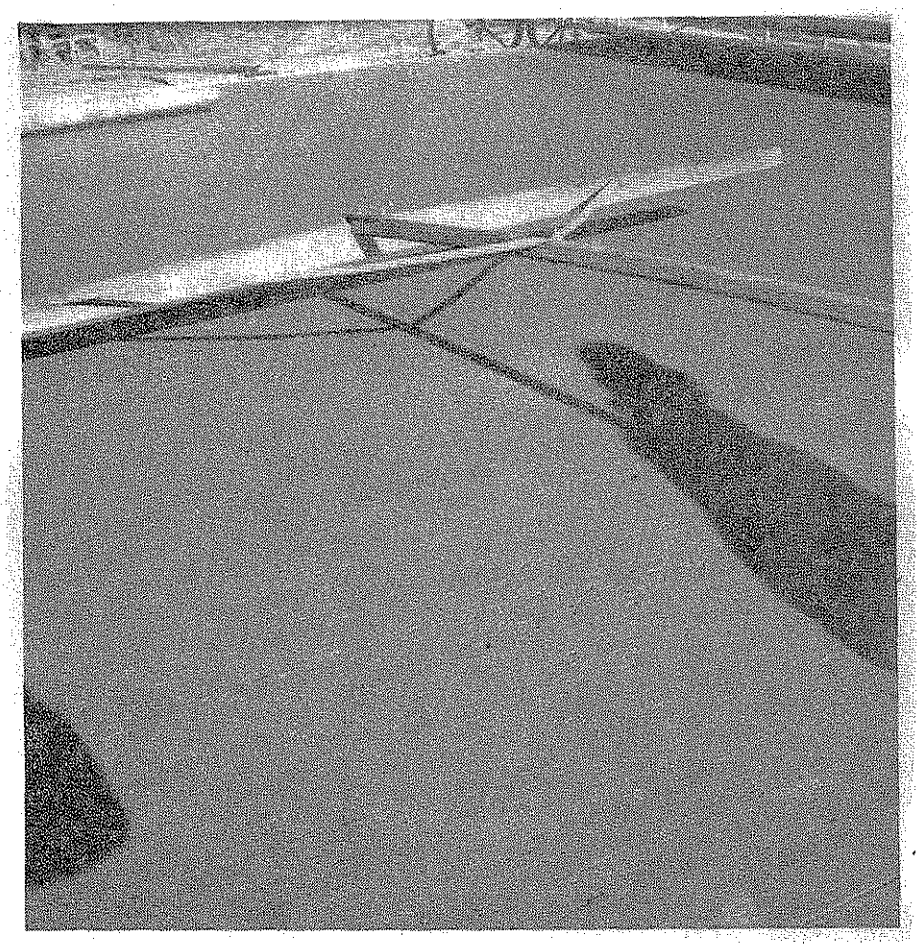


Figure 5: Finished pavement behind the Pave-Saver

MATERIALS AND QUALITY CONTROL

The following materials were used in the research project:

1. Coarse Aggregate - Gravel meeting Section 4115 gradation #3 of the Standard Specification 1977 Series. The source was L. G. Everist Co. pit located at Hawarden, Iowa.

2. Fine Aggregate - Sand meeting Section 4110 gradation #1 of the Standard Specification. The source was L. G. Everist Co. pit located at Hawarden, Iowa.

3. Ash Grove cement.

4. Fly Ash - Iowa Public Service Port Neal #3 plant.

5. Admixtures - Master Builders MBVR standard air entraining agent meeting ASTM C-260-74.

The concrete production for the project was a very normal operation. Two minor problems developed regarding specification compliance.

The first problem occurred during the placing of the C-4-15-1.5 mix. The air content of the concrete was less than the minimum specified (6.5 $\pm$ 1.5%) and the slump was near the upper specification limit.

Due to this condition and the short supply of cement available, concrete operations were suspended by the contractor. Concrete operations were resumed when additional cement was available. No further problems with air content in the mix were experienced.

A review of the incident was conducted by the District #3 Materials Staff. The following conclusions were reached:

1. The non-compliance occurred at about the same time that a shipment of cement was received.

2. The slump of the concrete prior to the non-compliance was near the 3" specification limit for fixed form paving.

3. Project control test results show that the air contents prior to the non-compliance of 5.5% and 5.8% (Specification 6.5 ± 1.5%).

