GUIDELINES FOR USING HYDRATED FLY ASH AS A FLEXIBLE BASE

by

Phillip T. Nash
Priyantha Jayawickrama
Sanjaya Senadheera
John Borrelli
A. S. M. Ashek Rana

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Texas Tech University

August, 1996

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16. Abstract: The cost of transportating granular materials for flexible bases can be a major portion of pavement construction costs. Sources of adequate construction aggregates are scarce in some areas of the State of Texas and pavement construction requires transporting significant quantities of aggregate to the construction site. High aggregate transportation costs create the need for alternative sources of materials that are locally available. Hydrated fly ash is a material currently used to make aggregate for flexible base material.

Hydrated fly ash is produced by allowing the powder fly ash from coal power plants to cure with moisture. The hydrated (cured) fly ash becomes a stiff material and is crushed to form an aggregate. When properly processed, the hydrated fly ash continues to gain strength after placement. Several Texas Department of Transportation districts use hydrated fly ash as flexible base. Special specifications have been developed for hydrated fly ash. However, specifications need further development in several areas including: (1) water demand of the fly ash; (2) curing conditions of the fly ash; (3) mechanism of bonding between the hydrated fly ash flexible base and the asphalt surfaces such as seal coats and asphalt concrete; and (4) mechanisms of formation of crystalline products in locations where the hydrated fly ash base is exposed to the environment (moisture). The purpose of this study is to develop specifications for using hydrated fly ash as flexible base.

The study included a comprehensive literature search on fly ash characteristics, selection and monitoring of a TxDOT pavement construction project, laboratory characterization of hydrated fly ash material, documentation and presentation of findings to TxDOT, and the development of specifications for fly ash as a flexible base.

Available information on hydrated fly ash to indicates that it has great potential to be used as a flexible base material provided that appropriate methods are adopted in its production. Several aspects of hydrated fly ash including its strength gain and microstructure were investigated. In addition, data from TxDOT sources which tested this material for suitability as a flexible base material was also made available.

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IMPLEMENTATION

This project will yield several products useful to the Texas Department of Transportation (TxDOT) , including: draft specifications for using fly ash as a flexible base, laboratory characterization of fly ash material available in the Amarillo district, guidance on the use of hydrated fly ash as flexible base, and a cost-benefit analysis.

FEDERAL/DEPARTMENT CREDIT

Prepared in cooperation with the Texas Department of Transportation, the Texas Natural Resource Conservation Commission, and the U.S. Department of Transportation, Federal Highway Administration.

DISCLAIMER

The contents of this report reflect the views of the authors who are responsible for the facts and the accuracy of the data presented herein. The contents do not necessarily reflect the official view or policies of the U.S. Department of Transportation, Federal Highway Administration, Texas Natural Resources Conservation Commission, or the Texas Department of Transportation. This report does not constitute a standard, specification, or regulation.

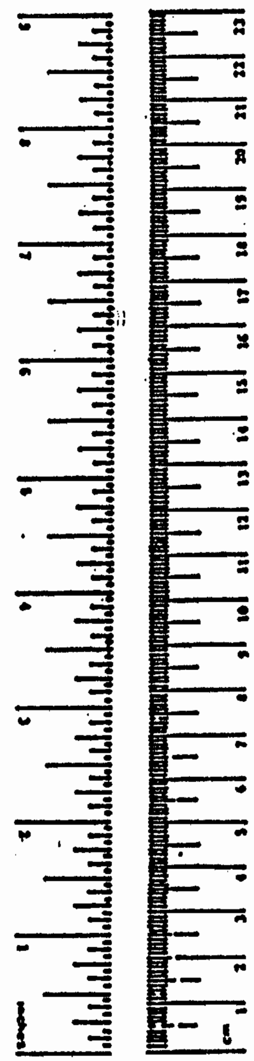
There was no invention or discovery conceived or first actually reduced to practice in the course of or under this contract, including any art, method, process, machine, manufacture, design or composition of matter, or any new useful improvement thereof, or any variety of plant, which is or may be patentable under the patent laws of the United States of America or any foreign country.

Not intended for construction, bidding, or permit purposes.

METRIC CONVERSION FACTORS

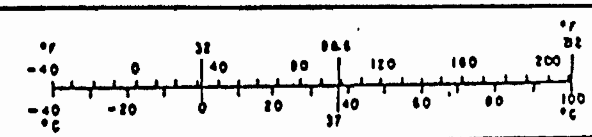
Approximate Conversions to Metric Measures

Symbol	When You Know	Multiply by	To Find	Symbol
		LENGTH		
in	inches	*2.5	centimeters	cm
ft	feet	30	centimeters	cm
yd	yards	0.9	meters	m
mi	miles	1.6	kilometers	km
		AREA		
in^2	square inches	6.5	square centimeters	cm^2
ft^2	square feet	0.09	square meters	m^2
yd^2	square yards	0.8	square meters	m^2
mi^2	square miles	2.6	square kilometers	km^2
	acres	0.4	hectares	ha
		MASS (weight)		
oz	ounces	28	grams	g
lb	pounds	0.45	kilograms	kg
	short tons (2000 lb)	0.9	tonnes	t
		VOLUME		
tsp	teaspoons	5	milliliters	ml
Tbsp	tablespoons	15	milliliters	ml
fl oz	fluid ounces	30	milliliters	ml
c	cups	0.24	liters	l
pt	pints	0.47	liters	l
qt	quarts	0.95	liters	l
gal	gallons	3.8	liters	l
ft^3	cubic feet	0.03	cubic meters	m^3
yd^3	cubic yards	0.76	cubic meters	m^3
		TEMPERATURE (exact)		
°F	Fahrenheit temperature	5/9 (after subtracting 32)	Celsius temperature	°C



Approximate Conversions from Metric Measures

Symbol	When You Know	Multiply by	To Find	Symbol
		LENGTH		
mm	millimeters	0.04	inches	in
cm	centimeters	0.4	inches	in
m	meters	3.3	feet	ft
m	meters	1.1	yards	yd
km	kilometers	0.6	miles	mi
		AREA		
cm^2	square centimeters	0.16	square inches	in^2
m^2	square meters	1.2	square yards	yd^2
km^2	square kilometers	0.4	square miles	mi^2
ha	hectares (10,000 m^2)	2.5	acres	
		MASS (weight)		
g	grams	0.035	ounces	oz
kg	kilograms	2.2	pounds	lb
t	tonnes (1000 kg)	1.1	short tons	
		VOLUME		
ml	milliliters	0.03	fluid ounces	fl oz
l	liters	2.1	pints	pt
l	liters	1.06	quarts	qt
l	liters	0.26	gallons	gal
m^3	cubic meters	35	cubic feet	ft^3
m^3	cubic meters	1.3	cubic yards	yd^3
		TEMPERATURE (exact)		
°C	Celsius temperature	9/5 (then add 32)	Fahrenheit temperature	°F



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SUMMARY

The cost of transporting granular materials for flexible bases can be a major portion of of pavement construction costs. Sources of adequate construction aggregates are scarce in some areas of the State of Texas and pavement construction requires transporting significant quantities of aggregate to the construction site. High aggregate transportation costs create the need for alternative sources of materials that are locally available. Hydrated fly ash is a material currently used to make aggregate for flexible base material.

Hydrated fly ash is produced by allowing the powder fly ash from coal power plants to cure with moisture. The hydrated (cured) fly ash becomes a stiff material that can be crushed to form an aggregate. When properly processed, the hydrated fly ash continues to gain strength after placement. Several Texas Department of Transportation districts use hydrated fly ash as flexible base. Special specifications have been developed for hydrated fly ash. However, specifications need further development in several areas including: (1) water demand of the fly ash; (2) curing conditions of the fly ash; (3) mechanism of bonding between the hydrated fly ash flexible base and the asphalt surfaces such as seal coats and asphalt concrete; and (4) mechanism of formation of crystalline products in locations where the hydrated fly ash base is exposed to the environment (moisture). The purpose of this study is develop specifications for using hydrated fly ash as flexible base.

The study included a comprehensive literature search on fly ash characteristics, selection and monitoring of a TxDOT pavement construction project, laboratory characterization of hydrated fly ash material, documentaion and presentation of findings to TxDOT, and the development of specifications for fly ash as a flexible base.

Available information on hydrated fly ash appears to indicate that fly ash has great potential to be used as a flexible base material provided that appropriate methods are adopted in its production so that it can provide the durability that a pavement structure requires. Several aspects of hydrated fly ash including its strength gain and microstructure were investigated. In addition, data from TxDOT sources which tested this material for suitability as a flexible base material was also evaluated.

INTRODUCTION

A major portion of the cost associated with the use of granular materials for flexible bases in pavements is the cost involved in the transportation of these materials from the source to the point of use. As a result, if suitable materials are not locally available, the cost can be very high. This problem exists in some parts of the state of Texas, particularly in the West Texas districts such as: Amarillo, Lubbock, and Childress. In these districts, the cost of base materials in some projects has been as high as $80 per ton. High aggregate transportation costs create the need to look for alternative sources of materials that are locally available thus reducing the cost of construction significantly. One such alternative material may be hydrated fly ash.

Several TxDOT districts including Amarillo, Childress and Atlanta have experimented with hydrated fly ash as a flexible base material. In fact, special specifications have been developed such that fly ash can be used on an experimental basis in districts where conventional flexible base materials are in short supply. One such specification is the Special Specification Item 2010 for Fly Ash Base (1993) being used in the Amarillo District.

Hydrated fly ash is a stiff material which is produced by allowing the powder fly ash from coal power plants to cure with moisture. Fly ash is currently used as a cement replacement in portland cement concrete. In Portland cement concrete, the fly ash is able to react with the calcium hydroxide formed as a by product in the cement hydration process. This reaction produces more of the calcium-silicate-hydrates necessary for the setting of cement in concrete. Fly ash with natural reactivity will set in stockpiles even in the absence of any organized curing. Hydrated (cured) fly ash is so stiff that it can attain compressive strengths as high as 15,000 kPa.

Several TxDOT districts have used crushed hydrated fly ash as a flexible base aggregate material on an experimental basis. The Amarillo and Childress districts used hydrated fly ash from the Harrington power plant in Amarillo, and the Atlanta district used hydrated fly ash from the Welch power plant in Cason, Texas. In the Harrington source, fly ash was allowed to cure in pits for up to 60 days. Experiences of the two districts using hydrated fly ash as a flexible base is mixed. In the Amarillo district, the sections of highways constructed using hydrated fly ash as a flexible base appear to be performing satisfactorily. Some of these pavement sections have been in service for a number of years. In the Childress district, two sections of highway detours were constructed using 100 percent of hydrated fly ash. These sections were in service for six to eight months and reportedly, their performance was even better than with conventional flexible base materials. Additionally, the Childress district has used crushed hydrated fly ash on a regular basis in combination with conventional flexible base materials similar to a conventional stabilization.

In the Atlanta district, several problems have been identified. One problem is the stripping away of the seal coat from the hydrated fly ash flexible base, particularly in the regions of the test sections where the vehicles accelerate or decelerate. TxDOT sources in Atlanta have indicated that there appears to be a lack of bond between the hydrated fly ash base and the seal coat. Another problem has been the formation of a white crystalline material near areas of pavement where the surface layer was damaged and the base layer was exposed to the environment.

Observations by TxDOT personnel indicate the following factors need to be investigated:

1. water demand of the fly ash
2. curing conditions of the fly ash
3. mechanism of bonding between the hydrated fly ash flexible base and the asphalt surfaces such as seal coats and asphalt concrete
4. mechanism of formation of crystalline products in locations where the hydrated fly ash base is exposed to the environment.

PROBLEM STATEMENT

Recent mandates from the Federal and State level require the careful consideration and, if possible, use of by-products and recyclable material in constructions. Fly ash and bottom ash already play an important role in the construction of transportation structures.

Specific design criteria for the use of these materials in the construction of flexible bases and data on their performance characteristics in terms of strength, deformability, drainage characteristics, shrink-swell potential etc. are not available at this time. Additionally, possible long-term environmental impact resulting from the use of these waste products in road beds and their cost-effectiveness must be investigated.

Close coordination with the Texas Fly Ash Utilization Group will enable this project to advance quickly.

OBJECTIVES

Project objectives were accomplished through the following seven (7) tasks:

1. Literature Search. Several organizations were contacted including TxDOT and flyash suppliers. A comprehensive literature search will seek additional information on flyash characteristics, experiences from using flyash in previous pavement projects, and any additional information leading to the development of specifications for using flyash.

2. Selection of a TxDOT Pavement Construction Project for Monitoring. The reconstruction of FM 809 in Deaf Smith County, Amarillo District will be monitored for documenting procedures and developing guidelines for using flyash.

3. Laboratory Characterization of the Hydrated Flyash. A variety of laboratory tests will be accomplished to characterize properties of the construction materials involving flyash. Tests will be conducted in TxDOT Lubbock laboratories and at Texas Tech University.

4. Review of Information and Recommendations to the Project Engineer. Information beneficial to the TxDOT Project Engineer will be reviewed and presented to TxDOT.

5. Documentation of the Construction Techniques and Test Section Performance. Researchers will monitor the construction and the performance of the test sections during and after the construction period. Performance evaluations will consist of visual distress survey, measurement of rutting and cracking and Falling Weight Deflectometer tests. Final results will include documentation of the construction practices used in the placement of the new base materials, problems during construction, possible remedial measures and comparison of the pavement performance recorded for each of the test sections.

6. Development of a Test Program for Long-term Field Performance Monitoring. Because of the short project duration, a plan will be developed for long-term monitoring of the construction project. The plan will be submitted to TxDOT.

7. Final Report Preparation. A final report will be submitted documenting the project and will include specifications for the use of hydrated fly ash, guidance on the use of hydrated fly ash as flexible base, and a cost-benefit analysis.

TECHNICAL INFORMATION AVAILABLE FROM THE LITERATURE

Powdered Fly Ash

Fly ash is an inorganic powdery by-product of coal burning associated with electric power generation. Power plants trap the fly ash using electrostatic precipitation methods. Fly ash is considered a pozzolanic material or a pozzolan. ASTM *(1)* defines a pozzolan as "a siliceous or alumino-siliceous material that in itself possesses little or no cementitious value, but that in finely divided form and in the presence of moisture will chemically react with alkali and alkaline earth hydroxides at ordinary temperatures to form or assist in forming compounds possessing cementitious properties".

From the ancient time people have been using natural pozzolans for building structures. Natural pozzolans include volcanic ashes and tuffs, pumicite, diatomaceous earth, opaline cherts, clays and shales. Mortars consisting of lime and natural pozzolans were used by the Romans in structures of many kinds. History provide us with ample evidence of the durability of these pozzolanic cementing agents. Fly ash, which is a synthetic pozzolan, is very popular because it is relatively inexpensive and readily available. Also, since fly ash is in the form of very fine spheres, it can enhance the workability of materials such as Portland cement concrete.

Available data indicate that only 15 to 20 percent of fly ash produced in the United States is currently being utilized. The remaining 80 to 85 percent is being dumped in landfills. In the United States, the generation of power from coal combustion is on an increasing trend. Therefore, the production of fly ash will also increase. Approximately 42 million tons of fly ash was produced in the United States in 1974 *(2)*. The current level of fly ash production is believed to be in excess of 50 million tons. If a 15 percent utilization level is assumed for fly ash, the excess fly ash will require approximately 16,000 acre-feet of landfill volume.

Fly ash is somewhat variable in composition, but it is primarily composed of silica (SiO_2), alumina (Al_2O_3) and various other oxides and alkalies. There is also considerable variability in the quality and reactivity of fly ash obtained from different sources. Such variability may be due to differences in coal composition from different sources, coal burning process, and the fly ash collection method in the power plant.

ASTM classifies fly ash as either Type C or Type F based on the amount of calcium oxide present. Type C fly ash has a higher proportion of calcium oxide in it. TxDOT classifies fly ash into Types A and B based on the chemical composition *(3)*.

Current utilization of fly ash is limited to its use as a replacement to cement in Portland cement concrete and as a soil stabilizing agent. Neither application involves bulk usage of fly ash.

Hydrated Fly Ash

When Type C fly ash powder is mixed with water, it forms a hard, homogeneous rock-like material which is referred to as hydrated fly ash. This self-hardening property of Type C fly ash in the presence of water and the high strength of the hydrated fly ash have drawn the interest of civil engineers.

