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

Construction Report For Iowa Highway Research Board Project HR-201

Highway Division
May 1979

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CONSTRUCTION REPORT

FOR

IOWA HIGHWAY RESEARCH BOARD

PROJECT HR-201

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

BY

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TABLE OF CONTENTS

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

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.

Due to recent cement shortages and the rapidly increasing highway construction costs, the Iowa Department of Transportation

[1] Highway Research Bulletin 284, Fly Ash Concrete 1961.

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 28 days verify that adequate strengths can be achieved in fly ash mixes to satisfy Iowa DOT strength requirements.

At this time, core data for the project is incomplete. A final report is to be written after six months and one year core strength results are available.

RECOMMENDATIONS

Based on preliminary 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.

Preliminary test results from the project indicate that 15% of the cement in the C-4 mix could be replaced with 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 is 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, includes 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 includes 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.

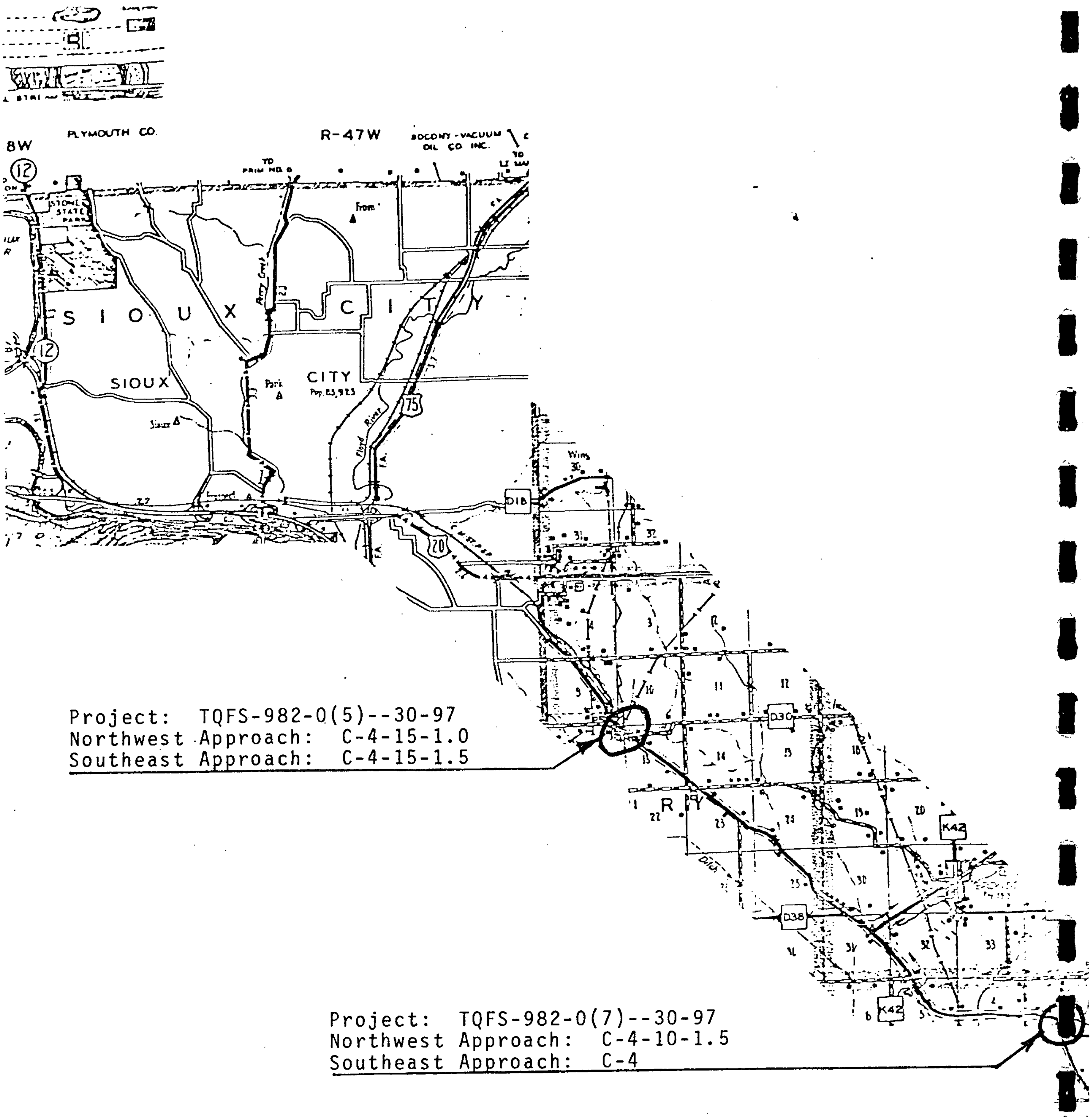

Figure 1. PROJECT LAYOUT FOR WOODBURY COUNTY HR-201

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 non-compliance, 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

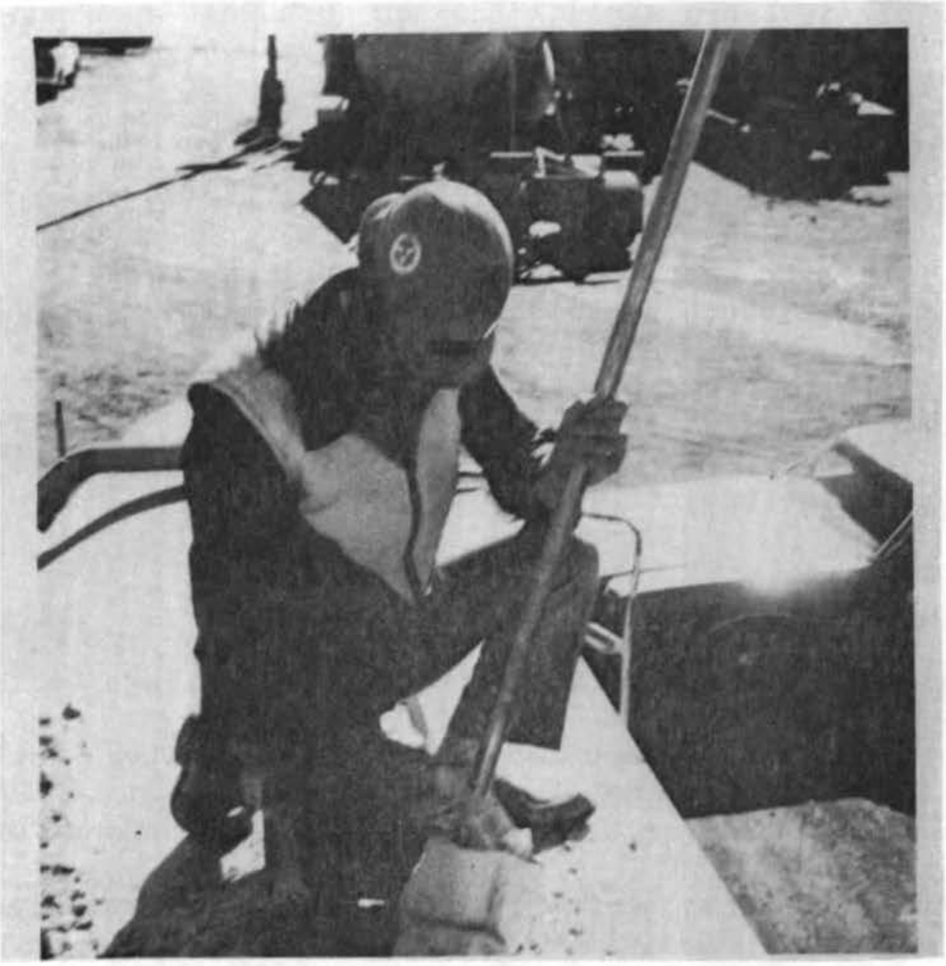

Figure 2. Sampling the individual transport load of fly ash.