The second specification problem relates to coarse aggregate gradation test results. Two out of three samples of coarse aggregate used in the C-4-15-1.0 mix on October 23, 1978, failed to meet the specification requirement on the ½" sieve (25 - 60% passing).

The results of the three samples tested ranged from 17% to 26% passing the ½" sieve yielding a coarser material on the ½" sieve than desired by the Specification.

PROJECT TEST RESULTS

Project control testing resulted in an average air content of 5.7% with the average slump being 2 3/4" for the C-4 mix. The air content of the C-4 mix ranged from 5.6% to 6.8% while the slump ranged between 2½" to 3". The average water cement ratio for the mix was 0.444.

The range of air content for 10 tests was 5.5% to 7.6% (average 6.7%) for the C-4-10-1.5 mix. This slump ranged from

1 3/4" to 3" (average 2 3/8"). Daily water cement ratios including both the weight of fly ash and cement in the mix were 0.403 and 0.385.

The C-4-15-1.0 mix air content ranged from 5.6% to 8.0% with the average of 12 tests being 6.6%. The average water/cement ratio was 0.417. The total weight of fly ash plus the weight of the cement was used in calculating the water/cement ratio.

The C-4-15-1.5 mix ranged in air content from 5.0% to 7.2% with an average of 5.9%. The slump ranged from 1½" to 3" with an average of 2¼". These averages are based on 7 air and slump tests. Daily water cement ratios of 0.383 and 0.352 are based on calculations including the weight of fly ash plus the weight of cement in the mix.

Due to the work load in the Residency, flexural beams were not broken regularly on a 7 day and 14 day interval as intended. Results of flexural beam strengths ranged from 502 psi at 7 days to 754 psi at 14 days for the C-4 mix. The C-4-10-1.5 flexural strengths varied from 592 psi at 5 days to 686 psi at 14 days. The C-4-15-1.0 beam breaks yielded strengths ranging from 481 psi at 5 days to 670 psi at 14 days.

The flexural strength in the C-4-15-1.5 mix ranged from 624 psi in 5 days to 695 psi in 14 days. The lowest strength

for the 10 beams made and tested with this mix was 582 psi flexural strength in 9 days.

A complete tabulation of flexural strength data is located in Appendix E.

Two cylinders were tested for compressive strength at 3, 7, and 14 day intervals. At 3 days, the average cylinder strength of the C-4-10-1.5 and C-4-15-1.5 mixes appear to be nearly equal and are slightly lower than the strength shown in the C-4 mix. The C-4-15-1.0 average was considerably lower than the C-4 mix. At 7 days, the 3 fly ash strength averages were nearly equal and approximately 800 psi less than the C-4 mix strength. At 14 days, the cylinder average compressive strengths varied considerably. A complete tabulation of the cylinder results is shown in Appendix F.

The average compressive strength of six cores cut from each mix were very similiar at 7 days. The average strength ranged from 3140 psi for the C-4-10-1.5 mix to 3390 psi for the C-4-15-1.0 mix for a difference of 8%.

At 14 days, the range for the average strength broadened with the low average strength occurring in the C-4-10-1.5 mix (3370 psi) and the high average strength occurring in the C-4-15-1.5 mix (4600 psi) for a 36% difference. The C-4-15-1.5 mix at 4600 psi was 8% higher than the C-4 mix average of 4240 psi.

At 28 days, the low average strength occurred in the C-4-10-1.5 mix (4350 psi). The high average strength occurred in C-4-15-1.0 mix (5210 psi). The C-4 mix and the C-4-15-1.5 mix both show average strength of 4610 psi, only 11% lower than the C-4-15-1.0 mix strength.

The one year test results show the C-4 mix and the C-4-15-1.5 mix with an equal average strength (6640 psi) about 6% higher than the other two mixes that were evaluated.

A complete tabulation of core strength results is included in Appendix G.

Durability beams were made from the plastic concrete at the paving train. These were cured and tested in the central laboratory. Due to the adverse effect of minor quantities of spall producing material in the coarse aggregate in the concrete mix, the test results have not been included in this report.

TESTING AND EVALUATION

Standard Specification compliance testing of air content, slump and flexural strength was conducted by the Sioux City Resident Engineer's staff.

