

**Parametric Study on Dynamic Characterization of  
Homogeneous and Stratified Soil-Ash Deposit under Low-  
Strain and High-Strain Conditions**



*Thesis submitted in partial fulfillment*

*for the Award of Degree*

**Doctor of Philosophy**

*by*

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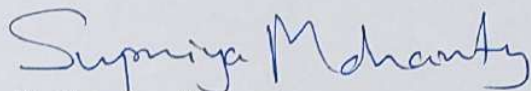
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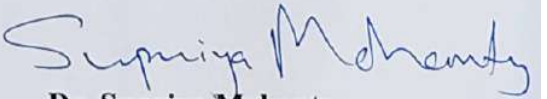
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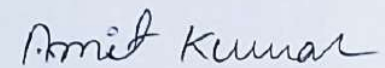
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THIS THESIS IS DEDICATED TO MY PARENTS

*For their endless love, devotion, support, and inspiration*

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# ABSTRACT

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The energy is the driving force of human inventions which make our day to day activities easier and effortless. The outmost demand of the energy compels us for the exertive utilization of the fossil fuel (coal, oil, natural gas) in order to meet the demand. Among all the fossil fuel available, the coal is the most abundantly available fossil fuel in India. Because of its availability and reasonable cost, it has been primarily utilized for the electricity production followed by steel & iron industries and cement & chemical industries. In India, the production of coal in the year 2021-22 was found to be 778.19 million tonnes (MT) which was increased by 8.67% as compared to the previous year. Also, the ash content potential of the Indian coal is around 35-45%. Taking this ash content percentage into account, the total amount of coal ash produced must be between 272.37 to 350.19 MT in the year 2021-22 and this is projected to cross 1000 MT by the upcoming decades. These generated coal ashes consist of a higher percentage of fly ash than that of the bottom ash, i.e., approximately 70-80%. In India, the amount of fly ash produced over a period of 25-year is approximately 3335.9 MT, of which only 55% (1834.83 MT) have been used and the remaining 45% (1501 MT) is still in their unutilized form. The generated ash usually dumped in slurry form near to the thermal power plant that causes scarcity of the valuable agricultural land. The dependency on the non-renewable energy resources will take another 2-3 decades to eliminate considering the current rate of development of the renewable resources.

The production of large amounts of coal ash and its land requirements for disposal is an alarming situation for the present scenario. Also, the very limited

fraction of it has been utilized in different sectors like cement, brick, soil stabilization, mine filling etc. Its bulk utilization is the major point of concern and that can only be possible by broadening its application area such as; embankment fill material, subgrade/sub-base material, foundation material for construction etc. Before this material can be used in bulk in fields as geomaterials in structures, it is important to check the behaviour of the considered material under realistic loading conditions (monotonic or dynamic). Contributing to this objective, a comprehensive experimental program has been planned in the present study.

In the present study, an attempt has been made to examine the insight behaviour of the fly ash and local soil collected from Renukoot (U.P), India and IIT(BHU), Varanasi campus respectively. Also, the implementation of coal ashes is generally done over the existing soil and follows the stratification of multiple layers. In order to simulate the realistic field condition, the interaction between the fly ash and local soil has also been investigated in the stratified form. Furthermore, along with the comprehensive physical, geotechnical, and chemical assessment, the dynamic behaviour of the homogeneous and stratified soil-ash deposits have been examined under large and small-strain conditions. A set of 105 strain-controlled cyclic triaxial test were performed under consolidated undrained conditions for dynamic behaviour and liquefaction study. In addition, the influence of independent parameters such as relative compaction, frequency of loading, effective confining pressure, shearing strain has been incorporated for the wider assessment of the shear modulus ( $G$ ) and damping ratio ( $D$ ) of the material. Furthermore, normalized modulus reduction and damping ratio curves of all the homogeneous and stratified soil-ash deposits have been plotted using the results of the cyclic triaxial and bender element tests.

The present fly ash contains a higher fraction of sand (61.52%) size particles followed by silt (33.19%) and clay (5.29%). Similarly, local soil is composed of maximum silt (81.77%) size particles followed by clay (16.11%) and sand (2.12%). Since, both the soils are satisfying the desirable condition of well graded soil, hence classified as well graded silty sand (fly ash) and silt of intermediate plasticity (local soil). In the same way, the outcome of the standard Proctor test shows that local soil has higher maximum dry density and lower optimum moisture content and vice-versa for fly ash. Also, significant improvement in the shear strength parameters of the considered local soil through a soil-waste layered system was observed in the saturated drained and undrained condition. From the dynamic study, the stratified soil-ash shows higher shear modulus than that of the fly ash and local soil for a shear strain of 0.3% & 0.6% and beyond 0.6%, it shows the comparable shear modulus as compared to the homogeneous one. Similarly, the damping ratio of the stratified soil-ash and local soil is slightly higher than that of the other soil, although the damping ratio of the fly ash is equivalent to that of the sand and clayey soil. Based on the results, it is highly recommended to use the asymmetric hysteresis loop (ASHL) approach, especially under large strain conditions irrespective of the soil type. In addition, the liquefaction assessment using energy method reveals that the energy required for liquefaction is dependent on all the considered parameters, whereas it is independent of the cycle needed to liquefy. From the experimental investigation, this can be concluded that the stratified soil-ash deposit shows enhancement in shear strength parameters (cohesion: 55-69 kPa & internal friction: 25-35°) and CBR value (Unsoaked: 13-30% and Soaked: 1.5-4.5%). Similarly, it shows high dynamic shear modulus (G: 2-8 MPa) that ultimately improve the liquefaction resistance. In the same way, the stratified soil exhibits reduction in

