

**GEOTECHNICAL CHARACTERIZATION, STRENGTH AND FLEXURAL
BEHAVIOR OF FLY ASHES STABILIZED WITH CEMENT AND
RANDOMLY ORIENTED DISCRETE FIBERS**

by

GAYATHRI V.

DEPARTMENT OF CIVIL ENGINEERING

*Submitted
in fulfilment of the requirements
of the degree of*

DOCTOR OF PHILOSOPHY

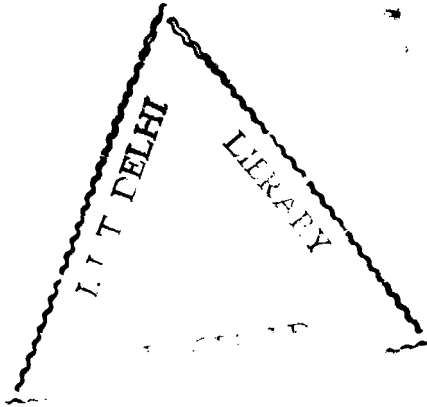
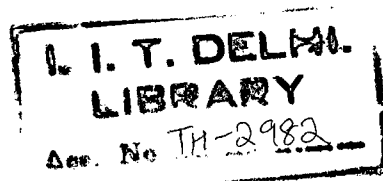
to the



INDIAN INSTITUTE OF TECHNOLOGY, DELHI

AUGUST, 2003

Gestechnural engineering
fly ash.



TH
624.13:662.613
GAY-G

TO
MY PARENTS AND TEACHERS

CERTIFICATE

This is to certify that the thesis entitled “GEOTECHNICAL CHARACTERIZATION, STRENGTH AND FLEXURAL BEHAVIOR OF FLY ASHES STABILIZED WITH CEMENT AND RANDOMLY ORIENTED DISCRETE FIBERS” being submitted by GAYATHRI V. Indian Institute of Technology, New Delhi, for the award of the degree of the DOCTOR OF PHILOSOPHY is a record of the bonafied research work carried out by her. Ms. Gayathri V. has worked under my supervision; she has fulfilled the requirements for the submission of this thesis, which to my knowledge has reached the requisite standard. This thesis, or any part thereof, has not been submitted to any university or institute for the award of any degree or diploma.



Prof. S. R. KANIRAJ

Department of Civil Engineering
Indian Institute of Technology
Hauz Khas, New Delhi
INDIA- 110 016.

ACKNOWLEDGEMENT

I wish to express sincere thanks and deep sense of gratitude to my supervisor Prof. S. R. Kaniraj for his valuable guidance, constant encouragement and inspiration during the phase of this research work. I am grateful for his co-operation, kind help and untiring enthusiasm extended throughout the study. The help and moral support rendered by Dr. K.K. Gupta and Dr. G. V. Ramana of Geotechnical group and Dr. Bhuvaneswari, Electrical Engineering Department is gratefully acknowledged.

I have the great pleasure in expressing sincere thanks to my fellow research scholars and friends particularly Dr. Vasant Havanagi, Dr. Santosh Rao, Dr. Rakesh, Dr. Amit Agrawal, Mrs. Sheela, Mrs. Chitra and Mr. R. P. Tiwari for their assistance and help throughout this work. The assistance rendered by the staff of Soil and Rock Mechanics Laboratory and Civil Engineering workshop is gratefully acknowledged. Special mention to D. C. Sharma, Scanning Electron Microscopy laboratory, Dr. A. Ramanan, Ms. Minakshi Asnani of Chemistry Department, Mr. R. Krishnamurthy, Deputy General Manager, Ash Utilization Division, National Thermal Power Corporation Limited, New Delhi, India. I would like to thank all those who have helped directly or indirectly during the entire research program.

I would like to record my deep sense of gratitude to my parents, without whose blessings and encouragement the thesis would not have seen the daylight.


(Gayathri V.)

ABSTRACT

The quantity of fly ash produced worldwide is huge and keeps increasing every year. In India alone about 100 million tons of fly ash is being produced annually. There is a large gap between the rate of production and utilization of fly ash. The current rate of utilization of fly ash in India is around 23% as against, 3-4% during early 1990's. The utilization of fly ash in other major fly ash producing countries is also rather small. There is a great need to improve the scope of utilization of fly ash to minimize the problems associated with the vast accumulation of the material. With a view to improve the utilization of fly ash in India, the Government of India commissioned Fly Ash Mission (FAM), in 1994. Fly Ash Mission has identified ten different thrust areas to promote the utilization of fly ash. Of these, "Roads and embankments" and "Ash ponds and dams" are the major areas of geotechnical applications. The need of the present study arises from the requirement to improve the overall utilization of fly ash and in particular in applications related to geotechnical engineering. The scope of the present study is related to utilization of fly ash in geotechnical applications such as construction of embankments, fills and pavements where fly ash can be utilized in bulk quantities. Experiments were conducted on two Indian fly ashes, from Dadri and Rajghat thermal power plants.