The following special sampling and testing was conducted by the District #3 and Central Office Materials Laboratory Staff:

1. Two 4½" x 9" cylinders tested for compressive strength of each mix at 3, 7, and 14 days.

2. Coring (5 per mix section) for compressive strength determination at 7, 14 and 28 days as well as 6 month and 1 year intervals.

3. Three 4" x 4" x 18" durability beams per mix section.

OBSERVATIONS

The project was constructed using normal equipment designed for ready mix concrete production and fixed form paving.

The fly ash was transported in regular cement transports. Both portable storage silos and permanent silos designed for handling cement were used for the fly ash. There appeared to be no problems in handling the fly ash or batching the fly ash through a central ready mix plant.

There was little difference in paving with the fly ash mixes as compared to the regular C-4 mix. The concrete finishers expressed that the fly ash concrete was easier to finish than the C-4. This is due in part to the fact that the fly ash particles are spherical in shape.

A minor problem with air content was encountered on one occasion when using the C-4-15-1.5 mix. The slump of the concrete was near the upper limit. It is my opinion, if the specification targets for the slump and air content had been observed more closely prior to the incident, appropriate slump and air content could have been achieved with little difficulty. I do

not feel that fly ash in the mix contributed to the control problem.

The paving was completed in October with the mean night-time low temperature at 36°F and the daytime mean high temperature at 67°F. Due to the cool conditions, the flexural beam and early cylinder and core compressive strengths are lower than one might expect during mid-summer paving with more favorable temperatures.

It appeared that the cool weather curing of the pavement was initially slower for the fly ash concrete than for the C-4 mix.

A recent field inspection has been completed on all test sections of the project. At this time, there is no visible difference in the surface appearance of the four test areas.

There is no evidence of pavement degradation after two winter seasons of use.

ACKNOWLEDGEMENTS

I would like to thank the contractor, Irving F. Jensen Company, Power Plant Aggregates, the Sioux City Construction Residency, and the Central Materials Department Staff of the Iowa DOT for their cooperation and assistance in this research project.

APPENDICES

FLY ASH SPECIFICATIONS

	ASTM C618 Class F	Typical Port Neal No. 3	Clinton	Bettendorf	Dubuque	Proposed
$SiO_2+Al_{2O3}+Fe_2O_3$	70.0% Min	75. %	92. %	87. %		70.0% Min
Sulfur Trioxide (SO_3)	5.0% Max	1.7 %	1.6 %	1.3 %	0.5%	5.0% Max
Moisture Content	3.0% Max	.03%	.05%	.05%	0.0%	3.0% Max
Loss on Ignition	12.0% Max	0.3 %	1.4 %	1.4 %	7.9%	5.0% Max
(1) Available Alkalies as NaO	1.5% Max	.04%	.13%	.19%	--	1.5% Max
Retained on 325 Mesh	34 % Max	16 %	20 %	10 %	34 %	34 % Max
Autoclave Expansion	0.8% Max	0.1 %	0.1 %	0.1 %	0.1%	0.8% Max
Quantities Available Tons/Yr		183,000	53,000	34,000	11,000	

(1) Optional requirement

FLY ASH MIXES
FLY ASH SOURCE - PORT NEAL NO. 3

C-4 Mix

% Cement Reduction	1:1 Replacement Comp. Str. - p.s.i.			1:1:5 Replacement Comp. Str. - p.s.i.		
	7 day	28 day	56 day	7 day	28 day	56 day
0	4800	5900	6700	4800	5900	6700
10	4800	5900	6800	4600	6300	7100
15	3900	5250	6100	4400	5800	6700
20	4100	5500	6500	3800	4900	6300

Durability Factor - ASTM C666 Procedure B
C. A. Source - Menlo

% Cement Reduction	1:1 Replacement	1:1.5 Replacement
0	76	76
10	68	74
15	72	77
20	59	57

SP-212

IOWA DEPARTMENT OF TRANSPORTATION

Ames, Iowa

SPECIAL PROVISION

for

PORTLAND CEMENT CONCRETE PAVING

USING FLY ASH

March 28, 1978

THE STANDARD SPECIFICATIONS, SERIES 1977, ARE AMENDED BY THE FOLLOWING SPECIAL PROVISIONS. THESE SHALL PREVAIL OVER THOSE PUBLISHED IN THE STANDARD SPECIFICATIONS.