pavement thickness as compared to local soil. But with geosynthetic reinforcement a significant reduction in pavement thickness between 19-32% has been observed for different traffic loading conditions. According to the performance, this layered arrangement can be recommended as a subgrade or fill material under moderate seismic conditions.

# TABLE OF CONTENTS

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<b>CERTIFICATE</b>		<b>i-iii</b>
<b>DEDICATION</b>		<b>iv</b>
<b>ACKNOWLEDGEMENT</b>		<b>v-vi</b>
<b>ABSTRACT</b>		<b>vii-x</b>
<b>TABLE OF CONTENTS</b>		
<b>LIST OF FIGURES</b>		<b>xvi</b>
<b>LIST OF TABLES</b>		<b>xxiii</b>
<b>NOMENCLATURE</b>		<b>xxv-xxxi</b>
<b>CHAPTER-I</b>	<b>INTRODUCTION</b>	<b>1</b>
1.1	GENERAL BACKGROUND	1
1.1.1	Global Overview on Fossil Fuel	2
1.1.2	India's Stance on Fossil Fuels	5
1.1.3	Coal and Its Ash Generation in India	7
1.1.4	Coal Ash Handling System	10
1.2	AN OVERVIEW AND PROBLEM IDENTIFICATION	14
1.3	STRATIFICATION PHENOMENON	18
1.4	OBJECTIVES	18
1.5	SCOPE OF THE STUDY	19
1.6	ORGANIZATION OF THE THESIS	21
<b>CHAPTER-II</b>	<b>REVIEW OF LITERATURE</b>	<b>25</b>
2.1	INTRODUCTION	25
2.2	FLY ASH RECOGNITION AS GREEN/NON-HAZARDOUS OR HAZARDOUS MATERIAL	26
2.3	FUNDAMENTAL AND GEOTECHNICAL CHARACTERIZATION STUDIES OF COAL ASH	28
2.4	GEOTECHNICAL CHARACTERIZATION STUDIES OF SOIL STABILIZED WITH COAL ASH	32
2.5	FLY ASH DOSAGE IN THE VARIOUS AREA OF ENGINEERING	37
2.6	LABORATORY STUDIES ON STRATIFIED SOIL-ASH DEPOSITS	40
2.7	DYNAMIC CHARACTERIZATION STUDIES OF SOIL AND COAL ASH	45
2.8	DYNAMIC CHARACTERIZATION STUDIES OF STRATIFIED SOIL-ASH DEPOSITS	51
2.9	PAVEMENT APPLICATION ASPECT	54
2.10	SUMMARY	56
<b>CHAPTER- III</b>	<b>MATERIALS, EXPERIMENTAL PROGRAM, METHODS, AND TEST PROCEDURES</b>	<b>61</b>

3.1	INTRODUCTION	61
3.2	SOURCE OF MATERIALS USED	63
3.2.1	Fly Ash	63
3.2.2	Local Soil	65
3.3	EXPERIMENTAL PROGRAM	65
3.3.1	Chemical Characterization	65
3.3.1.1	Scanning Electron Microscope (SEM) Test	65
3.3.1.2	X-Ray Diffraction (XRD) Test	66
3.3.1.3	X-Ray Fluorescence (XRF) Spectroscopy	67
3.3.1.4	Potential of Hydrogen (pH)	67
3.3.2	Geotechnical Characterization	68
3.3.2.1	Specific Gravity	68
3.3.2.2	Grain Size Distribution	68
3.3.2.3	Atterberg Limit	69
3.3.2.4	Standard Proctor Test	70
3.3.2.5	Falling Head Permeability Test	70
3.3.2.6	Triaxial Shear Test	71
3.3.2.6.1	Unconsolidated Undrained (UU) Triaxial Test	71
3.3.2.6.2	Consolidated Undrained (CU) Triaxial Test	72
3.3.2.6.3	Consolidated Drained (CD) Triaxial Test	72
3.3.2.7	California Bearing Ratio (CBR) Test	72
3.3.3	Dynamic Characterization	73
3.3.3.1	Cyclic Triaxial Test	73
3.3.3.1.1	Description of the Equipment	73
3.3.3.2	Sample Preparation for Cyclic Triaxial Test	75
3.3.3.3	Testing Procedure of Cyclic Triaxial Test	79
3.3.4	Small-Strain Shear Modulus Characterization	82
3.3.4.1	Bender Element Test	82
3.3.5	Testing Program	86
<b>CHAPTER- IV</b>	<b>CHEMICAL ANALYSIS RESULTS AND DISCUSSION</b>	<b>89</b>
4.1	INTRODUCTION	89
4.2	SCANNING ELECTRON MICROSCOPE (SEM) ANALYSIS	90
4.3	ENERGY DISPERSIVE X-RAY (EDX) ANALYSIS	94
4.4	X-RAY DIFFRACTION (XRD) ANALYSIS	98
4.5	X-RAY FLUORESCENCE (XRF) ANALYSIS	100