Hydrated fly ash is currently being produced by dumping Type C fly ash powder into curing pits. Water is added to these pits and fly ash is allowed to hydrate for several weeks. Once hydrated fly ash attains an acceptable level of strength, the homogeneous mass of hydrated fly ash is milled inside the pit using specialized equipment to produce an aggregate material which is similar to conventional granular materials.

The major pozzolanic reactions involved in the hydration of fly ash were presented by Pollard et al. *(4)*.

$$Ca(OH)_2 + SiO_2 + H_2O \rightarrow (CaO)_x(SiO_2)_y(H_2O)_z$$
calcium silicate hydrates

$$Ca(OH)_2 + Al_2O_3 + H_2O \rightarrow (CaO)_x(Al_2O_3)_y(H_2O)_Z$$
calcium aluminate hydrates

$$Ca(OH)_2 + Al_2O_3 + SiO_2 + H_2O \rightarrow (CaO)_x(Al_2O_3)_y(SiO_2)_Z(H_2O)_w$$
calcium aluminate silicate hydrates

$$Ca(OH)_2 + Al_2O_3 + SO_3 + H_2O \rightarrow (CaO)_x(Al_2O_3)_y(CaSO_3)_z(H_2O)_w$$
calcium aluminate calcium silicate hydrates

The coefficients w, x, y, and z can assume a range of values. These hydration products are generally poorly crystallized and have very high surface area. They are quite similar to those formed in the hydration of Portland cement. Therefore it can be postulated that hydrated calcium silicates and/or calcium aluminates are mainly responsible for the strength development during hydration of both Portland cement and fly ash *(5)*.

Hydrated fly ash has been in use in Texas for quite some time in oil field haul roads, city and county streets, parking lots and driveways. TxDOT has already used it as a flexible base material on an experimental basis in Amarillo, Atlanta, Childress and Lubbock districts. Up to now, the performance of this material has been encouraging. Hydrated fly ash very easily meets the TxDOT strength criteria for flexible base materials. Use of this material on an experimental basis has shown that it can satisfactorily function as a road base for an extended period.

Available Information on the Use of Hydrated Fly Ash

Hydrated fly ash has been used as embankment materials in a number of countries including England, France, West Germany, Finland, Poland and Ukraine *(6)*. In the United States, states such as Illinois, West Virginia, Michigan, New York and North Dakota have reportedly used this material in construction *(7)*.

A number of case histories point to the feasibility of using fly ash in embankment and road construction *(8)*. A few of these cases are presented below.

<u>F.A. Route 437, Section 8 Lake County, Illinois</u>: In 1965, Illinois Department of Transportation agreed to use fly ash as an alternative embankment material along a 2.4 km (1.5 miles) section of highway *(9)*. The average height of the embankment was 1.1 m (3.5 ft.). Construction was completed in 1974. Inspection of the embankment during 1974 and 1975 indicated no major distresses in the pavement *(10)*.

<u>Motorway M.5 Bristol, Somerset, England</u>: A 3.2 km (2 miles) long fly ash embankment section of the M.5 was constructed between Bristol and Avonmouth on a highly compressible layer of alluvium. The embankment was 2.1 m (7 feet) high along the carriageway. Fly ash was selected as the embankment material because of its relatively low unit weight in comparison to locally available borrow materials *(11,12)*.

<u>Alexandria By-Pass,Dumbarton, Scotland</u>: A weak saturated silt subsoil necessitated the use of a lightweight fill material. Approximately 450,000 m^3 (590,000 yd^3) of fly ash was placed and compacted in the embankments under Stage I. Grass was hydroseeded directly onto the side slopes of fly ash to provide a vegetative cover and protect against erosion. In stage II, an additional 60,000 m^3 (78,000 yd^3) of fly ash was used in the embankment, which reached a maximum height of 12 meters (39 feet). Two years after construction, the embankment had settled a total of only 25.4 cm (10 inches), which was considered to be quite satisfactory *(13)*.

<u>Clophill By-Pass, A.6, Bedfordshire, England</u>: Construction began in 1975 on a 2.4 meters (8 ft.) high road embankment along the A.6 motorway *(14)*. It was on a highly compressible peat of 5 meters (16 ft.) thick and the ground water table was at the level of the existing ground surface. Fly ash was used in the construction of embankment and the inspection of the embankment in late 1975 revealed no major problems and the settlement was 15.2 cm (6 inches), which was less than predicted.

<u>U. S. Route 250, Fairmont, West Virginia</u>: A slide caused by poor drainage occurred along US-250 near Fairmont, West Virginia *(15)*. Engineers of the West Virginia Department of Highways decided to remove the slide mass, install subsurface drainage, and replace the slide material with compacted fly ash. Approximately 5,000 tons of fly ash were used in the embankment which had an average height of 7.6 meters (25 feet). The surface of the embankment was sealed with a coat of hand-sprayed road tar.

Some Important Properties of Fly Ash

1. Fly ash has a low unit weight in the range of 1122 to 1523 kg/m^3 (70 - 95 lb/ft^3) compared to the other conventional flexible base materials *(16)*.

2. Due to its low unit weight, fly ash causes less settlement in the underlying layers *(8)*.

3. Pozzolanic reactions in fly ash are quite slow. The speed of its pozzolanic reaction is comparable to the hydration if belite (C_2S) in ordinary Portland cement *(17)*.

4. High carbon content in fly ash reduces its pozzolanic activity. A carbon content of 7 to 10 percent can be considered as a reasonable upper limit for using fly ash as a material of high strength and durability *(18,19)*.

5. Fine fly ash tend to be more reactive than coarser fly ash *(8)*.

6. Self-hardening property of fly ash can result in the development of shear strengths which exceed the shear stresses encountered by many soils *(8,20)*.

7. The self-hardening property of fly ash is inhibited by a saturated condition *(21)*.

8. Partially saturated fly ash tend to be less compressible than fully saturated samples *(8)*.

9. For fly ash which can self-harden, the time-dependent component of age-hardening can reduce both the magnitude of compressibility and the rate of consolidation *(20)*.

10. The undrained shear strength is significantly lower in fly ash samples compacted wet of optimum *(22)*.

11. Fly ash is susceptible to frost action in the frost penetration zone. Lightly stabilized fly ash using lime or cement can eliminate this problem *(8)*.

12. Strength of pozzolanic materials is both time and temperature dependent. At approximately 40° F and below, all reactions between lime and fly ash cease to exist. The higher the temperature, the more rapid are these reactions *(8,23,24)*.

EXPERIENCES FROM PREVIOUS TxDOT CONSTRUCTION PROJECTS

TxDOT has recently undertaken several experimental projects where hydrated fly ash was used as a flexible base material in pavement construction. These experimental pavement sections were located in Amarillo, Atlanta and Childress districts. Hydrated fly ash for these experimental pavement sections came from 3 locations as indicated in Table 1. Results from the tests TxDOT Materials and Tests Division performed on fly ash from these sources are indicated in Table A-1 in Appendix A. Results from tests performed on hydrated fly ash from these sources are indicated in Table A-2.

Table 1. Fly Ash Sources for TxDOT Experimental Projects.

TxDOT District	Power Company	Plant/Station	Location	Fly Ash Contractor
Amarillo	Southwestern Public Service Company (SPS)	Tolk Station	Muleshoe, TX	DePauw Fly Ash, Amarillo
Amarillo	Southwestern Public Service Company (SPS)	Harrington Station	Amarillo, TX	DePauw Fly Ash, Amarillo
Atlanta	SWEPCO	Welch Station,	Cason, TX	Gifford-Hill Fly Ash, Dallas
Childress	Southwestern Public Service Company (SPS)	Harrington Station	Amarillo, TX	DePauw Fly Ash, Amarillo

Amarillo District

Several experimental pavement sections were constructed by TxDOT in the Amarillo district *(25)*. These include Business IH-40 frontage road sections in Carson county, SH-207 north of IH-40 in Carson county and FM-1541 (South Washington) in Randall county. Hydrated fly ash for the construction of these pavement sections came from the Harrington and Tolk power plants of the Southwestern Public Service (SPS) power company. The fly ash contractor for SPS is DePauw Fly Ash and DePauw is responsible for fly ash from the moment the fly ash powder leaves the power plant. They maintain curing pits adjacent to the power plants and oversee the production of hydrated fly ash aggregate.

In the Amarillo district, TxDOT experience with the performance of pavements using hydrated fly ash as a flexible base material has been positive. However, TxDOT engineers pointed out difficulties in meeting existing TxDOT flexible base specifications on gradation. When this material was placed and compacted, it would crush to smaller particles thus altering the gradation at the construction site. But once the hydrated fly ash flexible base layer was placed, it would harden into a very stiff layer.

It was also observed that hydrated fly ash require a significantly large quantity of water for compaction. The optimum moisture contents for the fly ash from Harrington and Tolk power plants range from 20 to 30 percent. However, it was quite easy to achieve the required compaction levels.

Childress District

In the Childress district, TxDOT constructed two sections of highway detours on US-287 using hydrated fly ash as flexible base materials *(26)*. These sections were in service for six to eight months and reportedly , their performance had been even better than with conventional flexible base materials.

Atlanta District

In the Atlanta district, TxDOT constructed five experimental pavement sections using hydrated fly ash as flexible base *(27)*. These were SH-154 in Diana, South Frontage Road of IH-20 East of Longview in Harrison county, Loop 390 in Marshall, FM-560 in Bowie county and FM- 1520 in Kent county. Hydrated fly ash for these experimental pavement sections was produced using fly ash from the Welch power plant in Cason, operated by SWEPCO power company. Fly ash from SWEPCO is being marketed by Gifford-Hill Fly Ash of Dallas. Information from TxDOT indicated that the Welch power plant produced 650 tons of fly ash per day and that Gifford-Hill Fly Ash has the capability to crush 1200 tons of fly ash per day. It was estimated that the available supply in the curing pit was approximately 400,000 cubic yards. Their curing pit occupied an area of 18 acres with fly ash stockpiled 4.6 meters (15 ft.) deep.

Based on tests performed on hydrated fly ash at the Atlanta district lab, it was noted that the problem areas for using hydrated fly ash are its high liquid limit of around 40 or more and the high optimum moisture content for compaction which was in the range of 25 to 30 percent. The advantages were identified as a low unit weight resulting in economical haulage cost, high triaxial strength, ease of achieving the required degree of field density and the availabilility of a perpetual supply of fly ash.

TxDOT engineers in Atlanta identified two problems associated with pavements with seal coated surfaces containing hydrated fly ash base layers. One is the stripping away of the seal coat from the hydrated fly ash flexible base, particularly in the regions of acceleration and deceleration. It was noted that there appear to be a lack of bond between the hydrated fly ash base and the seal coat. It was also noted that a white crystalline material formed near areas of pavement where the surface layer was damaged and the base layer was exposed to environment. These problems were not observed in pavements where hot mix asphalt concrete (HMAC) was used in the surface layer.

CONSTRUCTION OF THE TEST SECTION (FM 809)

One of the objectives of this research was to provide clear and concise guidance on the proper construction techniques to be used with hydrated fly ash as a flexible base. This was particularly important since the use of hydrated fly ash is relatively new to TxDOT. A rehabilitation project on FM-809 in Deaf Smith County in the Amarillo District was selected as the test section for this project (Figure 1). Amarillo area appeared to have used this material more than any other area in the state and the Amarillo district of TxDOT used hydrated fly ash as a flexible base material with much success. Table 2 indicates the information pertaining to the test section.

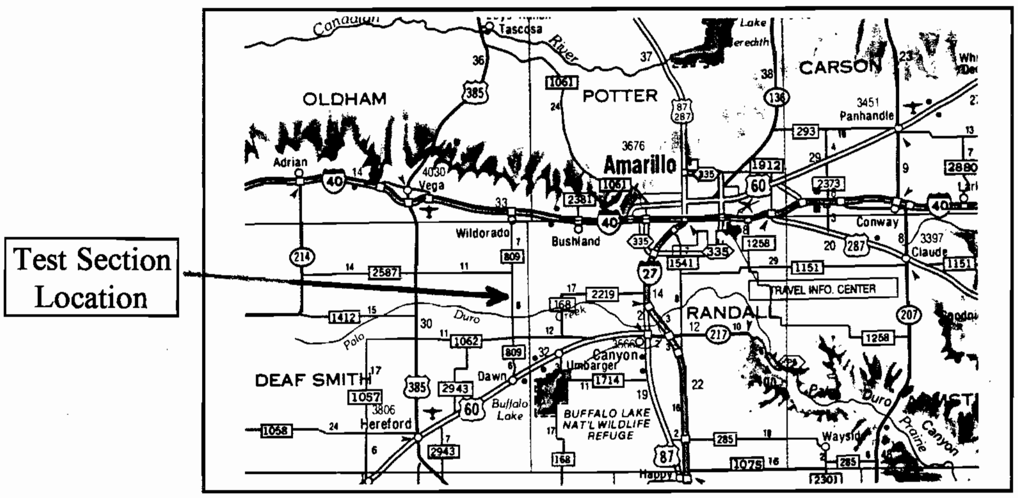

Figure 1. Map Indicating the Location of Test Section *(28)*.

Table 2. Information on the Test Section on FM-809.

Parameter	
TxDOT District	Amarillo
County	Deaf Smith
Highway	FM 809
Location	North of FM 1062; South of FM 2587
Length	7.8 km (4.8 miles)
Limits	Ref. Marker 108-0.511 to 112+0.336
Control-Section-Job No.	801-2-12
Type of Project	Improvement of existing highway
Type of Pavement Surface	Seal Coat
Lanes Prior to Improvement	Two 2.7 m (9 ft.) wide lanes / no shoulders
Lanes After Improvement	Two 3.7 m (12 ft.) wide lanes / two 0.9 m (3 ft.) shoulders
Resident Engineer	Don Day, P.E.
Project Engineer	Jacqueline Cato, P.E.
Hydrated Fly Ash Supplier	DePauw Fly Ash, Amarillo
Source of Fly Ash	Southwestern Public Service, Tolk Station, Muleshoe, Texas

Several trips were made to the site of the test section to record the construction procedure and to interview TxDOT personnel involved in the project. The project was classified as an improvement of an existing highway where a 2-lane 5.5 meters (18.0 ft.) wide highway was widened into a 9.1 meter (30.0 ft.) width. Figure 2 is a schematic of the cross sections of the widened highway. Two cross sections were used in the construction. In some sections, a 30.5 cm (12 inches) thick hydrated fly ash (HFA) base was placed by ripping off the existing pavement (Type-1 in Figure 2). In other sections, the existing pavement was reworked into a 5.5 meters (18 ft.) wide and 15.2 cm (6 inches) thick base, and a 15.2 cm (6 inches) thick fly ash base was placed over it. On either side of it, a 30.5 cm (12 inches) thick fly ash base was placed for the 1.8 meter (6 ft.) widening (Type-2 in Figure 2).