ADD the following to 2301.01:
The location, class, and mix proportion number of concrete to be used shall be as indicated on the plans or the proposal.

ADD the following to 2301.03:
When fly ash is required and used in the mix proportions, the fly ash shall meet the requirements of ASTM C 618 Class C except that the loss on ignition shall be a maximum of 5 percent, the available alkalies shall be limited to a maximum of 1.5 percent, and the total silicon dioxide (SiO_2) plus aluminum oxide (Al_2O_3) plus iron oxide (Fe_2O_3) shall be not less than 70% by weight.

Approval of the source of fly ash will be required. Fly ash will not be subject to certified gradation testing by the contractor. Inspection will be arranged by the engineer.

ADD the following proportions to 2301.04:

Basic Absolute Volumes Per Volume of Concrete

	B410-1.5	B610-1.5	B615-1.5	B615-1	C410-1.5	C415-1.5	C415-1
Coarse Aggr.	.346770	.275217	.273324	.278943	.329192	.324530	.3[illegible]26
Fine Aggr.	.346770	.412825	.409987	.418415	.329192	.324529	.331825
Air	.06	.06	.06	.06	.06	.06	.06
Water	.144231	.143637	.143637	.139482	.151947	.155508	.152540
Cement	.083928	.089031	.084117	.084117	.106422	.100562	.100562
Fly Ash	.018301	.019290	.028935	.019043	.023247	.034871	.023247

Approximate Quantities of Materials per Cubic Yard of Concrete: (Pounds)

Coarse Aggr.	1548	1229	1220	1245	1470	1449	1482
Fine Aggr.	1548	1843	1830	1868	1470	1449	1482
Cement	444	471	445	445	563	532	532
Fly Ash	74	78	117	77	94	141	94
Water	243	242	242	235	256	262	257
Design W/C Ratio	.47	.44	.43	.45	.39	.39	.41
Max. W/C Ratio	.53	.50	.49	.51	.45	.45	.47

Note: Fly Ash is included in the water/cement ration calculation.

Those quantities are based on the following assumptions:

Specific Gravity of Cement - 3.14

Specific Gravity of Fly Ash - 2.40

Specific Gravity of Coarse and Fine Aggregate - 2.65

Weight of one cu. ft. of water - 62.4 lbs.

DELETE the second and third paragraphs of 2301.04H.
It is not the intention to increase cement content or to adjust proportions to correct the yield for this project. The mixture characteristics are to be controlled within the limits specified in 2301.04H and I and within the specified maximum water-cement ratio; these are to be modified only with specific, prior authorization of the engineer.

Page 2

ADD the following to 2301.06A:

Fly ash shall be transported, stored, and batched in such a manner as to keep it dry. Proportioning equipment for the fly ash shall meet requirements of 2001.20, either Paragraph A, Manual Batching Equipment, or Paragraph B, Automatic Batching Equipment.

ADD the following:

Certain aspects of the work on this project are of a research nature. Because of this, the engineer may modify requirements in order to assure that meaningful research results are obtained.

FLY ASH - (Port Neil-Salix-Plant #3)