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

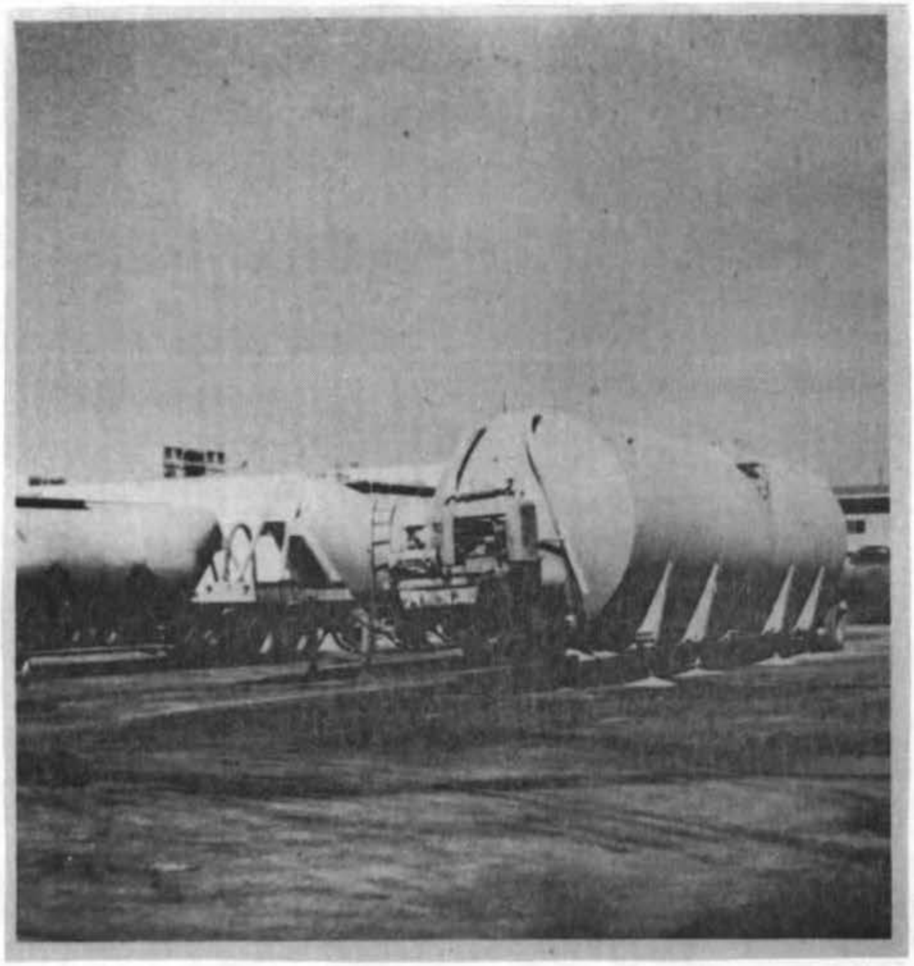

Figure 3: Portable storage tankers used to store approved fly ash.

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)