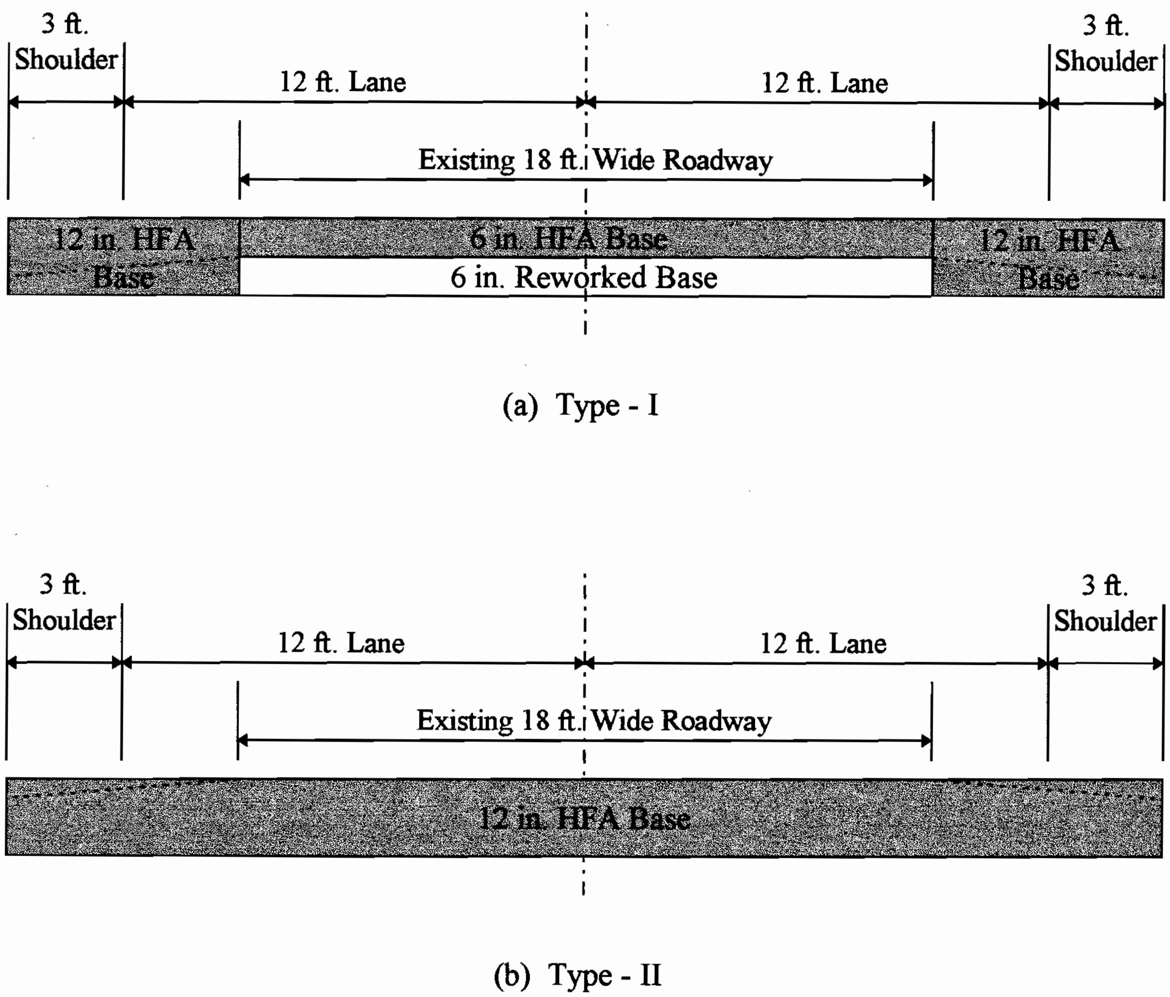

Figure 2. Schematic Diagram of Typical Cross Sections (a) Type-I, (b) Type-II.

The following chronological sequence of steps were followed during construction.

Sequence of Construction Steps

1. Placement of hydrated fly ash aggregate using belly dump trucks.
2. Levelling of the placed hydrated fly ash layer to the thickness required for compaction. The final compacted thickness of each lift of hydrated fly ash was 15.2 cm. (6 inches).
3. Sprinkling of water on hydrated fly ash. Even though the laboratory determined optimum moisture content for compaction was 25.4 percent, TxDOT personnel used a moisture content of 16.5 percent. The value of 16.5 percent was arrived at by trial and error to achieve a consistency which is satisfactory for compaction. A moisture content of 25.4 percent was found to make the material "soupy" which made it very difficult to compact.
4. Mixing of hydrated fly ash and water using the scarifier.
5. Compaction using the club foot roller. During this operation, larger aggregate particles are crushed into smaller sizes. The degree of crushing depends on the hardness of the hydrated fly ash aggregate particles.
6. Finishing compaction using the pneumatic roller.
7. Measurement of in-situ density using the nuclear density guage.
8. Continuous watering of the hydrated fly ash base to prevent it from drying. This watering was continued until the prime coat was placed over the hydrated fly ash base.
9. Repeat steps 1 to 8 until the required base layer thickness was achieved. For this pavement, base layer thicknesses of 15.2 cm (6 inches) and 30.5 cm (12 inches) were used.
10. Placement of the prime coat over the finished hydrated fly ash base. A MC-30 cutback bitumen was used as the prime coat.

Equipment Used in the Production of Hydrated Fly Ash Aggregate and in the Construction of Hydrated Fly Ash Base

1. Milling machine - Performs the milling of homogeneous hydrated fly ash mass formed in the curing pit
2. Elevator scraper - Transports milled hydrated fly ash aggregate from curing pit to stockpile
3. Belly dump truck - Transports hydrated fly ash from stock-pile to the roadway.
4. Front-end loader - Stock-piling and loading flyash to belly dump trucks
5. Motor grader - For blading, and levelling of material
6. Water truck - Sprinkles water on placed fly ash
7. Mixer - Mixes water and hydrated fly ash prior to compaction
8. Club-foot roller - Performs the initial compaction
9. Pneumatic roller - Provides finishing compaction of hydrated fly ash
10. Nuclear guage - Measures in-situ moisture content and density

LABORATORY CHARACTERIZATION OF HYDRATED FLY ASH

A laboratory experimental program was conducted to investigate whether hydrated fly ash meets the TxDOT requirements for flexible base material *(29)*. Laboratory experiments were performed on fly ash hydrated both in the Texas Tech University laboratories and at the Tolk Station Power Plant.

Experiments on Fly Ash Hydrated in the Laboratory

Compressive Strength Test

The objective of performing this test was to find out how the compressive strength of hydrated fly ash develops with age at different curing moisture contents. Cylindrical specimens with a diameter of 7.6 cm (3.0 in.) and a height of 15.2 cm (6.0 in.) were prepared with 20, 40, 60, and 100 percent curing moisture contents by weight of fly ash powder. Three replicates were made for each test condition. Specimens were tested after 3,7, 14 and 28 days of curing.

Powdered fly ash and distilled water were weighed in their mixing proportions and mixed for 30 seconds using a mixer rotating at 450 rpm. The mixing time was designed in such a way that all powdered fly ash could be thoroughly mixed. Then the mix was placed in the molds and slightly vibrated to ensure proper placement without any voids being present in the hardened specimen. Once all specimens were cast, polyethylene bags were used to cap the molds to avoid moisture loss by evaporation. The specimens were kept in the laboratory at 70 °F. Specimens were demolded about 15 minutes prior to testing to enable them to reach laboratory ambient conditions. It was observed that the specimens had a very good finish except for a couple of specimens which had some delamination damage close to the top surface during demolding. The specimens with damaged surfaces resulted in compressive strength values different from others and these values were not used in the calculation of the average strength. It was also observed that specimens with 20, 40 and 60 percent curing moisture contents were sufficiently hard to be tested for compressive strength test after 3 days but specimens with 100 percent curing moisture content were found to be too soft to test even after 28 days. Data from the compression tests are given in Table 4. The same data are illustrated in Figure 3.

Table 3. Laboratory Experiment Data on Compressive Strength Test.

Curing Moisture Content (%)	3-day Ultimate Compressive Strength (kPa)	7-day Ultimate Compressive Strength (kPa)	14-day Ultimate Compressive Strength (kPa)	28-day Ultimate Compressive Strength (kPa)
20	9493.90	11242.60	14718.51	16116.26
40	3465.18	4181.62	4941.15	7583.41
60	1361.70	1712.61	2059.94	-
100	specimen too soft for test.	specimen too soft for test.	specimen too soft for test.	specimen too soft for test.

Figure 3 indicates that the strength gain reached a plateau at a time nearing 4 weeks for all curing moisture contents. It can also be seen that the compressive strength decreases significantly with increasing curing moisture content. The difference between the compressive strength of specimens with 20 and 40 percent curing moisture contents is extremely large.

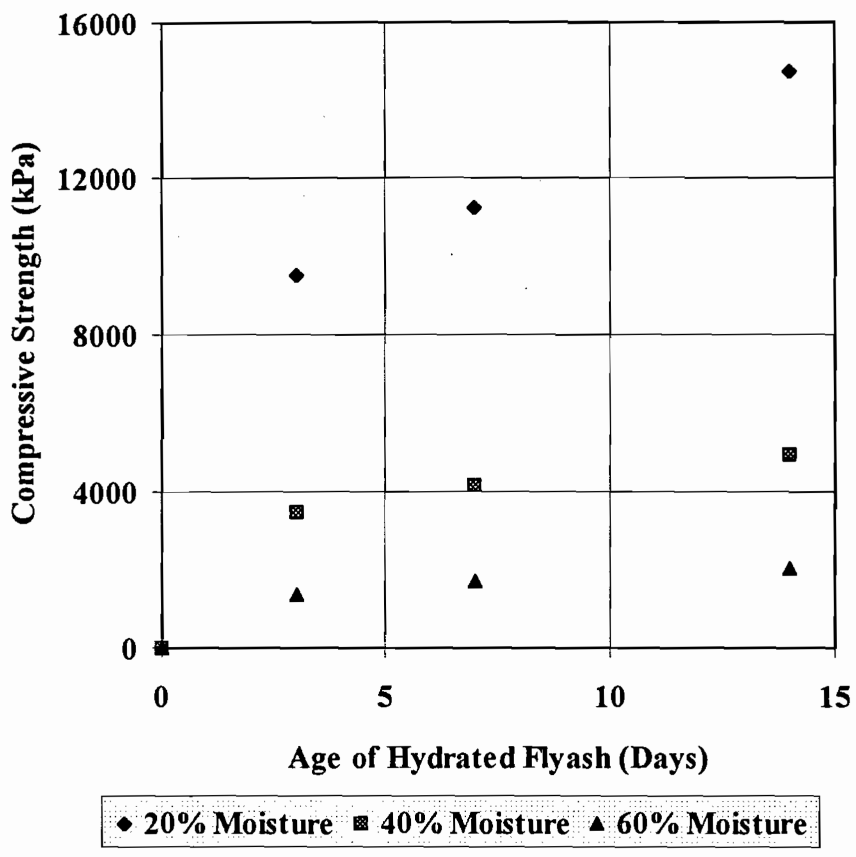

Figure 3. Development of Compressive Strength of Cylinderical Hydrated Fly Ash Specimens With Curing Age.

Wet Ball Mill Method for Determination of Resistance to Degradation

The Wet-Ball Mill Test was conducted on fly ash hydrated in the laboratory by adopting the TxDOT standard test procedure Tex-116-E *(30)*. The objective of the test was to observe the effect of hydrating moisture content on degradation of the aggregate. The failed compressive strength test specimens with curing moisture contents of 20 and 60 percent were further crushed to obtain aggregates used for this test. A gradation similar to that of the hydrated fly ash from the Tolk Station curing pits was obtained. Wet Ball Mill test results are shown in Table 4.

Table 4. Wet Ball Mill Test Data on Fly Ash Hydrated in the Laboratory.

Hydration Moisture Content (%)	Wet Ball Mill Value	Increase in Material Passing No. 40 Sieve (%)
20	23.00	14.00
60	70.32	61.32

Determination of Specific Gravity of Fly Ash Hydrated in the Laboratory

The objective of this test was to find out how the specific gravity of hydrated fly ash varies with the curing moisture content. Cylindrical specimens prepared for the compressive strength test were used. Pieces of specimens with different moisture content were cut into cylindrical disks and their weight and the geometric dimensions were measured. Then the specific gravity was calculated and the results are shown in Table 5.

Table 5. Variation of the Specific Gravity of Hydrated Fly Ash With Curing Moisture Content.

Curing Moisture Content (%)	Specific Gravity
20	1.85
40	1.40
60	1.13
100	0.88

Experiments on Fly Ash Hydrated in the Curing Pit at Tolk Station

Fly ash from the Tolk station curing pits were used in these experiments. Hydrated fly ash from this source had a gradation as presented in Table 6. Representatives of DePauw Fly Ash indicated that this material had been cured for 2 to 3 weeks.

Table 6. Gradation of Hydrated Fly Ash from Tolk Station.

Sieve Size	Cumulative Percent Retained
44.5 mm (1-3/4 in.)	-
38.1 mm (1-1/2 in.)	3
31.8 mm (1-1/4 in.)	4
22.2 mm (7/8 in.)	9
9.5 mm (3/8 in.)	33
No. 40	91

Wet Ball Mill Method for Determination of the Resistance to Degradation

Dry weight of sample (A) = 3.17 kg
Weight of material retained on No.40 sieve after drying (B) = 1.92 kg

Wet Ball Mill value = (A - B) * 100 / A = 39.43

Weight of material passing No.40 sieve before the test	=	0.22 kg
Percent material passing No. 40 sieve before the test	=	9 %
Weight of material passing No.40 sieve after the test	=	1.60 kg
Percent material passing No. 40 sieve after the test	=	45.5 %

Increase in material passing the No. 40 sieve = 36.55 %

Linear Shrinkage

The objective of this test was to determine linear shrinkage of hydrated fly ash using the shrinkage bar method. Linear shrinkage provides an assessment of the likelihood of subsequent shrinkage cracking of road base due to shrinkage. The test procedure Tex-107-E (Part 2) described in the TxDOT Manual of Testing Procedures *(30)* was adopted for this test.

Initial length of the fly ash bar, LW	=	12.70 cm
Final length of the fly ash bar, LD	=	12.60 cm

Linear shrinkage, LS = (LW - LD) * 100 / LW = 0.8 %

Particle Size Analysis

The objective of this test was to find the gradation of hydrated fly ash aggregate. The test procedure Tex-110-E (Part 1) described in the TxDOT Manual of Testing Procedures *(30)* was adopted for this test and the results are shown in Table 7.

Compaction Test

The objective of this test was to determine the dry density and the optimum moisture content to achieve dry density. The test was performed for hydrated fly ash under two gradations. One was well-graded and the other was gap-graded. Test procedure Tex-113-E described in the TxDOT Manual of Testing Procedures *(30)* was adopted for this test. The results are shown in Table 8.

Table 7. Compaction Test Results.

Gradation of Aggregate	Optimum Moisture Content (%)	Maximum Dry Density g/cm^3 (lb/ft^3)
Well-graded	24.0	1.34 (84.00)
Gap-graded	20.2	1.32 (82.23)

Determination of the Moisture Content

Both hygroscopic and saturated-surface-dry (SSD) moisture content were determined. For the hygroscopic moisture content determination, sample was weighed and then placed in an oven at a temperature of 230 °F until a constant weight was observed. For the SSD case, sample was first saturated by submerging it in water for 24 hours. Surface moisture was removed using a clean dry towel. Then the sample was weighed and placed in an oven at a temperature of 230 °F until it reached a constant weight. A hygroscopic moisture content of 11 percent and a SSD moisture content of 68.29 percent were obtained.

Microscopical Analysis.

The microscopical examination was conducted on both powder fly ash and hydrated fly ash. It was hoped that the microstructure of hydrated fly ash would provide clues regarding the stripping of asphalt cement seal coat from hydrated fly ash base as experienced in the Atlanta district of TxDOT.

Investigation on cylinderical hydrated fly ash test specimens cast in the laboratory indicated that there are three zones distinguishable by color in the hydrated fly ash specimens (Figure 4). Since this may give some clues to the formation of different compounds under different curing conditions, it was decided to conduct a microscopical investigation of these three regions. Powder fly ash and several samples of fly ash hydrated under different conditions were subjected to this microscopical investigation.

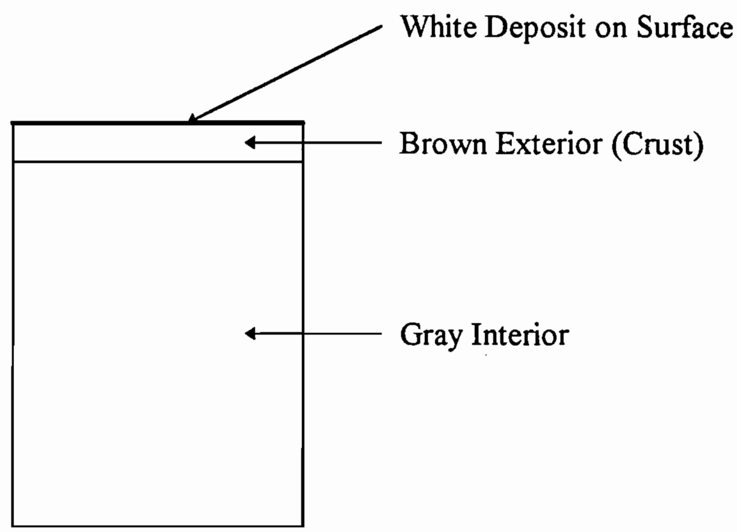

Figure 4. Different Zones in a Typical Cylinderical Hydrated Fly Ash Specimen.

Two microscopical analysis techniques were adopted.

Scanning and Transmission Electron Microscopy (STEM) Analysis:
Qualitative elemental analyses were carried out using the STEM to identify the chemical elements in the fly ash powder and hydrated fly ash.

Scanning Electron Microscopy Analysis (SEM):
The development of the microstructure and the hydration products of fly ash were monitored for different curing conditions.