Physical and Chemical Analysis
Monona and Woodbury Counties

Lab Test Number	Pozzolanic Activity %	Autoclave (Soundness) %	325 Mesh (Fineness) %	Sp Gr	Moisture %	Silicon Dioxide Aluminum Oxide Iron Oxide - %	Sulfur Trioxide SO_3 - %	Loss on Ignition (800°C)%	Availabl Alkali
ACM8-01	84.50	0.15	77.7	2.40	0.04	77.40	0.80	0.23	0.84
ACM8-02	130.44	0.18	79.8	2.33	0.05	78.84	0.87	0.26	0.84
ACM8-04	80.80	0.15	80.6	----	0.14	82.23	0.67	0.14	--
ACM8-05	78.20	0.14	80.6	--	0.17	86.92	1.07	0.34	--
ACM8-06	83.80	0.15	82.2	--	0.07	82.72	0.74	0.33	--
ACM8-07	---	--	--	--	0.07	86.82	0.47	0.17	1.20
ACM8-08	79.50	0.15	81.2	--	0.00	90.50	0.56	0.95	--
ACM8-09	88.0	0.10	77.8	--	0.13	83.14	0.57	0.02	--
ACM8-10	82.0	0.09	74.6	--	0.09	85.13	0.60	0.60	--
ACM8-11	81.80	0.09	74.8	--	0.12	85.86	0.57	0.00	--
ACM8-12	85.90	0.09	75.7	--	0.15	84.70	0.67	0.01	--
ACM8-13	86.3	0.09	78.2	--	0.00	78.67	0.65	0.09	--
ACM8-14	75.1	0.09	80.0	--	0.00	79.85	0.59	0.28	--
ACM8-15	82.0	0.09	82.1	--	0.04	80.13	0.57	0.30	--
ACM8-16	76.5	0.09	79.2	--	0.04	79.36	0.85	0.29	--
ACM8-17	79.0	0.09	79.2	--	0.06	80.53	0.93	0.14	
ACM8-18	82.2	0.10	78.2	--	0.05	79.23	0.81	0.19	--
ACM8-19	--	0.19	79.6	2.43	--	70.00	0.74	--	--
ACM8-20	--	0.08	--	--	--	---	--	--	--
ACM8-23A	42.8	unmeasurable	--	--	--	76.75	0.69	--	--
ACM8-23B		0.11							
ACM8-24	--	--	0.11	--	--	---	--	--	--
ACM8-25	--	--	--	--	--	---	--	--	--
ACM8-26	--	0.09	--	2.44	0	81.29	0.65	0.27	--
ACM8-27	--	0.10	80.6	--	0	87.62	0.74	0.30	--
ACM8-28	94.4	0.12	79.6	--	--	---	--	--	--
ACM8-29	--	0.11	--	--	0	86.68	0.65	0.28	--
ACM8-30	--	0.10	78.6	2.39	0	73.49	0.68	0.24	--
ACM8-31	--	0.10	--	2.41	0	71.15	0.95	0.22	--
ACM8-32	94.7	0.08	81.5	2.38	0	78.93	0.93	0.21	--
ACM8-33	--	0.09	--	--	0	46.76 Sio_z	0.77	0.23	--

FLEXURAL BEAM DATA

Woodbury Fly Ash Research

Identification	Age Days	Air Content	Slump	Water/ Cement	Flexural Strength
		C-4			
10-20-1	7	6.8%	3.0"	0.434	502 psi
10-17-1	8	5.8%	2.5"	0.444	604 psi
10-17-2	14	5.8%	2.5"	0.444	754 psi*
10-20-2	14	6.8%	3.0"	0.434	719 psi*

Water/cement ratio is calculated on the combined weight of cement and fly ash in the mix.
*Bridge approach handwork.

		C-4-10-1.5			
10-18-1	5	7.2%	2.5"	0.403	592 psi
10-18-2	5	7.2%	2.5"	0.403	592 psi
10-19-1	7	7.0%	2.0"	0.385	543 psi
10-18-3	8	6.5%	2.0"	0.403	663 psi
10-18-4	9	6.5%	2.0"	0.403	598 psi
10-18-5	10	6.8%	3.0"	0.403	701 psi
10-18-6	14	6.8%	3.0"	0.403	666 psi
10-19-2	14	7.0%	2.0"	0.385	686 psi

		C-4-15-1.0			
10-28-1	5	6.0%	1.5"	0.417	481 psi
10-28-2	6	6.0%	1.5"	0.417	538 psi
10-28-3	9	7.0%	2.0"	0.417	494 psi
10-28-4	10	7.0%	2.0"	0.417	511 psi
10-28-5	11	7.2%	2.0"	0.417	633 psi
10-28-6	14	7.2%	2.0"	0.417	670 psi

2 out of 3 gradations on C.A. were non-compliance on ½" sieve (average 22% passing; specification range 25-60%).