The scope of work includes the study of following topics: (a) Physical properties and chemical composition; mineralogy and morphology; and geotechnical properties of the fly ashes; (b) Unconfined compressive strength (UCS) of cement-stabilized fly ashes and the influence of curing methods including controlled and ambient conditions of curing on the strength; (c) Geotechnical behavior of fly ashes mixed with randomly oriented polymeric fibers; (d) Behavior of fly ash-cement-fiber specimens under compressive and flexural loading; and (e) Mineralogical and morphological studies of fly ash-cement and fly ash-cement-fiber specimens.

In the first part of the study, experiments were carried out to characterize the Dadri fly ash. The physical properties such as specific gravity, specific surface area, and loss on ignition and the chemical compositions were determined. X-ray diffraction analysis and scanning electron microscopic studies were carried out to determine the mineralogy and morphology. Geotechnical characterization was carried out to understand the engineering behavior. The tests included grain size distribution, Atterberg limit tests, compaction tests, unconfined compression tests, direct shear tests, triaxial shear tests unconsolidated undrained (UU) and consolidated drained (CD), consolidation and permeability tests. The characteristics of the Dadri and Rajghat fly ashes are presented in Chapter 3.

Fly ash is rich in oxides and is pozzolanic in nature. The engineering behavior of fly ash can be improved by addition of suitable chemical stabilizers. The primary objective of the second part of the study is to evaluate the strength characteristics of the cement-stabilized Rajghat and Dadri fly ashes as pavement base course material and the influence of factors such as cement content, method of curing, and curing period, on the Unconfined compressive strength. The design mixes of cement-stabilized Rajghat and Dadri fly ashes were determined to comply with the strength criteria prescribed by Electric Power Research Institute (EPRI). Cement content varying from 4% to 18% and 4% to 15% were added to Rajghat and Dadri fly ashes respectively. The specimens were cured for different periods from 7 days to 3 years. Six different methods of curing, including controlled and ambient conditions, that simulated different field conditions were adopted. To evaluate the impact of seasonal curing on the UCS, specimens were cured during summer, monsoon and winter seasons also. Many times, the unit weight and water content of the compacted base courses in the field may slightly differ from the MDD and OMC of the material. Therefore, experiments were also conducted to study the effect of water content (optimum moisture content OMC, dry-of-OMC, wet-of-OMC) and dry unit weight (maximum dry density MDD, and 95% MDD) on the UCS of the

cement-stabilized Rajghat fly ash specimens. X-ray diffraction and scanning electron microscopic studies were also performed to understand the micro structural changes and the reaction products formed due to cement stabilization. The results of the investigations on the cement-stabilized fly ashes are reported in Chapter 4.

Recent studies show that discrete fiber inclusion improves the geotechnical behavior of soils. Investigations on fly ash-fiber mixtures are relatively scarce. The third part of the experimental study was therefore carried out to investigate the influence of randomly oriented fiber inclusions on the geotechnical behavior of Dadri and Rajghat fly ashes. The geotechnical behavior of the raw fly ashes and fly ash-fiber mixtures have been compared. The deviator stress-axial strain behaviors in the UU and CD tests were represented by hyperbolic model and the different hyperbolic model parameters were determined. The results of the study are presented in Chapter 5.

No experimental study wherein fly ash-fiber specimens have been stabilized with high cement content that satisfies the strength requirements of pavement base courses is reported in literature. Therefore in the final part of the present study, experiments were carried out on Dadri and Rajghat fly ashes to investigate their compressive strength and flexural behaviors as cement-stabilized and fiber-reinforced base course materials. Dadri and Rajghat fly ashes were mixed, respectively with 15% and 18% cement content by dry weight. This stabilizer content was chosen to comply with the EPRI strength criteria. Polyester fibers, 6 mm and 20 mm long, and polypropylene fibers, 9 mm long, were used at 1% by dry weight of fly ash-cement mixture. The specimens were cured for different periods up to a maximum of 90 days. Unconfined compression tests and flexure tests were conducted on the cured specimens. A steel mold and accessories, required for the preparation of the flexure test specimens, were designed and fabricated. Flexure tests were carried out on fly ash-cement and fly ash cement-fiber beams. Portions of specimens were also scanned selectively to study the micro structural

development. The results of the study on fly ash-cement-fiber specimens are presented in Chapter 6.

The conclusions of the various experimental studies are summarized at the end in Chapter 7.