Preparation of Hydrated fly ash samples for Electron Microscopy

To prepare hydrated fly ash samples for microscopy, powder fly ash was mixed with water for 30 seconds using a mechanical mixer. Test specimens prepared from fly ash hydrated with the curing moisture contents of 30, 40, 60, and 100 percent by weight of the powdered fly ash. After mixing the hydrated fly ash with water, the samples were subjected to different curing conditions. Some samples were kept sealed using polyethylene sheets and others were cured under exposure to ambient conditions in the laboratory. All samples were kept in the laboratory environment at a temperature of 70 ^{0}F and 50 percent humidity. The samples were tested at the ages of 10 days, 21 days, 28 days, and 42 days.

Discussion

The qualitative elemental information of powder fly ash obtained from STEM analysis indicate the presence of the following elements: Ca, Mg, Al, Na, Si, K, Ti, Fe, C, O, Br, Ba. The elements present in the hydrated fly ash were also the same. The SEM micrograph of powder ash reveals that fly ash is a mixture of spherical particles of different sizes.

Results from the scanning electron microscopy are summarized in Table 8. The images from the scanning electron microscopy are shown in Appendix B in figures B-1 to B-15. At the age of 10 days the samples with 60 and 100 percent moisture content showed white spots on the top surface and the SEM micrograph of the white spots of this sample indicate the formation of rod-like ettringite crystals on the surface of hydrated fly ash. The same sample at the age of 42 days was seen with a white fungus like growth on the outer surface and the SEM micrograph of these growth ensure them as well-crystallized particles. This type of white growth was seen by the TxDOT engineers on the exposed surface of hydrated fly ash flexible base in Atlanta district.

The samples with 20, 30 and 40 percent moisture content did not show such a phenomenon on the surface. Instead SEM micrographs of these specimens indicate the formation of compounds which are similar to monosulfoaluminate and calcium silicate hydrate formed in Portland cement hydration. The SEM micrographs of the inside surface of the specimens also indicate monosulfoaluminate and calcium silicate hydrates formation. The observations from SEM micrographs are summarized in Table 8 and the table refers to figures appropriate to the observations.

Important observations to note from the microscopical examination are as follows:

1. Curing moisture has a strong influence on microstructure formation of hydrated fly ash.
2. Curing exposure conditions appear to have an influence on hydration product.
3. Microstructure of hydrated fly ash is different in the interior regions and in regions exposed to the curing environment.
4. Particle size distribution of the powder fly ash seems to have influence in the hydration process. Larger particles take longer time to react with water or react partially or remain

inactive. This can be observed from the micrograph of hydrated fly ash with 100 percent moisture content and at the age of 42 days.

Table 8. Summary of Observations from SEM Microscopy.

Figure No.	Sample ID	Curing Moisture (%)	Age (days)	Area Investigated (as in Fig. 4)	Observations
B-1	Powder Fly Ash	-	-	-	Spherical particles of different sizes.
B-2	FA-40-10	40	10	Top Surface	Appear similar to $Ca(OH)_2$ crystals which have hexagonal prism morphology. SEM micrograph indicates formation of C-S-H.
B-3	FA-40-10	40	10	Gray Interior	Clusters of plates probably produced from crystallization of monosulfoaluminate. Presence of C-S-H on Fly Ash particles. Some unhydrated Fly ash particles.
B-4	FA-100-10	100	10	White deposit on top surface	SEM micrographs of white deposits show a microstructure of mostly long needlelike formations similar to ettringite.
B-5	FA-100-10	100	10	Gray Interior	Three different microstructures have been observed. Poorly clustered platey structures (Monosulfoaluminate), rod-like ettringite and burr-like spiny C-S-H.
B-6	FA-30-21	30	21	Gray Interior	Layered platy structures have been observed along with burr-like spiny microstructure, both of which can be considered as C-S-H.
B-7	FA-30-21	30	21	Brown Exterior	Irregular shaped large well-packed crystals have been observed.
B-8	FA-40-21	40	21	White deposit on top surface	
B-9	FA-40-21	40	21	Gray Interior	Hydration products are monosulfoaluminate-like plates and C-S-H on Fly Ash particles.
B-10	FA-40-21	40	21	Brown Interior	Formation of web-like materials, which may be C-S-H have been observed.
B-11	FA-40-28	40	28	Top Surface	Small cube-like materials have been observed to be formed on Fly Ash particle surface.
B-12	FA-40-28	40	28	Gray Interior	The SEM micrographs shows similar type microstructures as in FA-40-21.
B-13	FA-100-28	100	28	Top Surface	
B-14	FA-100-28	100	28	Gray Interior	Few ettringites have been seen with C-S-H and Monosulfoaluminate-like materials.
B-15	FA-100-42	100	42	White Growth on Outer Surface	White fungus-like growth was observed on the outer surface of specimens after a few weeks. SEM images indicated that this growth is well-crystallized. These particles could be a different type of C-S-H crystals.

ECONOMIC FEASIBILITY ANALYSIS FOR USE OF HYDRATED FLY ASH AS AN ALTERNATIVE TO CONVENTIONAL BASE MATERIALS

Procedure

First, an attempt was made to obtain estimated costs for the primary activities during construction. The construction taking place at Canyon was used as the source of information regarding the construction steps. This source provided the sequence of operations and the equipment used during the construction. The corresponding operating costs for equipment and the drivers, were obtained from the MEANS building construction cost data *(31)*. Table 9 details the various costs involved in the construction process. The material cost, including transportation, for fly ash ($10.25/ton) was obtained from sources at the construction site. The corresponding cost for gravel ($25/ton) was obtained from bid documents.

Conversations with various experts in the pavement construction field, provided the information that the construction processes for fly ash and gravel based pavements are basically similar, and that minor differences, if any, would not change the total construction cost significantly. This led to the conclusion that the major difference in the total construction cost of fly ash based pavements and gravel based pavements would primarily result from the differences in material costs. Tables 9 and 10 show estimates of the total construction costs (including material cost), for a one mile stretch of pavement, for fly ash and gravel based pavements, respectively. These amounts ($66,989.66 vs. $197,575), indicate that capital cost requirements for fly ash based pavements is far lower than that for gravel based pavements, at least for the FM 809 location. From this, it was deduced that, for the total life-cycle cost of fly ash based pavements to be higher than conventional pavements, its present worth of maintenance and repair costs would have to be much higher in order to give a significant cost advantage to the FM 809 project.

Carnahan, et al. *(32)*, provide an expected pavement condition index (PCI) curve for conventional pavements from data collected through a survey (reproduced in Figure 5). They also provide unit costs for different maintenance and repair alternatives (Table 11). Based on this, total present worth of maintenance and repair costs over a 20 year period was calculated. Due to the unavailability of similar cost data for fly ash based pavements, costs were estimated from hypothetical PCI curves, as described below.

First, a minimum pavement condition level of 50 was chosen for analysis. It was assumed that routine maintenance was performed each year until the pavement condition deteriorated to a PCI below 50, at which point, repair operation was performed to bring the pavement back to its original condition. From the expected PCI curve, the state of the pavement (Table 11) was obtained for each year. Based on the current state, routine maintenance costs were obtained from Table 13. When the PCI fell below 50, Table 14 was used to get the type of repair operation necessary to bring the pavement back to its original condition. From this point on, the cycle of routine maintenance each year with repair in the end was continued for 19 years. At year 20, repair is performed to again bring the pavement back to its original state from its current state. Table 15 details a set of sample calculations.

Table 9. Construction Costs for Pavements With Hydrated Fly Ash Bases.

Primary Activity	Material/Equipment		Unit	Unit Cost ($)	No. of Units	Total Cost ($)
PLACING	Fly Ash		ton	10.25	6380	65,395.00
	Dump truck, 16 Ton (for hauling)		day	438.45	1	438.45
		Driver	hr	30.35	10	303.50
	Motor Grader, 30,000 lbs. (for blading)		day	568.50	1	568.50
		Operator	hr	37.35	1x0.33	12.33
	Water tank, 5000 Gal.		day	220.00	1	220.00
	Truck, 30 Ton		day	322.50	1	322.50
		Driver(heavy)	hr	30.35	1x0.1	3.04
	Motor Grader, 30,000 lbs. (for scarifying)		day	568.50		568.50
		Operator	hr	37.35	1x0.33	12.33
	Water tank, 5000 Gal.		day	220.00	1	220.00
	Truck, 30 Ton		day	322.50	1	322.50
		Driver(heavy)	hr	30.35	3x0.1	9.11
	Road Mixer, 310 H.P. (mix water with aggregate)		day	1041.05	1	1,041.05
		Operator	hr	37.35	3x0.33	36.98
	Sheeps foot roller, 130 H.P.		day	578.80	1	578.80
		Operator	hr	37.35	2x0.25	18.68
COMPACTING	Motor Grader, 30,000 lbs.					
		Operator	hr	37.35	2x0.33	24.65
	Neumatic tire rollers		day	239.95	1	239.95
		Operator	hr	37.35	2x0.25	18.68
	Neumatic tire rollers					
		Operator	hr	37.35	4x0.25	37.35
	Water tank, 5000 Gal.					
	Truck, 30 Ton					
		Driver(heavy)	hr	30.35	1x0.1	3.04
	Pneumatic tire rollers (for sealing)					
		Operator	hr	37.35	5x0.25	46.69
FINISHING	Asphalt emulsion (MC 30) (0.1 Gallon/S.Y) (for prime coat)		gal	1.00	1759.9	1,759.90
	Dist. tank truck, 3K Gal.		day	367.40	1	367.40
CURING		Operator	hr	30.35	1x0.166	5.04
	Asphalt (AC 5) for seal coat		gal	0.85	1759.9	1,495.92
	Dist. tank truck, 3K Gal.					
		Operator	hr	30.35	1x0.166	5.04
						74,074.89

Table 10. Construction Costs for Pavements with Gravel Bases.

Primary Activity	Material/Equipment		Unit	Unit Cos ($	No. of Units	Total Cos ($
PLACING	Gravel		ton	25.0	7903	197,575.0
	Dump truck, 16 Ton (for hauling)		day	438.4	1	438.4
		Driver	hr	30.3	10	303.5
	Motor Grader, 30,000 lbs. (for blading)		day	568.5	1	568.5
		Operator	hr	37.3	1x0.33	12.3
	Water tank, 5000 Gal.		day	220.0	1	220.0
	Truck, 30 Ton		day	322.5	1	322.5
		Driver(heavy)	hr	30.3	1x0.1	3.0
	Motor Grader, 30,000 lbs. (for scarifying)		day	568.5		568.5
		Operator	hr	37.3	1x0.33	12.3
	Water tank, 5000 Gal.		day	220.0	1	220.0
	Truck, 30 Ton		day	322.5	1	322.5
		Driver(heavy)	hr	30.3	3x0.1	9.1
	Sheeps foot roller, 130 H.P.		day	578.8	1	578.8
		Operator	hr	37.3	2x0.25	18.6
COMPACTING	Motor Grader, 30,000 lbs.					
		Operator	hr	37.3	2x0.33	24.6
	Neumatic tire rollers		day	239.9	1	239.9
		Operator	hr	37.3	2x0.25	18.6
	Neumatic tire rollers					
		Operator	hr	37.3	4x0.25	37.3
	Water tank, 5000 Gal.					
	Truck, 30 Ton					
		Driver(heavy)	hr	30.3	1x0.1	3.0
	Neumatic tire rollers (for sealing)					
		Operator	hr	37.3	5x0.25	46.6
FINISHING	Asphalt emulsion MC-30 for prime coat (0.1 gal./yd^2)		gal	1.0	1759.9	1,759.9
	Dist. tank truck, 3K Gal.		day	367.	1	367.4
CURING		Operator	hr	30.3	1x0.166	5.0
SURFACING	Asphalt (AC 5) for seal coat		gal	0.8	1759.9	1,495.9
	Dist. tank truck, 3K Gal.					
		Operator	hr	30.3	1x0.166	5.0
						205,176.8

The unit costs were then converted to costs for a one mile stretch of road. A discount rate of 8% was used in the present worth calculations.

The expected PCI curve was then shifted to get hypothetical PCI curves for mean values of the data, mean - one standard deviation, and for the worst case scenario (which was formed by joining the worst data at each year). Present worth calculations, as described above, were performed for these new curves at the minimum pavement condition level of 50. Next, for each of these four curves, similar present worth cost calculations were made at minimum pavement condition levels of 40 and 60. An on site material cost of $8/ton for gravel (30) and an on site material cost of $3.50/ton for fly ash (obtained from the Canyon construction site) were used to make comparisons. The gravel cost was added to the expected PCI present worth calculations for minimum pavement condition levels of 40, 50, and 60, and the fly ash cost was added to the expected PCI, mean PCI, mean - 1 SD PCI, and worst case scenario, present worth calculations. Tables 16 and 17 provides a summary.

Conclusions

There was no specific information available on the maintenance costs for roads using fly ash for a base. Conversations with several persons projected maintenance costs to be equivalent to gravel based roads and better than roads using caliche for a base. These observations from experienced practitioners probably are valid although they are generated from observations of alloy constructed of fly ash and roads with fly ash bases which are only a few years in age.

If one assumes long term maintenance to be equal for roads with gravel and fly ash bases, the cost advantage would go to the material that could be delivered to the construction site at the least cost. Due to the apparent variability of caliche, no cost comparisons were made for caliche.

Figure 5. Plot of Expected Pavement Condition vs. Age for a Sample Data Set, as Adapted From *(32)*.

Table 11. Pavement Condition Representation by PCI, as Adapted From *(32)*.

PCI Rating	Condition Representation
91-100	8
81-90	7
71-80	6
61-70	5
51-60	4
41-50	3
21-40	2
0-20	1

Table 12. Set of Repair Alternatives, as Adapted From *(32)*.

Repair Alternative Index, i	Type of Repair, Ri
0	Routine maintenance
1	1-in. overlay
2	2-in. overlay
3	4-in. overlay
4	6-in. overlay
5	Reconstruction

Table 13. Cost Per Square Yard of Repair Alternatives in 1995 Cost Index Dollars, as Adapted From *(32)*.

Pavement Condition State	Routine Maintenance	Overlays				Reconstruction
		1-in.	2-in.	4-in.	6-in.	
8	0.05	2.38	4.76	9.51	14.28	32.46
7	0.19	2.50	4.89	9.64	14.40	32.46
6	0.39	2.75	5.14	9.89	14.65	32.46
5	0.81	5.91	8.30	13.04	17.81	32.46
4	1.04	8.94	11.33	16.08	20.84	32.46
3	1.75	10.98	13.36	18.11	22.88	32.46
2	2.50	13.00	15.39	20.14	24.90	32.46
1	8.63	24.88	27.26	32.01	36.78	32.46

Table 14. Optimal Maintenance Action for 20-Year Horizon, as Adapted From *(32)*.

Pavement Condition State	Ri	
	Years 1-19	Year 20
8	0	0
7	0	0
6	1	0
5	2	2
4	3	3
3	3	3
2	5	5
1	5	5

Table 15. Present Worth Calculations for Maintenance and Repair.

Year	Pavement Condition State	Ri	Cost/yd^2 ($)	1995 Cost/yd^2 ($)	Cost/Mile ($)	Present Worth ($)
0						
1	8	0	0.04	0.05	879.95	814.77
2	8	0	0.04	0.05	879.95	754.42
3	7	0	0.15	0.19	3,299.82	2,619.51
4	7	0	0.15	0.19	3,299.82	2,425.47
5	7	0	0.15	0.19	3,299.82	2,245.81
6	7	0	0.15	0.19	3,299.82	2,079.45
7	6	0	0.31	0.39	6,819.64	3,979.19
8	6	0	0.31	0.39	6,819.64	3,684.44
9	6	0	0.31	0.39	6,819.64	3,411.52
10	5	0	0.65	0.81	14,299.24	6,623.32
11	5	0	0.65	0.81	14,299.24	6,132.70
12	4	0	0.83	1.04	18,259.03	7,250.91
13	4	0	0.83	1.04	18,259.03	6,713.81
14	3	3	14.49	18.11	318,763.08	108,526.41
15	8	0	0.04	0.05	879.95	277.40
16	8	0	0.04	0.05	879.95	256.85
17	7	0	0.15	0.19	3,299.82	891.84
18	7	0	0.15	0.19	3,299.82	825.78
19	7	0	0.15	0.19	3,299.82	764.61
20	7	0	0.15	0.19	3,299.82	707.97
					Total Present Worth	160,986.16

Table 16. Summary of Present Worth Calculations.