		C-4-15-1.5			
10-26-1	5	5.5%	2.0"	0.352	624 psi
10-24-1	6	5.8%	3.0"	0.383	613 psi
10-26-2	6	5.5%	2.0"	0.352	657 psi
10-24-2	7	5.8%	3.0"	0.383	619 psi
10-26-3	7	6.3%	2.25"	0.352	668 psi
10-26-4	8	6.3%	2.25"	0.352	690 psi
10-24-3	9	5.5%	2.50"	0.383	582 psi
10-26-5	11	6.0%	2.0"	0.352	715 psi
10-24-4	14	5.5%	2.5"	0.383	653 psi
10-26-6	14	6.0%	2.0"	0.352	695 psi

COMPRESSIVE STRENGTH RESULTS

Woodbury Fly Ash Research — 3 Day Results - Cylinders

Cylinder No.	Mix No.	Air Content %	Slump Inches	W/C ** Ratio	Compressive Strength PSI
C-4-1-1	C-4	6.0	4	0.434	3,433
1-2	C-4	6.0	4	0.434	3,125
				Average	3,279
3JY-197	C-4-10-1.5	7.2	3	0.403	2,584
197-2	C-4-10-1.5	6.5	2	0.403	2,880
				Average	2,732
3CH8-111-1	C-4-15-1.0	8.0	3	0.417	2,320*
111-2	C-4-15-1.0	8.0	3		2,446*
				Average	2,383*
3CH8-107-1	C-4-15-1.5	5.5	3	0.383	2,880
107-2	C-4-15-1.5	5.5	3	0.383	2,754
				Average	2,817

* Non-complying coarse aggregate was reported for the mix included in the cylinder samples. Specification range for material passing ½" sieve is 25-60%. Project control gradation passing ½" sieve was 22% (average of 3 tests.

** Water/cement ratio is calculated on the combined weight of cement and fly ash in the mix.

COMPRESSIVE STRENGTH RESULTS

Woodbury Fly Ash Research — 7 Day Results - Cylinders

Cylinder No.	Mix No.	Air Content %	Slump Inches	W/C** Ratio	Compressive Strength PSI
3CH-105-3	C-4	5.0	3¼	0.434	4,722
105-4	C-4	5.0	3¼	0.434	4,732
				Average	4,727
101-3	C-4-10-1.5	6.4	2.5	0.403	4,332
101-4	C-4-10-1.5	6.8	3.0	0.403	3,810
				Average	4,071
3CH8-111-3	C-4-15-1.0	8.0	3	0.417	3,905*
111-4	C-4-15-1.0	8.0	3	0.417	3,905*
				Average	3,905*
3CH8-107-3	C-4-15-1.5	5.5	2½	0.383	3,678
107-4	C-4-15-1.5	5.5	2½	0.383	3,942
				Average	3,810

* Non-complying coarse aggregate was reported for the mix included in the cylinder samples. Specification range for material passing the ½" sieve is 25-60%. Project control gradation passing ½" sieve was 22% (average of 3 tests).

** Water/cement ratio is calculated on the combined weight of cement and fly ash in the mix.

COMPRESSIVE STRENGTH RESULTS

Woodbury Fly Ash Research — 14 Day Results - Cylinders

Cylinder No.	Mix No.	Air Content %	Slump Inches	W/C** Ratio	Compressive Strength PSI
CH8-105-5	C-4	6.25	2	0.434	5,049
105-6	C-4	6.25	2	0.434	5,112
				Average	5,082
JY8-197-5	C-4-10-1.5	6.0	2	0.403	4,854
197-6	C-4-10-1.5	7.0	1 3/4	0.403	3,678
				Average	4,266
3CH8-111-5	C-4-15-1.0	8.0	3	0.417	4,464*
111-6	C-4-15-1.0	8.0	3	0.417	4,854*
				Average	4,659*
3CH8-10-5	C-4-15-1.5	6.0	2	0.383	5,483
10-6	C-4-15-1.5	6.0	2	0.383	5,238
				Average	5,360

* *Non-Complying coarse aggregate gradation reported for mix included in the cylinder samples. Specification range for material passing ½" sieve 25-60%. Project control gradation passing ½" sieve was 22% (average of 3 tests).*

** Water/cement ratio is calculated on the combined weight of cement and fly ash in the mix.

COMPRESSIVE STRENGTH SUMMARY

Woodbury Fly Ash Research Cylinders

Mix No.	Compressive Strength Average		
	3 day	7 day	14 day
C-4	3,279	4,727	5,082
C-4-10-1.5	2,732	4,071	4,266
C-4-15-1.0	2,383	3,905	4,659
C-4-15-1.5	2,817	3,810	5,360