CONTENTS

	Page No.
CERTIFICATE	I
ACKNOWLEDGEMENT	II
ABSTRACT	III
CONTENTS	VII
LIST OF FIGURES	XV
LIST OF TABLES	XXV
LIST OF NOTATION	XXVII

CHAPTER 1 INTRODUCTION

1.1	GENERAL	1
1.2	PRODUCTION AND COLLECTION OF FLY ASH	1
1.3	METHODS OF DISPOSAL	4
1.4	UTILIZATION OF FLY ASH	4
1.5	NEED OF THE STUDY	6
1.6	SCOPE OF WORK	7
1.6.1	Geotechnical characterization of fly ash	8
1.6.2	Strength and morphological studies of cement-stabilized fly ashes	8
1.6.3	Geotechnical behavior of randomly oriented fiber reinforced fly ashes	10
1.6.4	Behavior of fly ash-cement-fiber specimens under compressive and flexural loading	10
1.7	ORGANIZATION OF THESIS	11

CHAPTER 2 GENERAL LITERATURE REVIEW

2.1	INTRODUCTION	15
2.2	GENERAL	15
2.3	PRODUCTION AND DISPOSAL OF FLY ASH IN DADRI THERMAL POWER PLANT	16
2.4	CHARACTERISTICS OF FLY ASH	21
2.4.1	Physical properties of fly ash	21
2.4.2	Chemical compositions of fly ash	22
2.4.3	Mineralogy of fly ash	23
2.4.4	Morphology of fly ash	23
2.4.5	Geotechnical characteristics of fly ashes	27
2.5	ENVIRONMENTAL CONSIDERATION	35
2.6	FLY ASH AS FILL/STRUCTURAL/EMBANKMENT FILL	37
2.7	CONCLUSIONS FROM LITERATURE REVIEW	41

CHAPTER 3 GEOTECHNICAL CHARACTERIZATION OF FLY ASH

3.1	INTRODUCTION	42
3.2	MATERIALS	42
3.3	EXPERIMENTAL PROGRAM	43
3.3.1	Physical properties	43
3.3.2	Chemical composition	43
3.3.3	Determination of pH	43
3.3.4	Mineralogy	46
3.3.5	Morphology	46
3.3.6	Geotechnical characterization	46

3.4	PHYSICAL PROPERTIES	46
3.4.1	Test procedure	46
3.4.2	Results	46
3.5	CHEMICAL COMPOSITION	47
3.5.1	Test procedure	47
3.5.2	Results	47
3.6	DETERMINATION OF pH	49
3.6.1	Test procedure	49
3.6.2	Results	49
3.7	X-RAY DIFFRACTION (XRD) STUDIES	49
3.7.1	Test procedure	49
3.7.2	Results	50
3.8	SCANNING ELECTRON MICROSCOPIC (SEM) STUDIES	53
3.8.1	Test procedure	53
3.8.2	Results	53
3.9	GEOTECHNICAL CHARACTERIZATION TESTS	56
3.9.1	Test procedure	56
3.9.1.1	Grain size distribution	56
3.9.1.2	Atterberg limit test	56
3.9.1.3	Compaction characteristics	56
3.9.1.4	Unconfined compression tests	57
3.9.1.5	Direct shear tests	58
3.9.1.6	Unconsolidated undrained tests	58
3.9.1.7	Consolidated drained tests	58
3.9.1.8	Consolidation and permeability tests	59

3.9.2	Results	63
3.9.2.1	Grain size distribution	63
3.9.2.2	Atterberg limit test	63
3.9.2.3	Compaction characteristics	65
3.9.2.4	Unconfined compression tests	68
3.9.2.5	Direct shear tests	68
3.9.2.6	Unconsolidated undrained triaxial shear tests	72
3.9.2.7	Drained triaxial shear tests	75
3.9.2.8	Permeability test	80
3.9.2.9	Consolidation test	87
3.10	SUMMARY OF RESULTS	94
3.11	CONCLUSIONS	96

CHAPTER 4 STRENGTH AND MORPHOLOGICAL STUDIES OF CEMENT

STABILIZED FLY ASHES

4.1	INTRODUCTION	99
4.2	LITERATURE REVIEW	100
4.2.1	General	100
4.2.2	Mechanism of chemical stabilization of fly ash	100
4.2.3	Effect of temperature on strength of stabilized fly ash	105
4.2.4	Unconfined compressive strength of stabilized fly ashes	106
4.2.5	Scanning electron microscopic studies	111
4.2.6	Use of fly ash in road applications	116
4.2.7	Conclusions from literature review	119
4.3	SCOPE AND OBJECTIVES OF THE STUDY	120