	Limit = 40	Limit = 50	Limit = 60
Expected	233,458	160,986	154,210
Mean	244,832	176,137	174,247
Mean - 1 S.D.	391,544	304,057	302,920
Worst Scenario	517,080	388,141	433,707

Table 17. Summary of Present Worth Calculations:
Total Present Worth (Materials + Maintenance + Repair Cost).

	Limit = 40		Limit = 50		Limit = 60	
Condition	Gravel	Fly Ash	Gravel	Fly Ash	Gravel	Fly Ash
Expected	311,053	256,090	238,581	183,618	231,806	176,842
Mean		267,464		198,770		196,880
Mean - 1 S.D.		414,176		326,689		325,552
Worst Scenario		539,712		410,773		456,339

SPECIFICATIONS FOR THE USE OF HYDRATED FLY ASH AS FLEXIBLE BASE

Draft specifications for using fly ash as flexible base are presented in Appendix C. The specifications describe material requirements, construction methods, maintenance, thickness measurement, measurement and payment.

CONCLUSIONS

Available information on hydrated fly ash appear to indicate that from the standpoint of strength, it has great potential to be used as a flexible base material. However, results from this research indicate that unless appropriate methods are adopted in its production, durability problems may arise. Several TxDOT districts including Amarillo and Atlanta have used hydrated fly ash as a flexible base material with mixed results.

Several aspects of hydrated fly ash including its strength characteristics and microstructure were investigated in this study. In addition, data from TxDOT sources which tested this material for suitability as a flexible base material was also available (Table A-2). Based on the available data and on limited experience with the material in flexible base construction, the following observations can be made.

1. The material is extremely strong when compared to TxDOT specification triaxial classes. It meets the TxDOT Class I base material unconfined compressive strength criterion very easily *(29)*.

2. It was observed that the material gets crushed during compaction and as a result, the master grading criteria in the TxDOT specifications may not have been strictly adhered to. However, it appeared to have had little impact on achieving maximum dry density.

3. It was observed in the field that the material undergoes further hydration after placement, thus forming a stiff, nearly homogeneous layer. Therefore, strict adherence to the gradation specification may not be needed.

4. Laboratory compaction tests using hydrated fly ash with two different gradations (gap-graded and well-graded) revealed that both gradations gave nearly the same maximum dry density values, but at different optimum moisture contents.

5. Powdered fly ash hydrated at lower moisture contents provide much higher strengths resulting in better resistance of the aggregate to degradation. Also, thorough mixing with the water should be emphasized.

6. Aggregates produced using higher hydrating moisture contents posses lower unit weight and lower strength.

7. Care must be taken during the curing process to ensure that the material attain the required level of strength before it is milled. Otherwise, the material may not pass the specifications for degradation and durability.

8. Care must be taken during the curing process and during construction to ensure that the material is not allowed to dry excessively. If allowed to dry, it will form undesirable compounds that may have an undesirable effect on the durability of the material.

9. Hydrated fly ash has a high water demand. Therefore, sufficient allowance should be made for subsequent wetting during curing and construction.

10. Shrinkage cracks may appear in the base if the fly ash has not reached an advanced stage of hydration in the curing ponds.

RECOMMENDATIONS

Hydrated fly ash has the potential to perform just as well as any other flexible base material in use today. More investigations are needed to enhance the understanding of the material, particularly with regard to its durability.

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APPENDIX A

RESULTS FROM TxDOT TESTS ON HYDRATED FLY ASH

Table A-1. Averages for Chemical and Physical Test Data for Powdered Fly Ash From Welch, Tolk and Harrington Power Plants (as of 12/29/1994).

	Welch Plant	Tolk Plant	Harrington Plant
CHEMICAL TEST DATA			
Sum of SiO_2, Al_2O_3 and Fe_2O_3 (%)	50.47	55.12	56.62
CaO (%)	29.05	27.00	26.24
SO_3 (%)	3.84	1.87	1.87
MgO (%)	5.75	5.23	4.97
Moisture Content (%)	0.00	0.00	0.00
Loss on Ignition (%)	0.59	0.24	0.48
Available Alkalies (%)	1.34	1.41	1.53
PHYSICAL TEST DATA			
Strength Activity Index (%)	104.29	105.58	109.39
Water Requirement (%)	94.92	94.52	94.77
Fineness (%)	12.88	16.90	22.16
Soundness (%)	0.013	0.024	0.025
Specific Gravity	2.7	2.65	2.66
Shrinkage (%)	0.004	0.009	-0.001

Table A-2. Properties of Hydrated Fly ash Tested by TxDOT Laboratories.

Test Parameter	Hydrated Fly Ash Source		
	Welch Plant	Harrington	Tolk Station
Unconfined Compressive Strength (kPa)	1517	1207-1517	
Dry Loose Unit Weight (g/cm^3)	1.09	1.27	
Compacted Density (g/cm^3)	1.37	1.54	1.44
Optimum Moisture Content (%)	28.6	22.0	24.4
Rodded Unit Weight (g/cm^3)	1.20		
Specific Gravity	1.873		
LA Abrasion Value	47		
Liquid Limit		40.9	42.7
Plasticity Index		3.4	0.3
Wet-Ball Mill Value (TxDOT Spec.)		23.16	
Wet-Ball Mill % Increase of -#40 Size		18.81	
Absorption (%)	29.3		
Swell at Capillary Moisture (%)	1		
Durability	No damage, No vol. change		

APPENDIX B

MICROSCOPIC IMAGES OF FLY ASH FROM SCANNING ELECTRON MICROSCOPE (SEM)

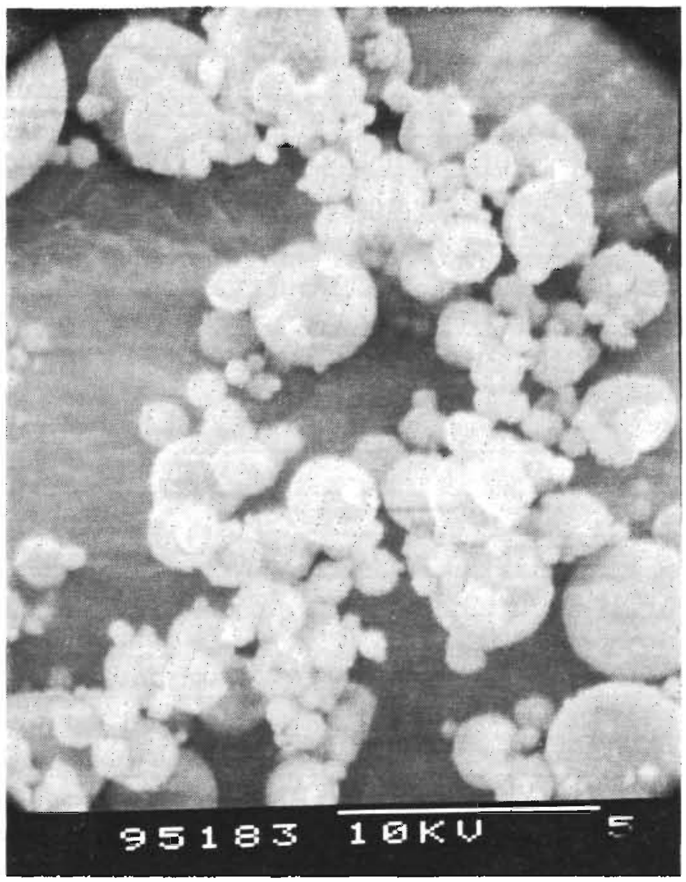

Figure B-1. Microstructure of the Powdered Fly Ash Specimen at 5000 Magnification.

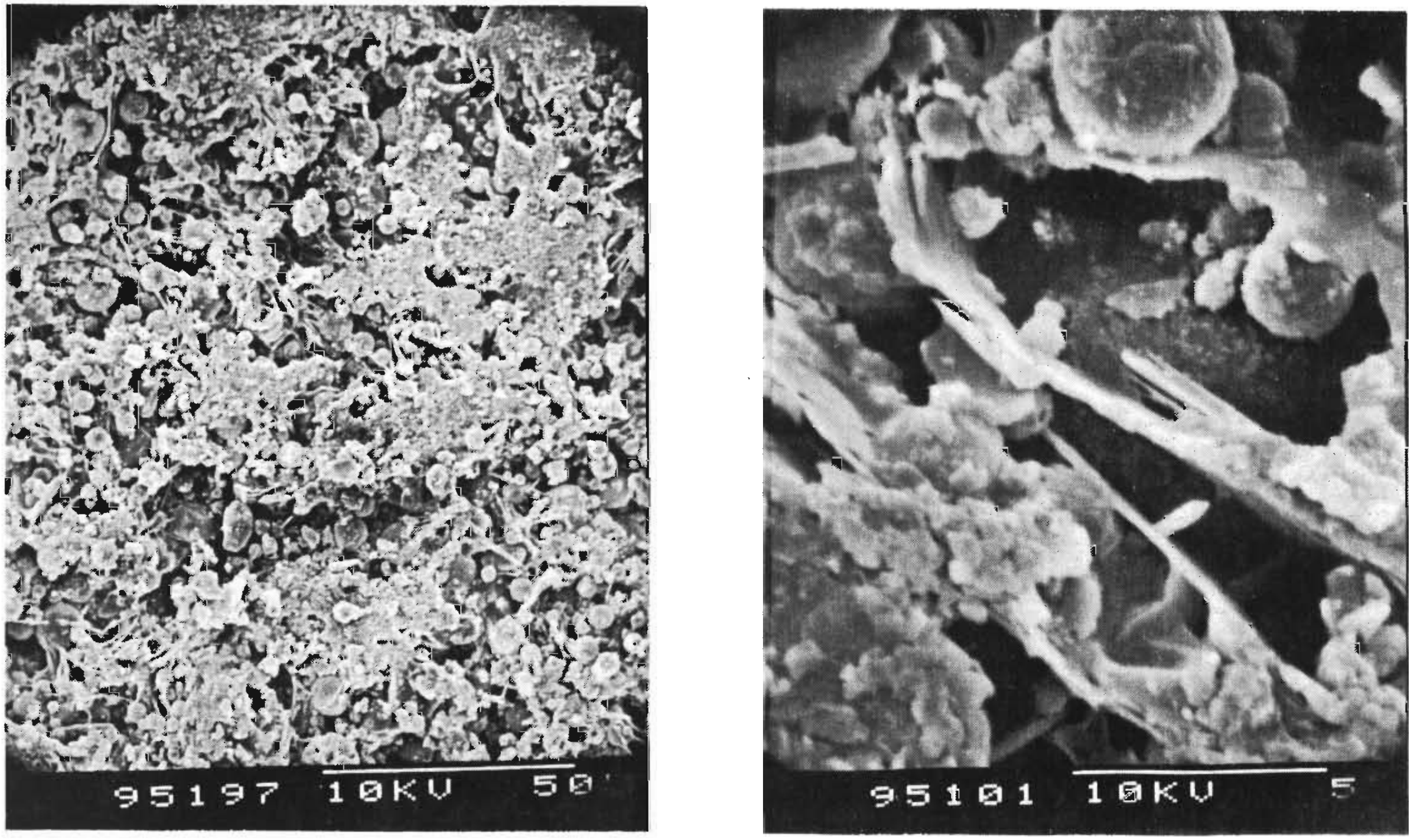

Figure B-2. Microstructure of the Top Surface of Hydrated Fly Ash Specimen With 40% Curing Moisture.

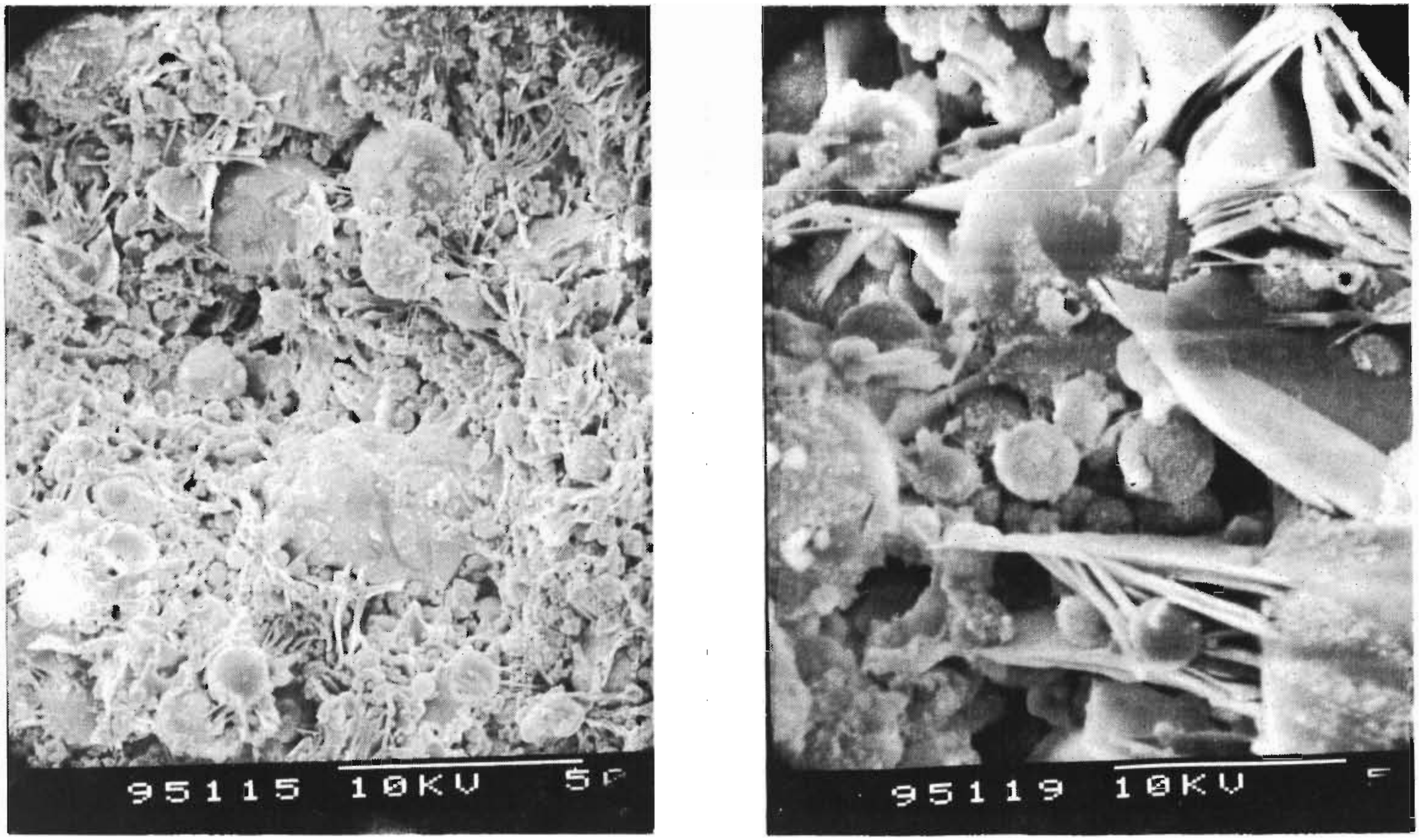

Figure B-3. Microstructure of the Gray Interior of Hydrated Fly Ash Specimen With 40% Curing Moisture.