COMPRESSIVE STRENGTH RESULTS FOR
WOODBURY FLY ASH RESEARCH

Mix Number	Compressive Strength (PSI)				
	7 day	14 day	28 day	6 mo.	1 year
C-4	3570	4270	5180	6260	6460
	3440	4390	4800	5700	5710
	3580	4270	4680	5860	6900
	3200	3440	4030	5150	6980
	3110	4820	4340	6000	7140
C-4-10-1.5	4040	3680	4610	5620	5840
	2780	3250	4830	5780	6030
	3910	3560	4170	5440	5420
	2700	2820	3950	4690	6560
	3180	3530	4190	----	7450
C-4-15-1.0	3920	3990	5740	5450	6485
	3900	3820	4900	3040	7040
	3020	3860	4580	4580	6405
	3250	3420	5210	5060	5460
	2850	3300	5600	5530	5945
C-4-15-1.5	2280	5660	4310	4210	5700
	3510	4450	5000	5270	8220
	3910	4660	3900	5225	5580
	3760	4180	4990	4850	7200
	2900	4030	4830	5375	7370

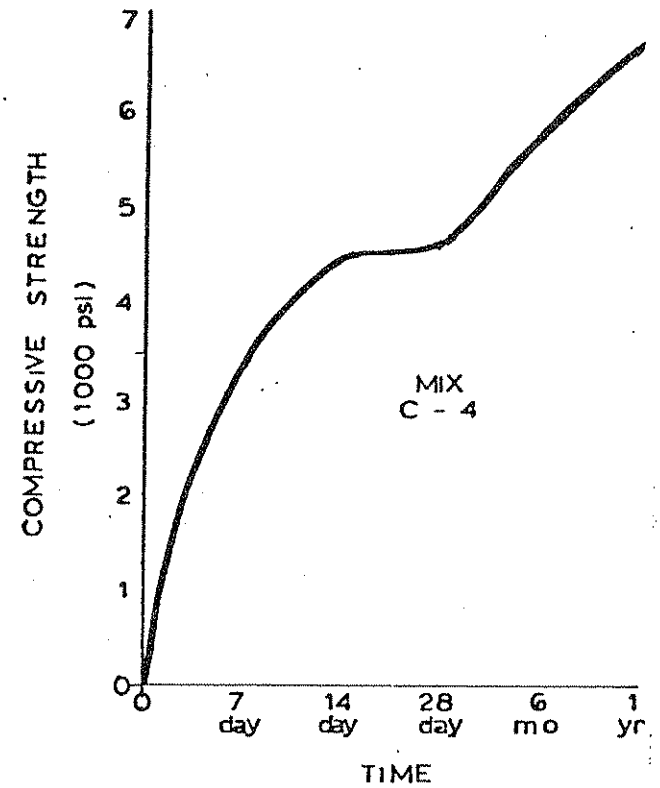
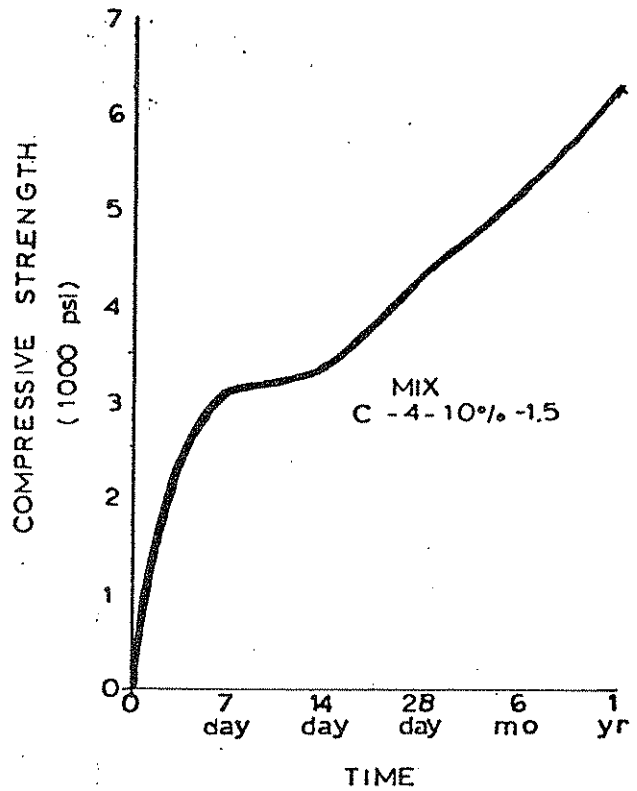
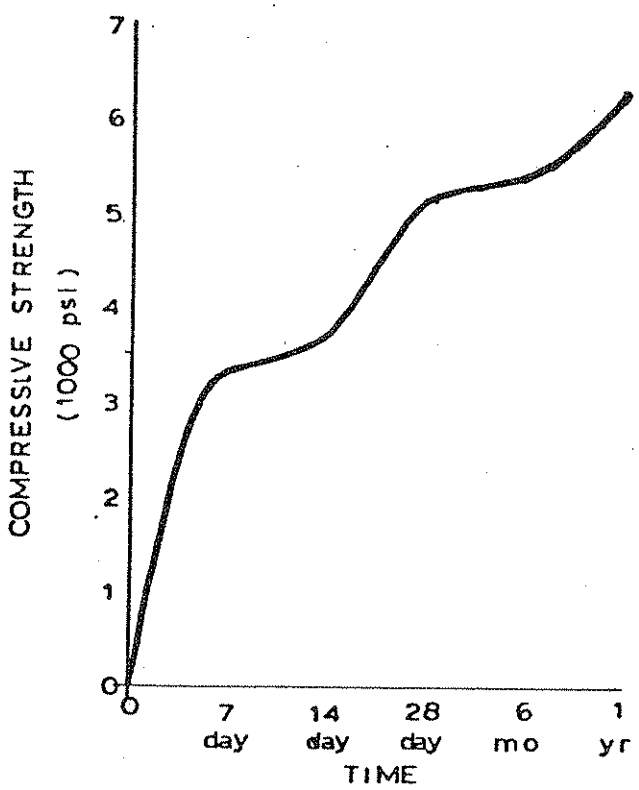
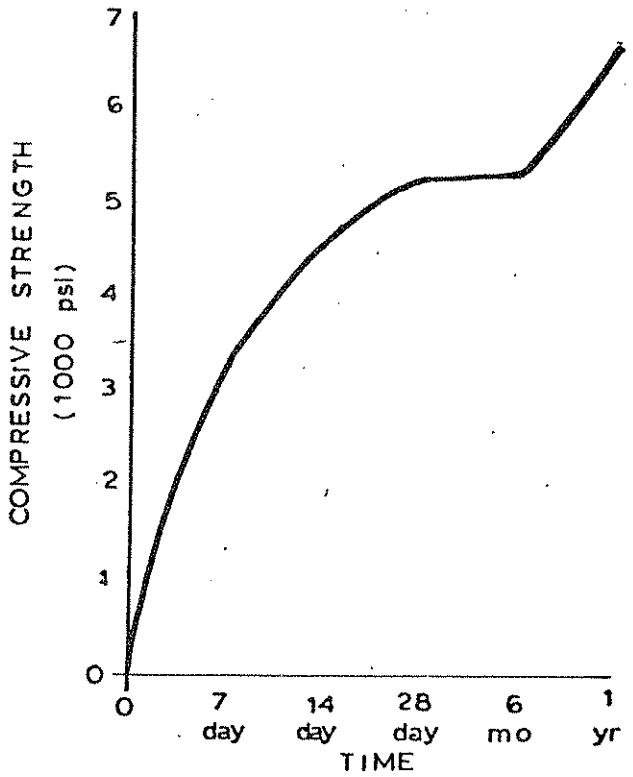
COMPRESSIVE STRENGTH SUMMARY

Woodbury Fly Ash Research — Cores

Mix No.	Compressive Strength Average				
	7 day	14 day	28 day	6 mo.	1 year
C-4	3380	4240	4610	5800	6640
C-4-10-1.5	3140	3370	4350	5150	6260
C-4-15-1.0	3390	3680	5210	*5160	6270
C-4-15-1.5	3270	4600	4610	5410	6640

*One core @ 3040 psi was not utilized in this average as it did not appear to fit the remaining core strength population.

AVERAGE CONCRETE PAVEMENT

CORE COMPRESSIVE STRENGTH

PROJECT HR- 201