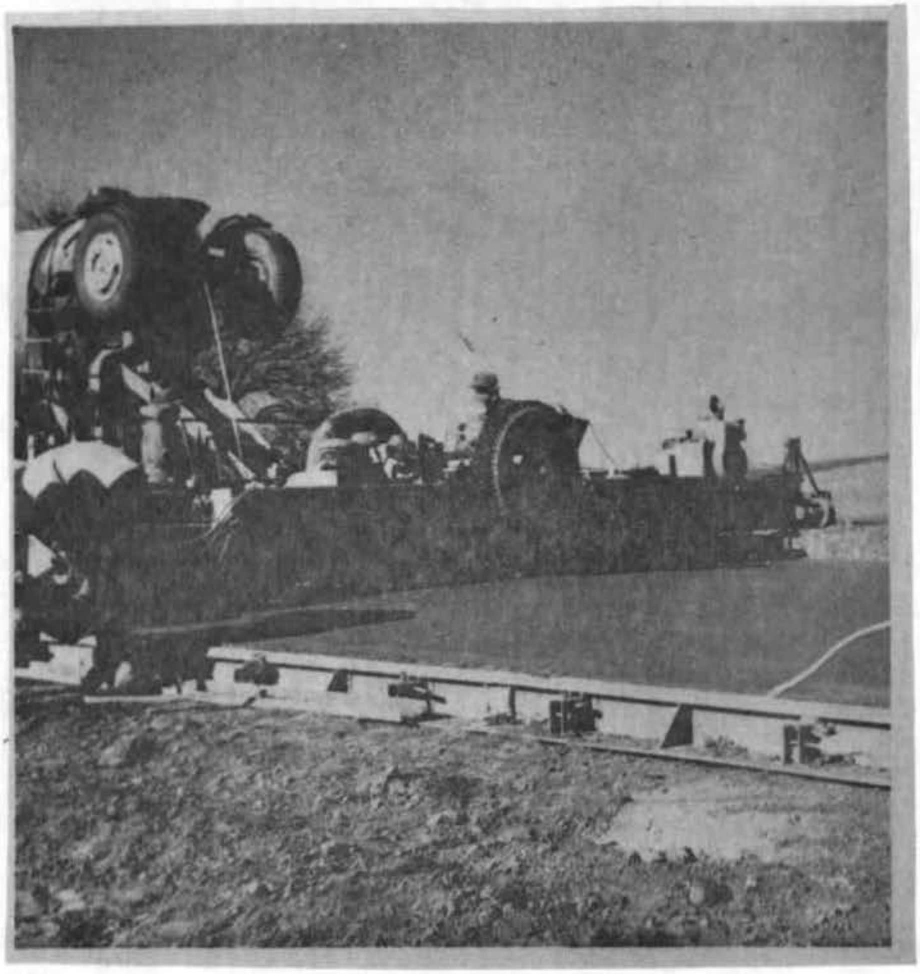

Figure 4: Pave-Saver finish machine in operation

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.