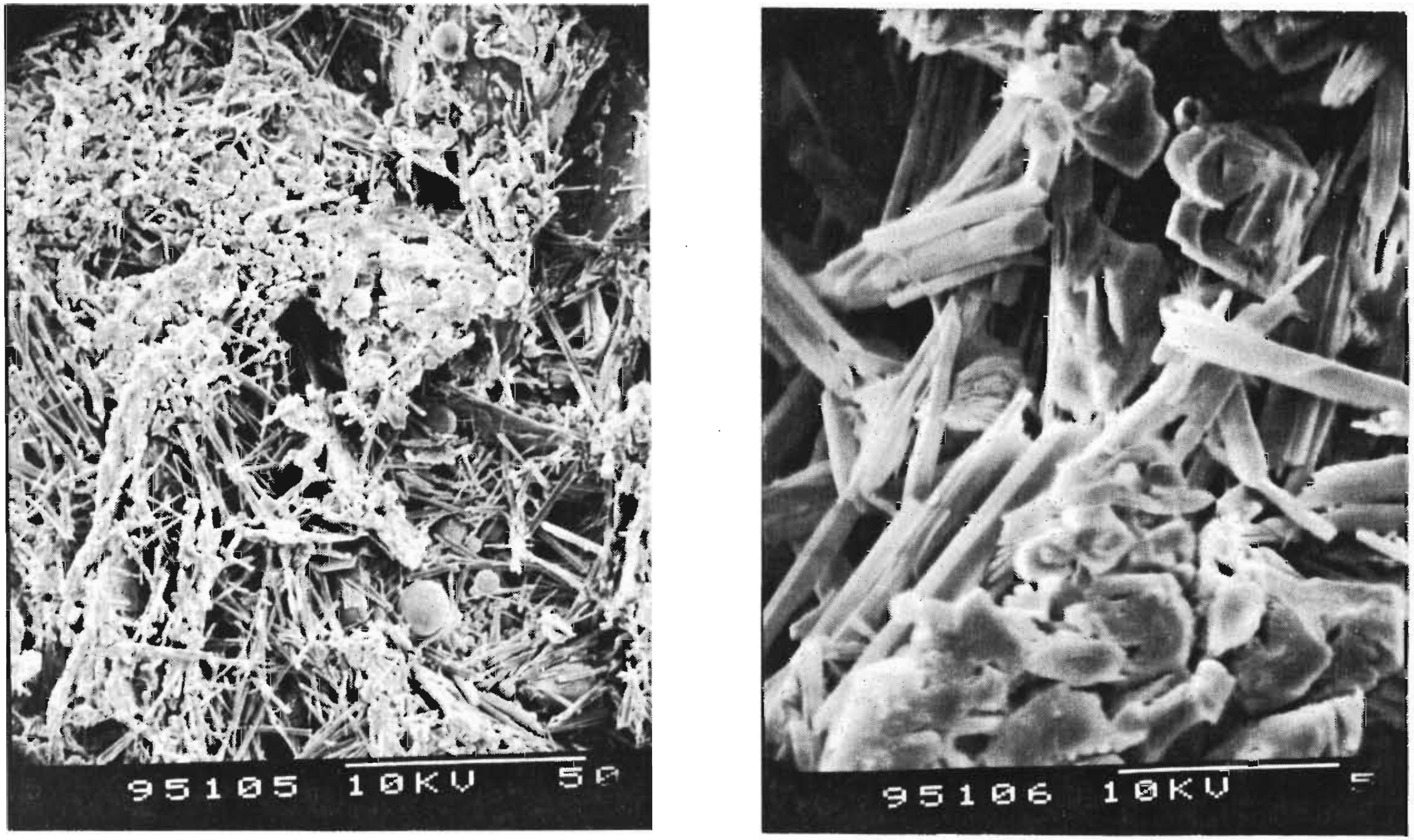

Figure B-4. Microstructure of White Deposit on Top Surface of Hydrated Fly Ash Specimen With 100% Curing Moisture.

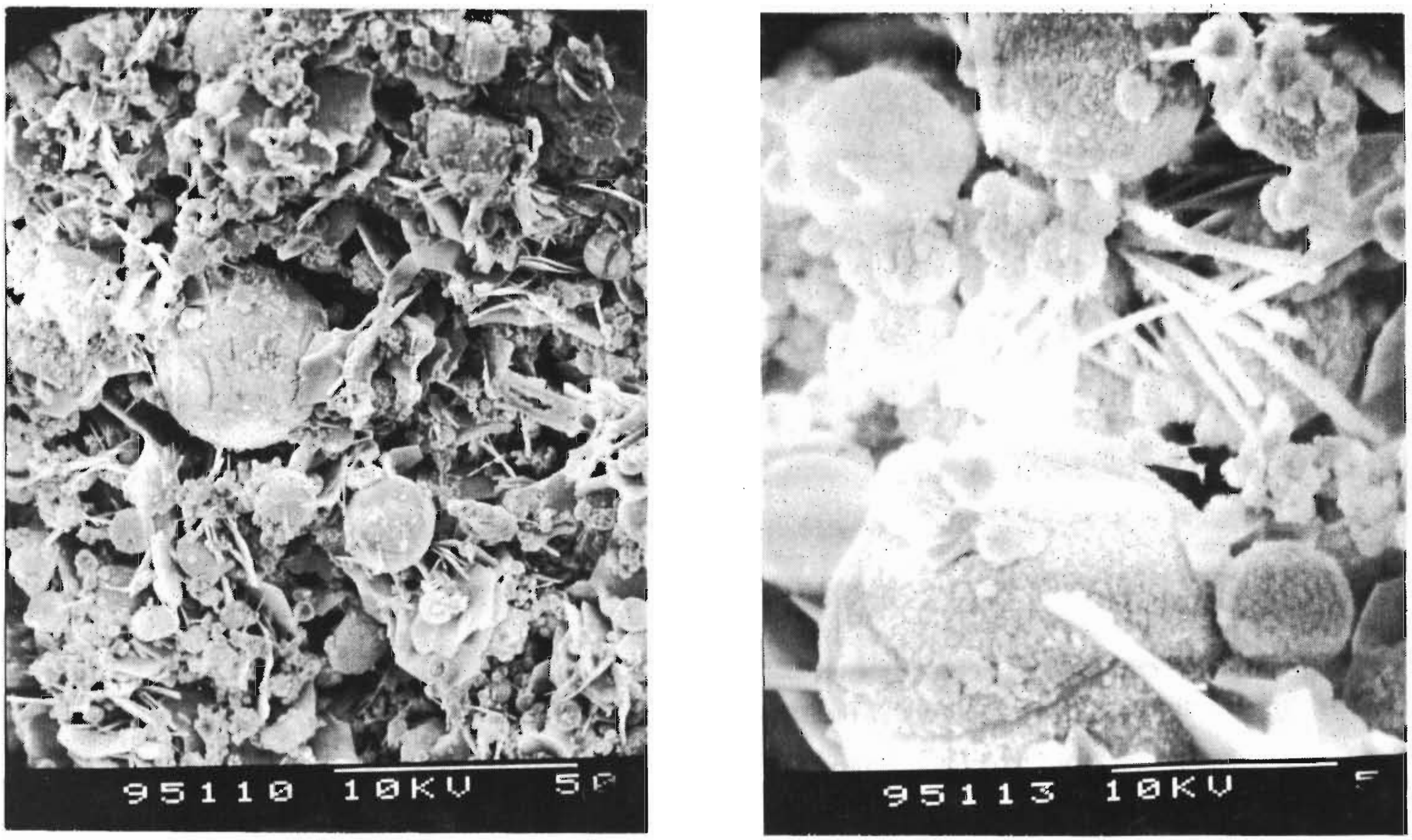

Figure B-5. Microstructure of the Gray Interior of Hydrated Fly Ash Specimen With 100% Curing Moisture.

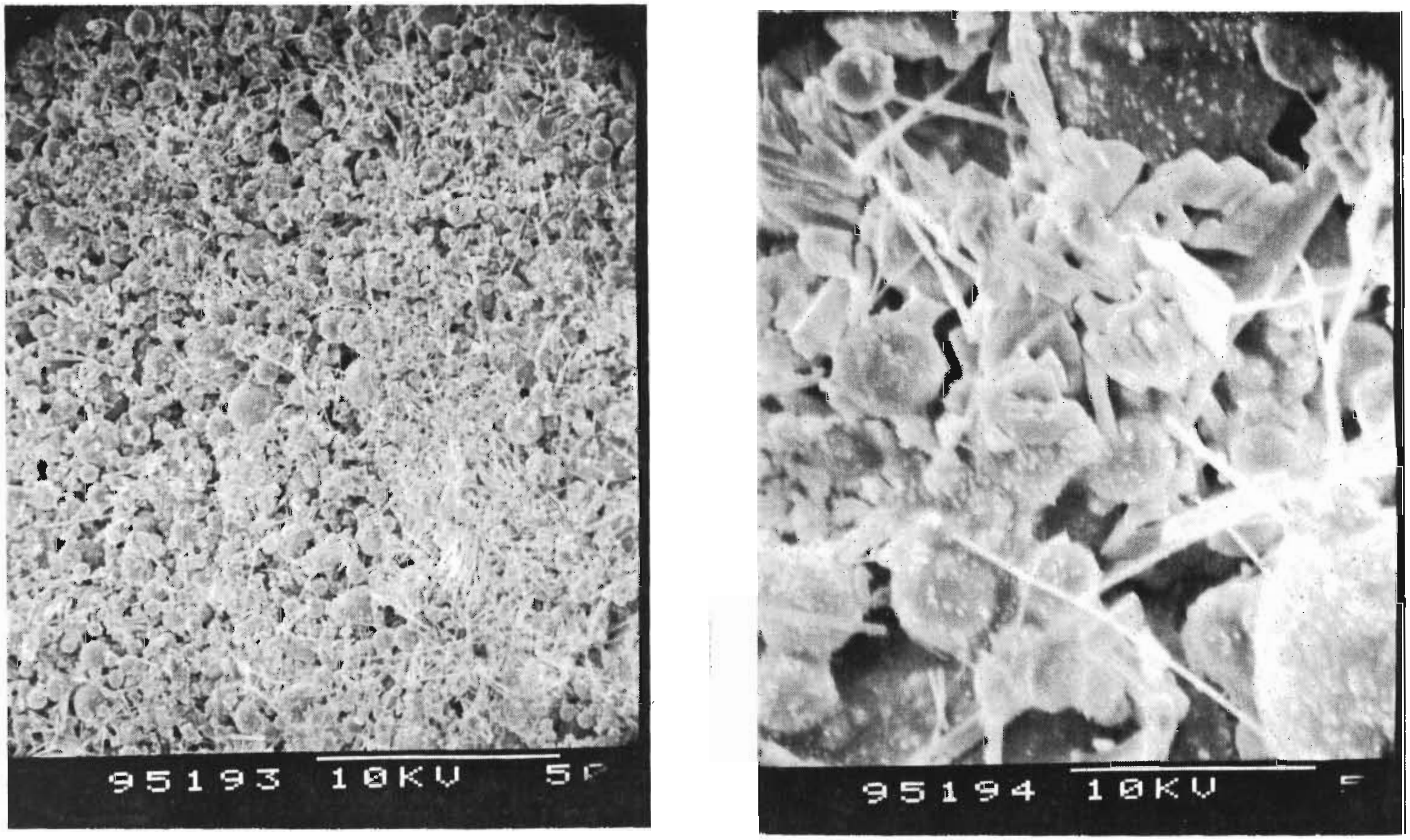

Figure B-6. Microstructure of the Gray Interior of Hydrated Fly Ash Specimen With 30% Curing Moisture.

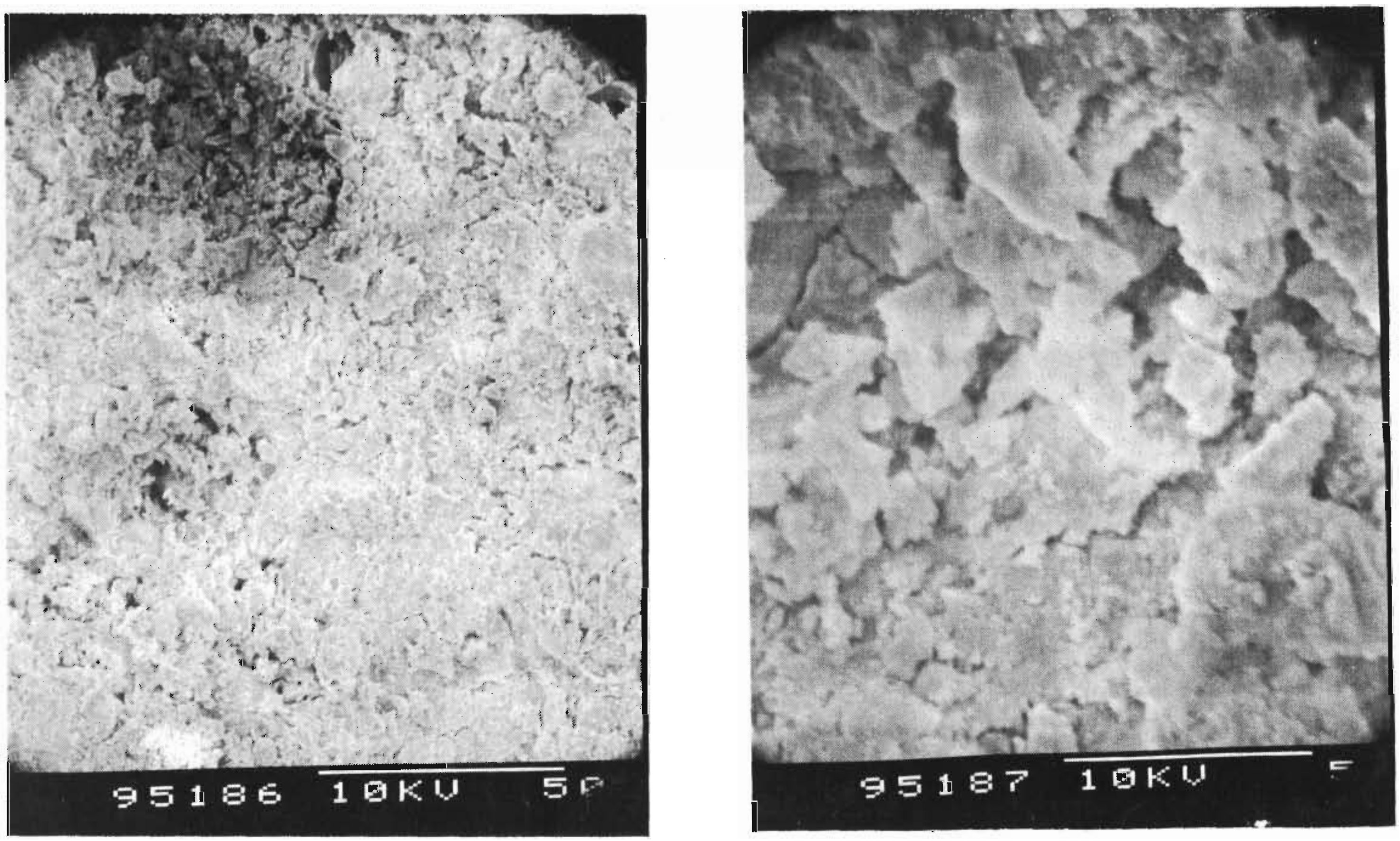

Figure B-7. Microstructure of the Brown Exterior of Hydrated Fly Ash Specimen With 30% Curing Moisture.

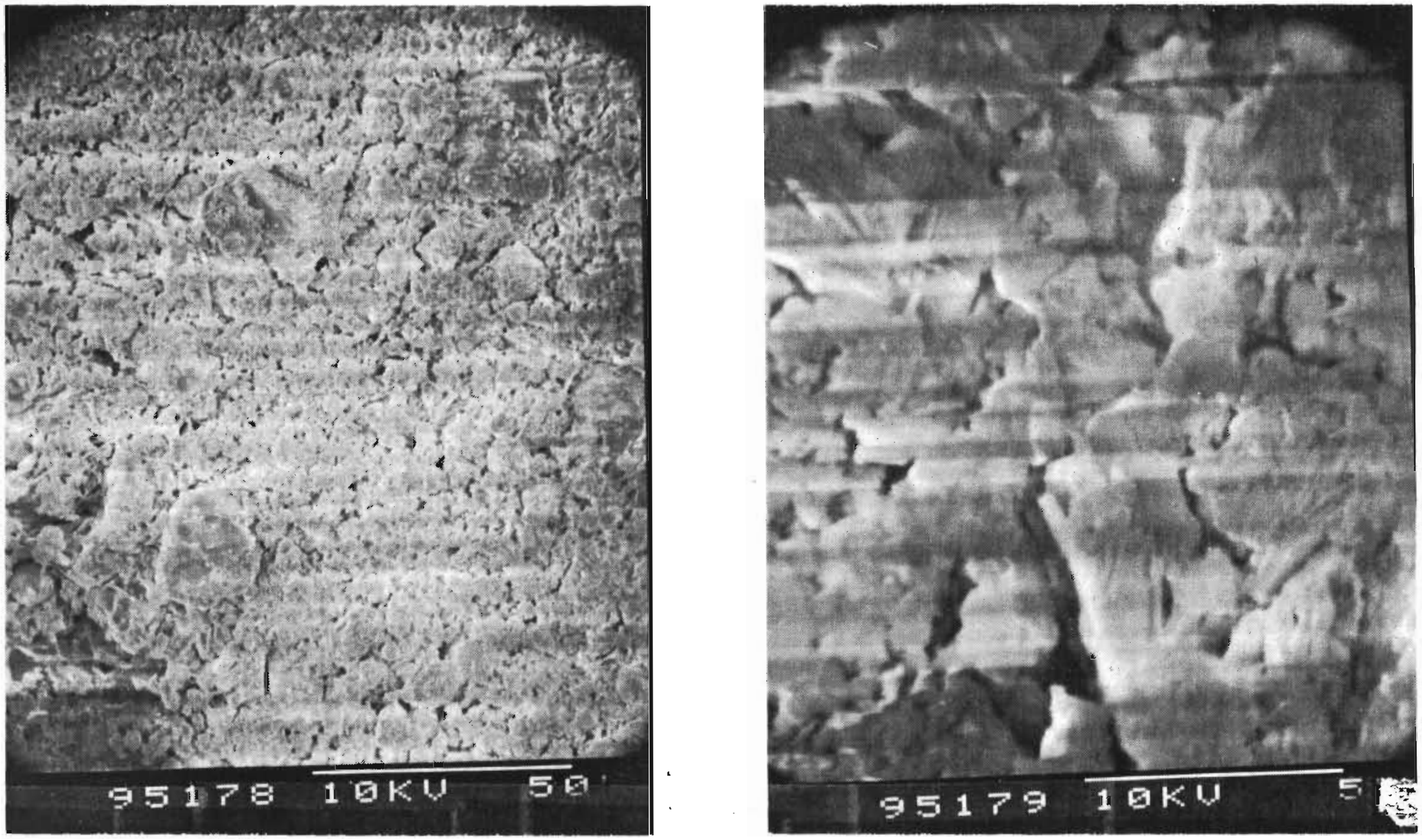

Figure B-8. Microstructure of White Deposit on Top Surface of Hydrated Fly Ash Specimen With 40% Curing Moisture.