4.4	STABILIZED FLY ASH BASE COURSES	121
4.5	MATERIALS	123
4.6	EXPERIMENTAL PROGRAM	123
4.6.1	Notation	123
4.6.2	Overview of experimental program	123
4.7	UNCONFINED COMPRESSION TESTS	124
4.7.1	Specimen preparation	125
4.7.2	Method of curing	128
4.7.3	Method of testing	132
4.8	DETERMINATION OF DESIGN MIXES	134
4.8.1	Relationship to calculate water content	138
4.9	X-RAY DIFFRACTION STUDIES ON STABILIZED FLY ASH SPECIMENS	141
4.9.1	Specimen preparation and testing	141
4.10	SCANNING ELECTRON MICROSCOPIC STUDIES ON STABILIZED FLY ASH SPECIMENS	142
4.11	RESULTS AND DISCUSSIONS	143
4.12	UNCONFINED COMPRESSIVE STRENGTH OF STABILIZED FLY ASHES	143
4.12.1	Effect of cement content, curing period and immersion of the specimens	144
4.12.2	Effect of unit weight and water content	152
4.12.3	Effect of the methods of curing	156
4.12.4	Effect of the methods of curing adopted during the climatic seasons	160
4.13	X-RAY DIFFRACTION STUDIES OF STABILIZED FLY ASH	174
4.14	SCANNING ELECTRON MICROSCOPIC STUDIES OF STABILIZED FLY ASHES	182
4.14.1	Effect of cement content, curing period and curing method	182

4.14.2	Effect of curing time	183
4.14.3	Effect of curing method	183
4.15	CONCLUSIONS	200

CHAPTER 5 GEOTECHNICAL BEHAVIOR OF RANDOMLY ORIENTED FIBER REINFORCED FLY ASHES

5.1	INTRODUCTION	203
5.2	LITERATURE REVIEW	204
5.2.1	Studies on fiber reinforced soils	204
5.2.2	Studies on fiber reinforced fly ash	210
5.2.3	Field studies on fiber reinforced soils	211
5.2.4	Conclusions from literature review	212
5.3	SCOPE AND OBJECTIVE OF THE STUDY	213
5.4	MATERIALS	214
5.5	EXPERIMENTAL PROGRAM	214
5.5.1	Notation	214
5.5.2	Overview of experimental program	215
5.6	GEOTECHNICAL CHARACTERIZATION OF FIBER REINFORCED FLY ASHES	215
5.6.1	Fly ash-fiber mixture preparation	216
5.6.2	Fly ash-fiber specimen preparation	217
5.7	RESULTS, ANALYSIS AND DISCUSSIONS	218
5.7.1	Scanning electron microscopic studies	218
5.7.2	Light compaction tests	218
5.7.3	Unconfined compression tests	218

5.7.4	Unconsolidated undrained (UU) tests	226
5.7.5	Consolidated drained (CD) tests	235
5.7.6	Hyperbolic analysis of stress-strain behaviors	242
5.7.6.1	Hyperbolic analysis of UU and CD tests data	245
5.8	CONCLUSIONS	257

CHAPTER 6 BEHAVIOR OF FLY ASH-CEMENT-FIBER SPECIMENS UNDER COMPRESSIVE AND FLEXURAL LOADING

6.1	INTRODUCTION	259
6.2	LITERATURE REVIEW	259
6.2.1	Conclusions from literature review	262
6.3	SCOPE AND OBJECTIVE OF THE STUDY	263
6.4	MATERIALS	263
6.5	EXPERIMENTAL PROGRAM	264
6.5.1	Notation of fly ash-cement-fiber mixtures	264
6.5.2	Overview of experimental program	264
6.6	METHOD OF FLY ASH-CEMENT-FIBER MIXTURE PREPARATION	266
6.7	UNCONFINED COMPRESSION TESTS	267
6.7.1	Specimen preparation, curing and testing	268
6.8	SCANNING ELECTRON MICROSCOPIC STUDIES	269
6.9	FLEXURE TESTS	269
6.9.1	Mold and accessories	270
6.9.2	Method of preparation and curing of beams	270
6.9.3	Method of flexure test	273
6.10	RESULTS, ANALYSIS AND DISCUSSIONS	274

6.10.1	Unconfined compression tests	274
6.10.2	Scanning electron microscopic studies	281
6.10.3	Flexure tests	282
6.11	CONCLUSIONS	296

CHAPTER 7 SUMMARY OF CONCLUSIONS

7.1	GEOTECHNICAL CHARACTERIZATION OF FLY ASH	299
7.2	STRENGTH AND MORPHOLOGICAL STUDIES OF CEMENT STABILIZED FLY ASHES	302
7.3	GEOTECHNICAL BEHAVIOR OF RANDOMLY ORIENTED FIBER REINFORCED FLY ASHES	305
7.4	BEHAVIOR OF FLY ASH-CEMENT-FIBER SPECIMENS UNDER COMPRESSIVE AND FLEXURAL LOADING	307
7.5	SCOPE FOR FURTHER RESEARCH	309

REFERENCES	312
-------------------	-----

BIO-DATA OF AUTHOR