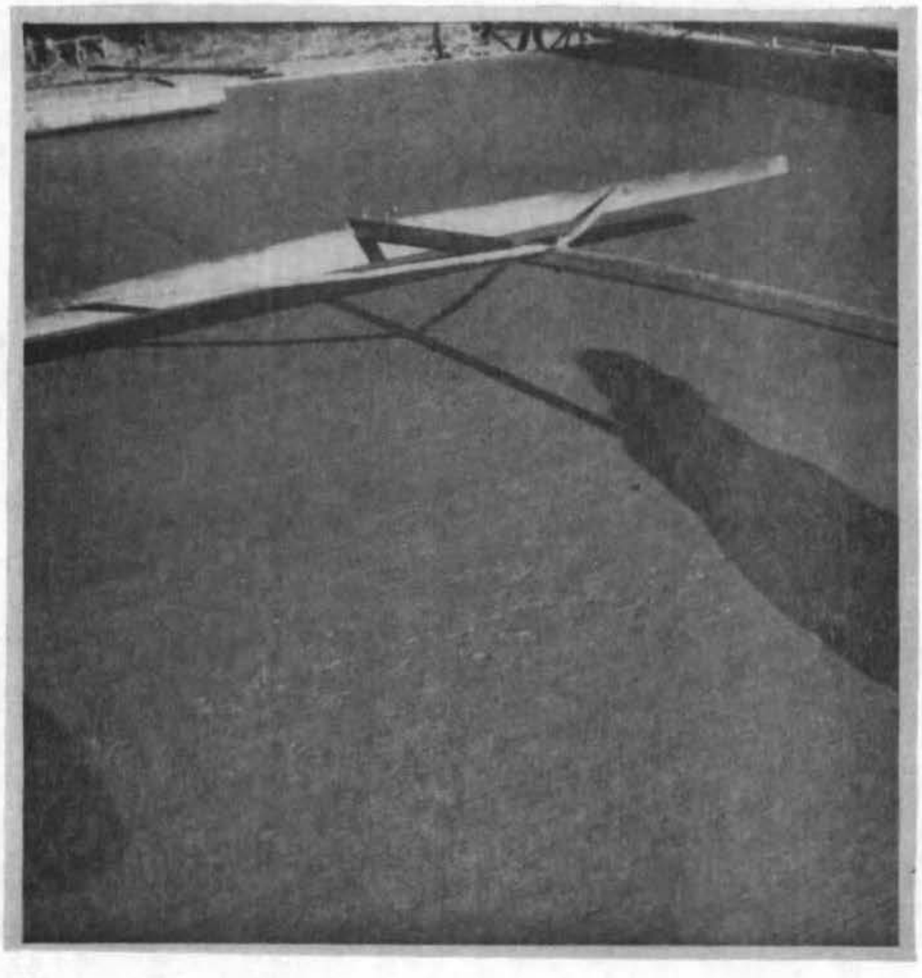

Figure 5: Finished pavement behind the Pave-Saver

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 $\pm$ 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 28, 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 6 cores cut from each mix were very similar at 7 days. The average ranged from 3140 psi for the C-4-10-1.5 to 3390 psi for the C-4-15-1.0. At 14 days, the range for the average broadened with the low strength occurring in the C-4-10-1.5 mix (3370 psi) and the high strength occurring in the C-4-15-1.5 mix (4600 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 the C-4-15-1.0 mix (5210 psi). A complete tabulation of core results for 7, 14, 28 day strength is included in Appendix G.

Cores have been cut for 6 month evaluation, but strength results are not available at this time.

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 is being 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 nighttime low temperature at 36°F and the day time 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. This was observed in the C-4-10-1.5 mix. Paving operations progressed through the C-4 section into the C-4-10-1.5 mix in the middle of a days production. This established the same curing condition for both mixes. Transverse sawing was completed in C-4 mix with no raveling evident. Raveling was noticed immediately in the C-4-10-1.5 section. Sawing was delayed several hours to avoid raveling. This delay is to be expected and especially in cooler weather as the fly ash does act as a retarder.

ACKNOWLEDGEMENTS

I would like to thank the contractor Irving F. Jensen Company, 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

APPENDIX A

FLY ASH SPECIFICATIONS

	ASTM C618 Class F	Typical Port Neal No. 3	Clinton	Bettendorf	Dubuque	Proposed
$SiO_2+Al_2O_3+Fe_2O_3$	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	.33[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)

	B410-1.5	B610-1.5	B615-1.5	B615-1	C410-1.5	C415-1.5	C415-1
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_2	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.

Identification	Age Days	Air Content	Slump	Water/ Cement	Flexural Strength
		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%).

Identification	Age Days	Air Content	Slump	Water/ Cement	Flexural Strength
		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	Core No.	Comp. Str. (days) 7	14	28
C-4	2627	3570		
	2628	3440		
	2629	3580		
	2630	3200		
	2631	3110		
	2745		4270	
	2746		4390	
	2747		4270	
	2748		3440	
	2749		4820	
	2707			5180
	2708			4800
	2709			4680
	2710			4030
	2711			4340
	Average	3380	4240	4610
C-4-10-1.5	2622	4040		
	2623	2780		
	2624	3910		
	2625	2700		
	2626	3180		
	2740		3680	
	2741		3250	
	2742		3560	
	2743		2820	
	2744		3530	
	2712			4610
	2713			4830
	2714			4170
	2715			3950
	2716			4190
	Average	3140	3370	4350

COMPRESSIVE STRENGTH RESULTS FOR WOODBURY FLY ASH RESEARCH

Mix Number	Core No.	Comp. Str. (days) 7	14	28
C-4-15-1.0	2675	3920		
	2676	3900		
	2677	3020		
	2678	3250		
	2679	2850		
	2702		3990	
	2703		3820	
	2704		3860	
	2705		3420	
	2706		3300	
	2722			5740
	2723			4900
	2724			4580
	2725			5210
	2726			5600
	Average	3390	3680	5210
C-4-15-1.5	2735	2280		
	2736	3510		
	2737	3910		
	2738	3760		
	2739	2900		
	2680		5660	
	2681		4450	
	2682		4660	
	2683		4180	
	2684		4030	
	2717			4310
	2718			5000
	2719			3900
	2720			4990
	2721			4830
	Average	3270	4600	4610

COMPRESSIVE STRENGTH SUMMARY

Woodbury Fly Ash Research — Cores

Mix No.	Compressive Strength Average		
	7 day	14 day	28 day
C-4	3380	4240	4610
C-4-10-1.5	3140	3370	4350
C-4-15-1.0	3390	3680	5210
C-4-15-1.5	3270	4600	4610