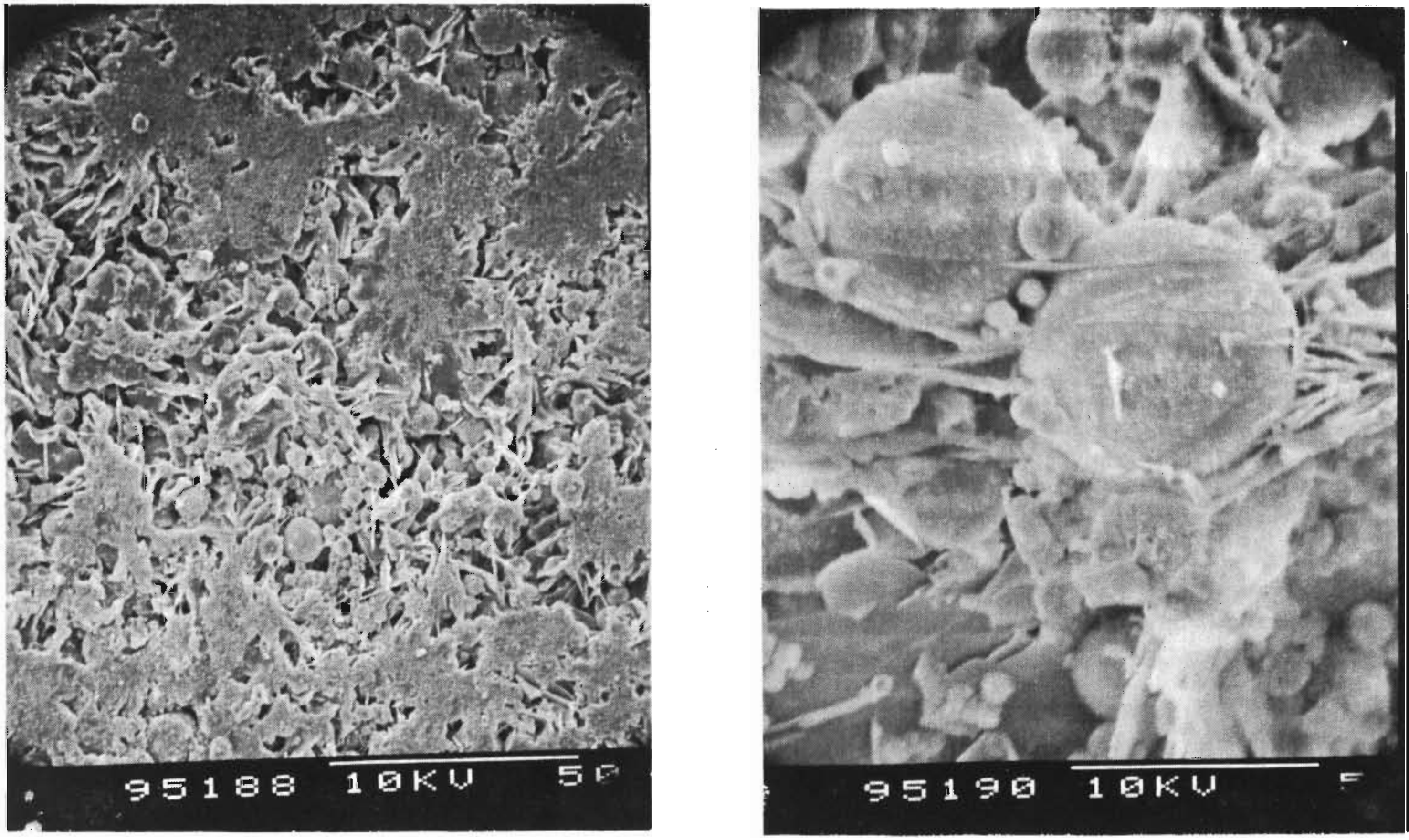

Figure B-9. Microstructure of the Gray Interior of Hydrated Fly Ash Specimen With 40% Curing Moisture.

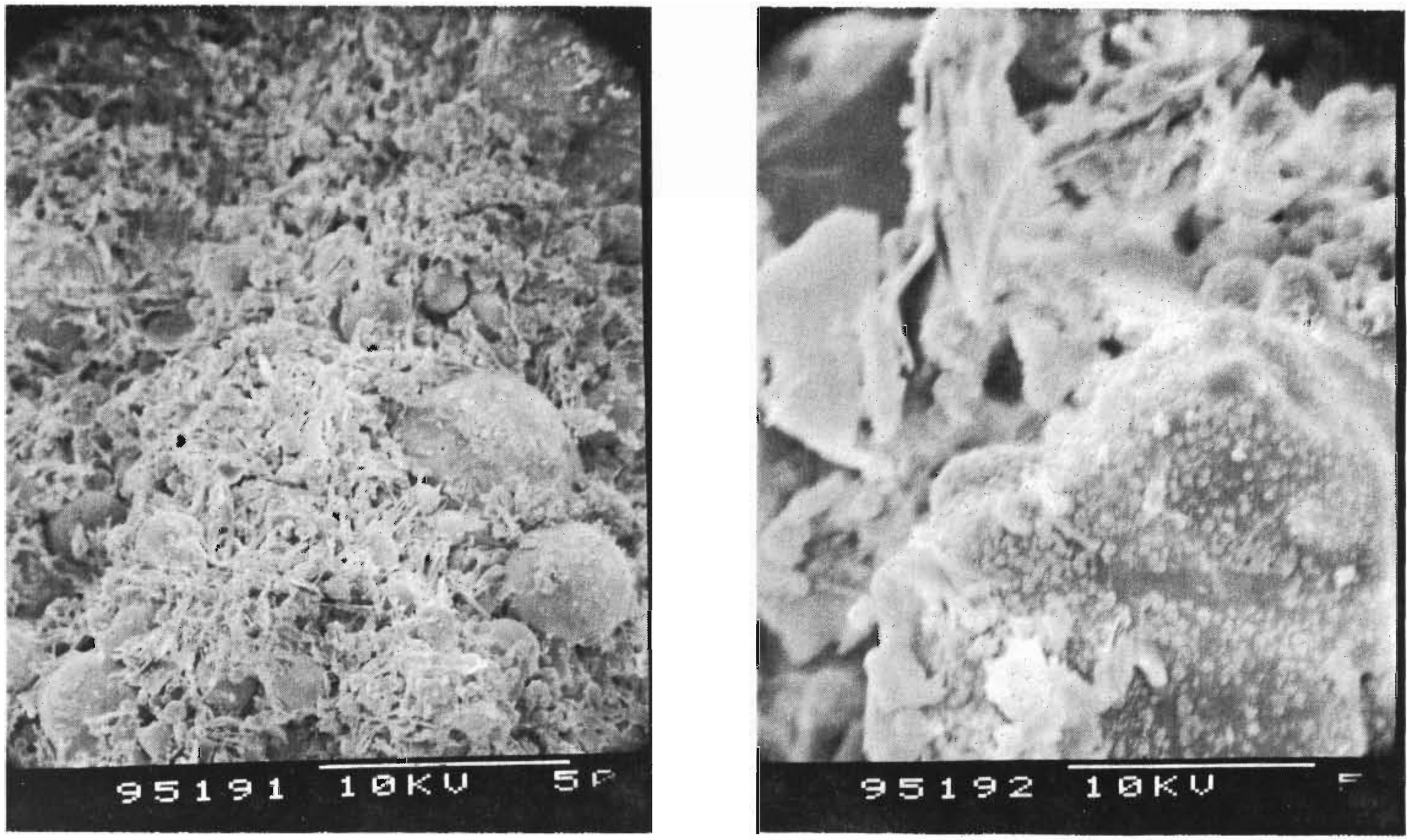

Figure B-10. Microstructure of the Brown Interior of Hydrated Fly Ash Specimen With 40% Curing Moisture.

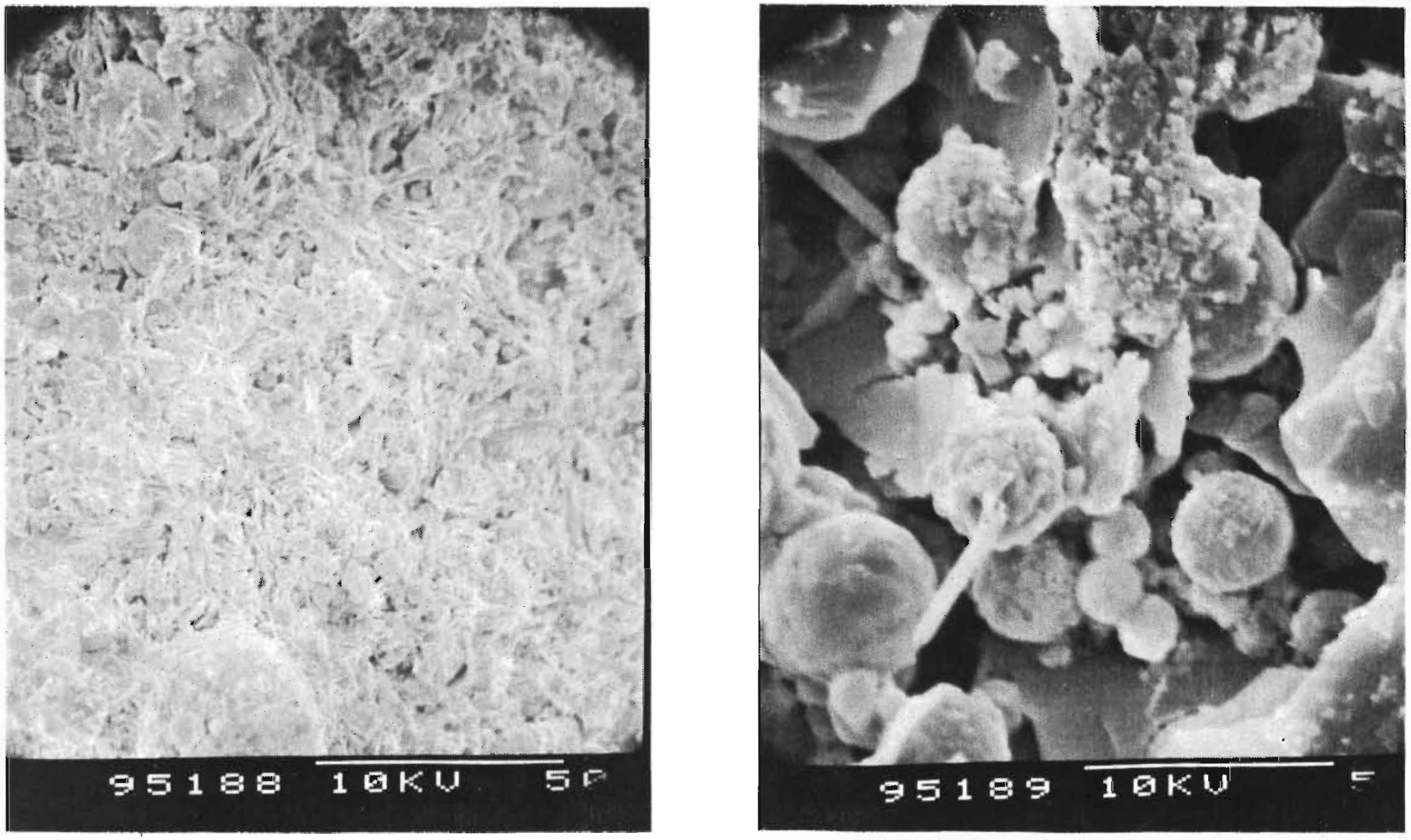

Figure B-11. Microstructure of the Top Surface of Hydrated Fly Ash Specimen With 40% Curing Moisture.

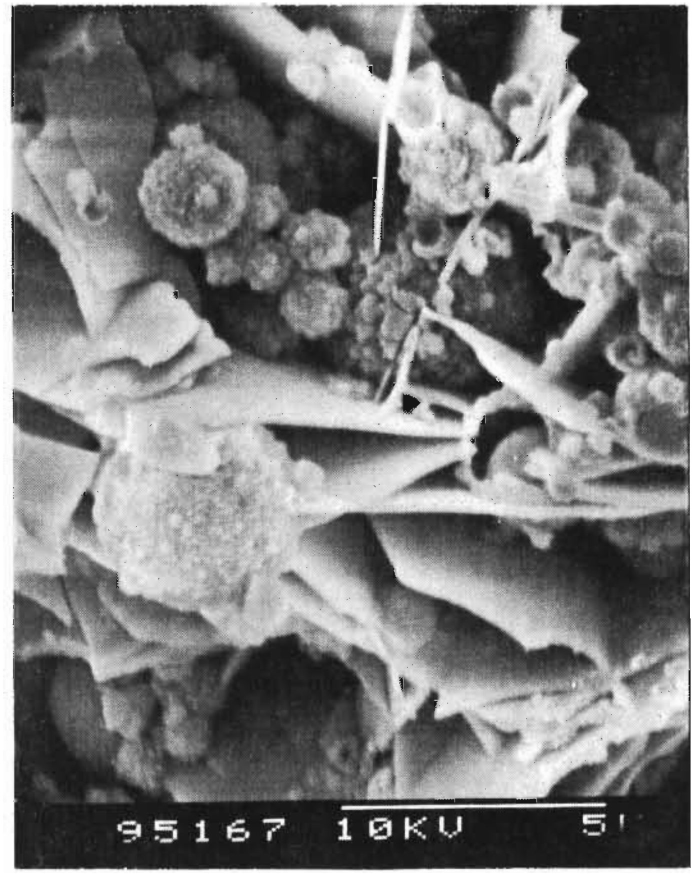

Figure B-12. Microstructure of the Gray Interior of Hydrated Fly Ash Specimen With 40% Curing Moisture.

Figure B-13. Microstructure of the Top Surface of Hydrated Fly Ash Specimen With 100% Curing Moisture.

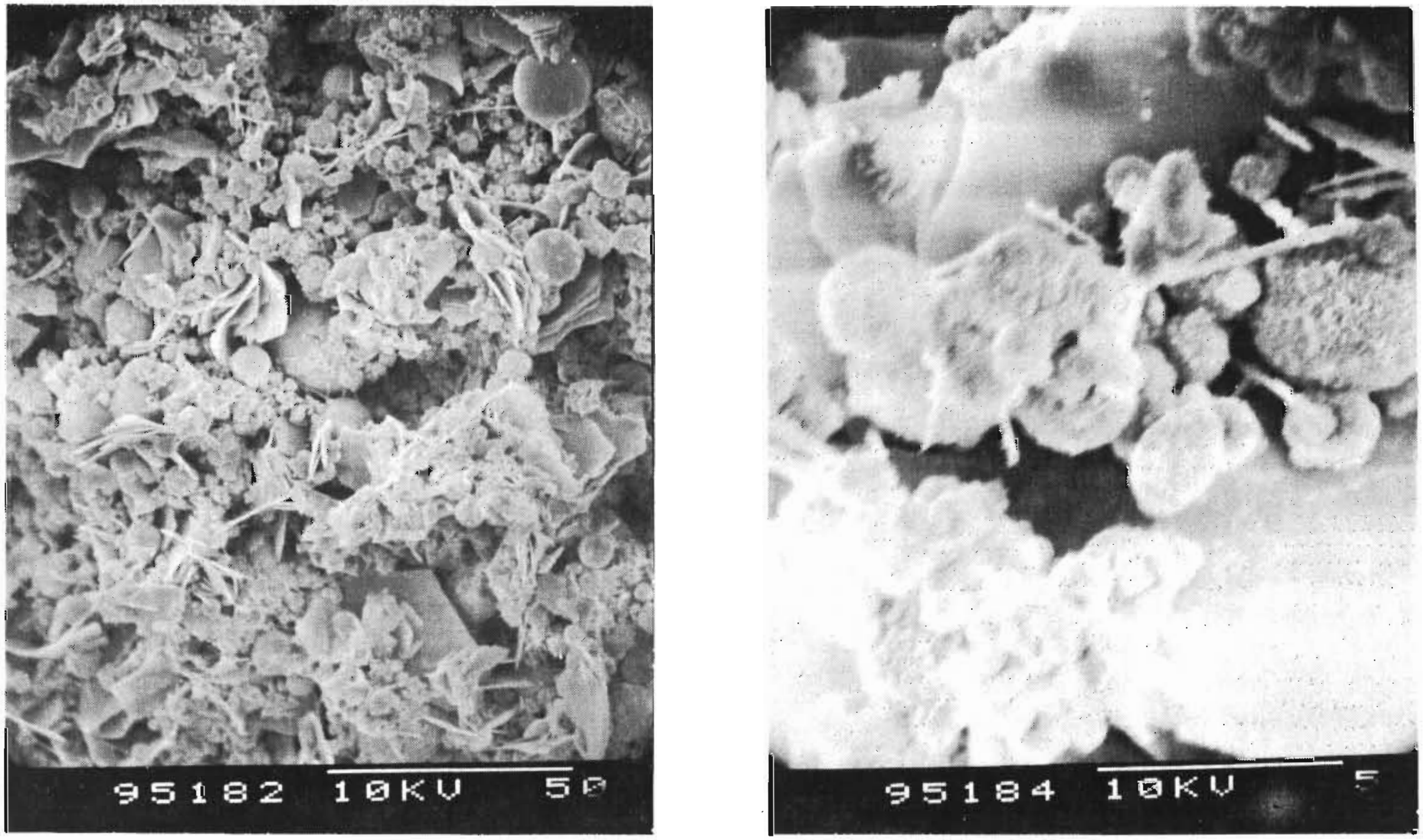

Figure B-14. Microstructure of the Gray Interior of Hydrated Fly Ash Specimen With 100% Curing Moisture.

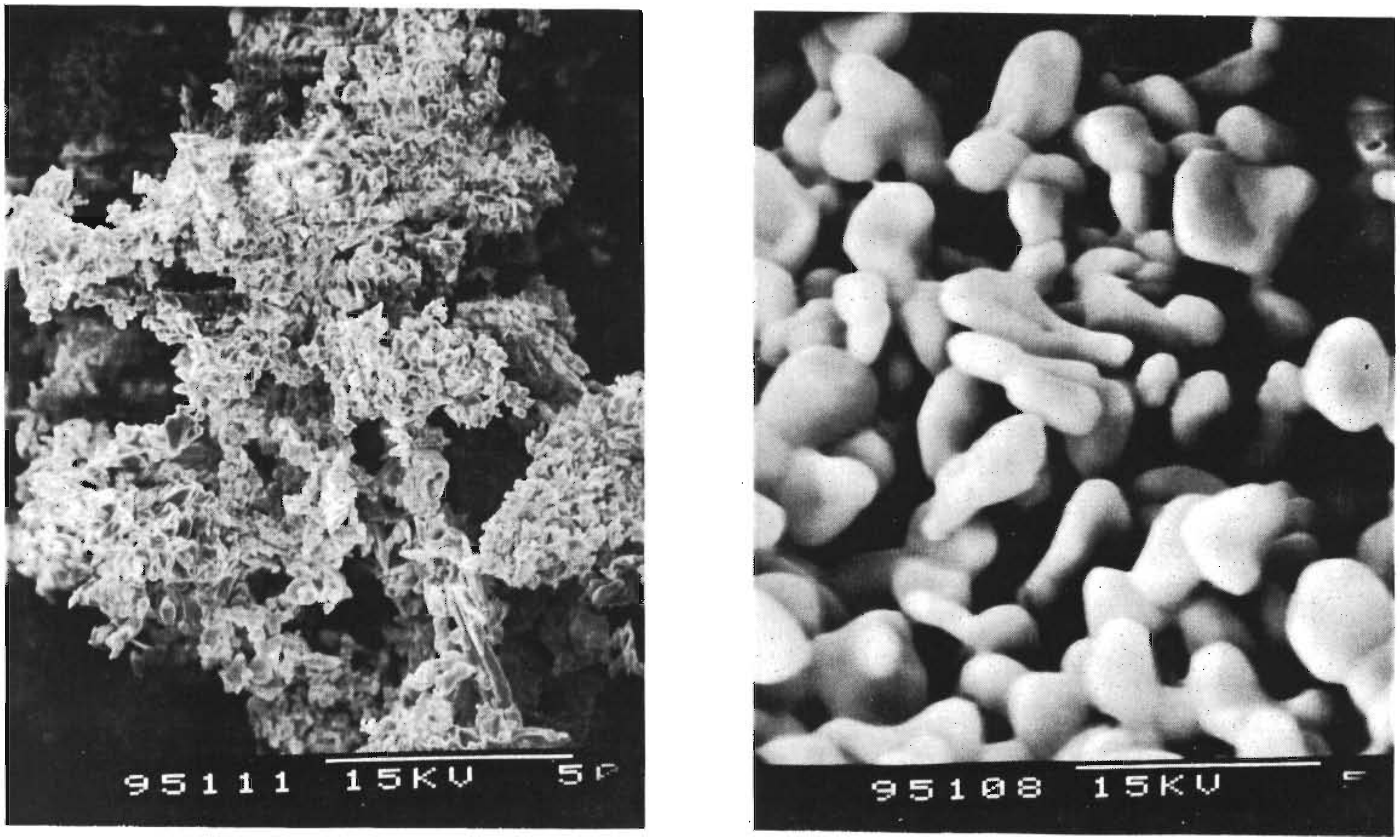

Figure B-15. Microstructure of White Growth on Surface of Hydrated Fly Ash Specimen With 100% Curing Moisture.

APPENDIX C

DRAFT SPECIFICATIONS FOR USING FLY ASH AS A FLEXIBLE BASE

Draft Specification

HYDRATED FLY ASH AS A BASE COURSE MATERIAL

2010.1. Description.

This item shall govern for the delivery, stockpiling and/or the construction including the placement, compaction, finishing and shaping of foundation or base courses as herein specified and in conformity with the typical sections and to the lines and grades shown on the plans or established by the Engineer.

2010.2. Materials.

(1) Crushed, Hydrated Fly Ash. Crushed, hydrated fly ash is an aggregate material prepared by mining, crushing and sizing of hydrated fly ash. The crushed, hydrated fly ash shall be free of injurious or hazardous products and free of organic material or other foreign matter. The contractor is responsible for furnishing the Engineer with documentation certifying that the crushed, cured fly ash complies with class 3 industrial waste requirements in accordance with 30 TAC 335.507. The source shall be approved by the Engineer prior to use.

(2) Fly Ash. Fly Ash shall meet the requirements of "Departmental Materials Specification D-9-8900, Fly Ash".

(3) Water. Water shall meet the material requirements of Item 204, "Sprinkling".

(4) Asphalt. Asphalt shall conform to the requirements of Item 300, "Asphalts, Oils and Emulsions".

(5) Physical Requirements.

(a) General. Crushed hydrated fly ash shall meet the physical requirements for the specified grade as set forth in Table 1.

Additives, such as, but not limited to, lime, cement, or fly ash, shall not be used to alter the soil constants or strengths shown in Table 1, unless otherwise shown on the plans.

Unless otherwise shown on the plans, the base material shall have a minimum bar linear shrinkage of 2 percent as determined by Test Method Tex-107-E, Part II.

Unless otherwise shown on the plans, the optimum moisture content for compaction for the crushed hydrated fly ash as determined by Test Method Tex-113-E, shall be no more than 25 percent.

Unless otherwise shown on the plans, the dry density of crushed hydrated fly ash as determined by Test Method Tex-113-E, shall not be less than 85 pounds per cubic foot.

TABLE C-1
PHYSICAL REQUIREMENTS FOR CRUSHED, HYDRATED FLY ASH

Physical Property	Parameter	Value
Strength	Triaxial Class	1.0
	Compressive Strength at 0 psi Lateral Pressure	45 psi
	Compressive Strength at 15 psi Lateral Pressure	175 psi
Master Grading	Cumulative Percent Retained on Sieve 1-3/4"	0
	Cumulative Percent Retained on Sieve 7/8"	10-35
	Cumulative Percent Retained on Sieve 3/8"	30-60
	Cumulative Percent Retained on Sieve No. 4	45-70
	Cumulative Percent Retained on Sieve No. 40	70-85
Atterberg Limits	Maximum Liquid Limit	40
	Maximum Plasticity Index	10
Wet Ball Mill Value	Maximum Value	40
	Maximum Increase in Passing No. 40	20

(6) Pilot Grading. When pilot grading is required on the plans, the flexible base shall not vary from the designated pilot grading of each sieve by more than five (5) percentage points. However, the flexible base grading shall be within the master grading limits as shown in Table 1. The pilot grading may be varied by the Engineer as necessary to insure that the base material produced will meet the physical requirements shown in Table 1.

2010.3. Construction Methods.

(1) General. It is the primary requirement of this specification to secure a completed base course of fly ash base uniformly compacted to the specified density with no loose or poorly compacted areas, and with uniform moisture content, well bound throughout its full depth and with a surface finish suitable for placing a surface course. It shall be the responsibility of the contractor to regulate the sequence of work, maintain the work, and rework the courses as necessary to meet the requirements of this specification.

(2) Preparation of Subgrade. The roadbed shall be excavated and shaped in conformity with the typical sections shown on the plans to the lines and grades established by the Engineer. All suitable or otherwise objectionable material or roots shall be removed from the subgrade and replaced with approved material. All holes, ruts and depressions shall be filled with approved material and, if required, the subgrade shall be thoroughly wetted with water and reshaped and rolled to the extent directed in order to place the subgrade in an acceptable condition to receive the base material. The surface of the subgrade shall be finished to lines and grades as established and shall be in conformity with the typical sections shown on the plans. A subgrade planer may be used. Any deviation in excess of one-half inch in cross section or one-half inch in a length of 16 feet measured longitudinally shall be corrected by loosening, adding or removing material, reshaping and re-compacting by sprinkling and rolling. Sufficient subgrade shall be prepared in advance to insure satisfactory progression of the work. Material excavated in preparation of the subgrade shall be utilized in the construction of adjacent shoulders and slopes or otherwise disposed of as directed by the Engineer. Work required for preparation of subgrade will be measured and paid for under item 110, "excavation" and item 132, "embankment" or in accordance with the provisions of other applicable bid items.

The prepared subgrade surface shall be adequately wetted to the satisfaction of the Engineer immediately prior to the placement of the base course material. This is to ensure that no excessive moisture loss occurs from the base material to the subgrade.

(3) Placing. The fly ash base shall be placed in uniform layers on the prepared moist subgrade to produce the depth specified on the plans. The materials shall be consolidated with rollers capable of compacting from the bottom up. The depth of layers shall be as approved by the Engineer. To insure homogeneous distribution of the fly ash base material in each layer, the material shall be placed using an approved spreader. The spreading operations shall be done in such a manner as to eliminate nests or pockets of material of non-uniform gradation resulting from segregation in the hauling or dumping operations and in such a manner as to eliminate planes of weakness.

The fly ash base shall not be placed when the air temperature is below 40 °F and is falling, but may be placed when the air temperature is above 35 °F, and is rising, with the temperature being taken in the shade and away from artificial heat and with further provision that fly ash base shall be mixed or placed only when weather conditions in the opinion of the Engineer are suitable for such work.

(4) Construction Joints. If a road section is not completed at the end of a construction day, a straight transverse construction joint shall be formed by cutting back into the completed work to form a vertical face.

(5) Compaction. Unless otherwise shown on the plans, the fly ash base shall be sprinkled as required and compacted to a density of not less than 97 percent of compaction ratio density, Test Method Tex-113-E and shall be checked in the field by Test Method Tex-115-E. The moisture content of the mixture during compaction operations shall be maintained within a range from optimum percentage to two (2) percentage points above or 5.0 percentage points below the optimum percentage or within the range directed by the Engineer. If the obtained density does not satisfy requirements, the contractor shall make adjustments in roller weight, lift thickness or material moisture level or replace the material in question. The material shall not be compacted until the necessary shape and thickness has been achieved by grading. When additional lifts are necessary, the existing layer shall be lightly sprinkled prior to placing the additional courses. Additional lift(s) shall be mixed with previous lifts to ensure the base is homogeneous.

(6) Finishing. After the final course of the fly ash base, except the top mulch, is compacted, the surface shall be finished to grade and section by blading and shall be sealed with approved pneumatic tire rollers. When directed by the Engineer, surface finishing methods may be varied from this procedure provided a dense uniform surface is produced and further provided that the construction of compaction planes is avoided.

Unless otherwise shown on plans,

(a) not more than two (2) hours shall elapse between the start of mixing and the time of starting the compaction of the fly ash base on the prepared subgrade.

(b) any mixture of aggregate, fly ash and water that has not been compacted shall not be left undisturbed for more than 90 minutes.

(c) all finishing operations shall be completed within a period of eight (8) hours after fly ash is added to the aggregate and water.

(7) Curing. Immediately after the fly ash base has been brought to line and grade, an asphaltic membrane shall be placed on the fly ash base to prevent evaporation of water and provide curing. The asphalt used for curing shall be of the type and grade shown on the plans or as approved by the Engineer and shall be applied at the rate of approximately 0.1 gallon per square yard unless the plans require otherwise.

If there is a time delay prior to application of the asphalt membrane which is sufficient to cause surface drying, the Engineer may require the surface to be moistened.

If some drying has taken place at the surface prior to the placement of the curing membrane, the contractor shall scrape off any compounds that may have been formed on the surface due to drying to the satisfaction of the Engineer.

(8) Traffic. The fly ash base shall be opened to traffic as specified on the plans or as directed by the Engineer.

2010.4. Maintenance

The contractor will be required within the limits of his contract to maintain the fly ash base in good condition until all work has been completed and accepted. Maintenance shall include immediate repair of any defects that may occur. This work shall be done by the contractor at his entire expense and shall be repeated as often as may be necessary to keep the area continuously intact. Repairs to fly ash base shall be effected by replacing the fly ash base for its full depth rather than by adding a thin layer of fly ash base to the layer of base in need of repair.

2010.5. Thickness Measurement

The fly ash base will be measured for depth in units of 4000 square yards, or fraction thereof. The measurements will be at location(s) determined by the Engineer and performed in accordance with the Test Method Tex-140-E. In any unit where fly ash base is deficient by more than 1/2 inch in thickness, the deficiency shall be corrected by scarifying, adding material as required, reshaping, re-compacting and refinishing at the contractor's expense.

2010.6. Measurement

This item will be measured by the square yard of surface area in the completed and accepted position.

2010.7. Payment

The work performed and materials furnished in accordance with this item and measured as provided under "measurement" will be paid for at the unit price bid for "fly ash base (density control)" of the depth specified.

This price shall be full compensation for securing and furnishing all materials; including all royalty, freight and storage involved; for all processing, crushing and loading; for all hauling, delivering, stockpiling, placing, spreading, blading, mixing, stripping, dragging, finishing, curing and maintaining; for all fine grading; for wetting and compacting and all manipulation, labor, tools and incidentals necessary to complete the work.