4.6	POTENTIAL OF HYDROGEN (pH)	104
4.7	SUMMARY	105
<b>CHAPTER- V</b>	<b>GEOTECHNICAL CHARACTERIZATION TEST RESULTS AND DISCUSSION</b>	<b>107</b>
5.1	INTRODUCTION	107
5.2	SPECIFIC GRAVITY	108
5.3	GRAIN SIZE DISTRIBUTION	109
5.4	CONSISTENCY LIMITS	113
5.5	COMPACTION BEHAVIOUR	114
5.6	PERMEABILITY BEHAVIOUR	119
5.7	CALIFORNIA BEARING RATIO (CBR)	120
5.8	SUMMARY	122
<b>CHAPTER- VI</b>	<b>SHEAR STRENGTH PARAMETERS OF HOMOGENEOUS AND STRATIFIED SOIL- ASH DEPOSIT</b>	<b>125</b>
6.1	INTRODUCTION	125
6.2	SIGNIFICANCE OF SHEAR STRENGTH	127
6.3	TRIAXIAL TEST TECHNIQUES	128
6.4	EXPERIMENTAL PLAN	129
6.5	RESULTS AND DISCUSSION	130
6.5.1	Evaluation of Cohesion and Angle of Internal Friction	130
6.5.2	Failure Mechanism Assessment	134
6.5.3	Assessment of Initial Tangent Modulus and Secant Modulus	139
6.5.4	Interpretation of Ultimate Bearing Capacity of Strip Footing	140
6.6	SUMMARY	144
<b>CHAPTER- VII</b>	<b>DYNAMIC SHEAR MODULUS AND LIQUEFACTION ASSESSMENT OF HOMOGENEOUS AND STRATIFIED SOIL- ASH DEPOSIT</b>	<b>145</b>
7.1	INTRODUCTION	145
7.2	SIGNIFICANCE OF SHEAR MODULUS	147
7.3	METHODOLOGY AND EXPERIMENTAL PROGRAM	147
7.4	RESULTS AND DISCUSSION	150
7.4.1	Evaluation of Dynamic Shear Modulus of Homogeneous Soil and Fly Ash Specimens	150
7.4.2	Evaluation of Dynamic Shear Modulus of Stratified Soil-Ash Deposit	155
7.4.3	Evaluation of Liquefaction Potential by Energy Approach	158

7.4.4	Assessment of Strain Energy Correlation with Independent Parameters	162
7.4.5	Comparison of Present Study Results with Past Literature	164
7.5	SUMMARY	168
<b>CHAPTER- VIII</b>	<b>DAMPING CHARACTERISTICS OF HOMOGENEOUS AND STRATIFIED SOIL-ASH DEPOSIT</b>	<b>171</b>
8.1	INTRODUCTION	171
8.2	SIGNIFICANCE OF DAMPING PROPERTIES	173
8.3	METHODOLOGY AND EXPERIMENTAL PROGRAM	173
8.4	RESULTS AND DISCUSSION	177
8.4.1	Damping Response of Homogeneous Soil and Fly Ash Specimens	179
8.4.2	Damping Response of Stratified Soil-Ash Deposit	184
8.4.3	Identification of an Appropriate Method for the Evaluation of Damping Ratio of Homogeneous and Stratified Soil-Ash Deposit	187
8.4.4	Assessment of the Influence of Cycle Position on Damping Ratio	192
8.4.5	Comparison of Present Study Results with Past Literature	197
8.5	SUMMARY	203
<b>CHAPTER- IX</b>	<b>MAXIMUM SHEAR MODULUS OF HOMOGENEOUS AND STRATIFIED SOIL-ASH DEPOSIT AND CORRELATION STUDIES</b>	<b>205</b>
9.1	INTRODUCTION	205
9.2	METHODOLOGY	206
9.3	RESULTS AND DISCUSSION	207
9.3.1	Identification of an Appropriate Method for the Estimation of Shear Wave Velocity	208
9.3.2	Assessment of Maximum Shear Modulus of Homogeneous and Stratified Soil-Ash Deposit	211
9.3.3	Assessment of Normalized Shear Modulus and Model Fitting	215
9.3.4	Assessment of Damping Ratio and Model Fitting	218
9.3.5	Development of Excess Pore Pressure Ratio Response Model using Strain Energy Approach	222
9.4	SUMMARY	227
<b>CHAPTER- X</b>	<b>PERFORMANCE OF HOMOGENEOUS AND STRATIFIED SOIL-ASH DEPOSIT AS A PAVEMENT MATERIAL</b>	<b>229</b>
10.1	INTRODUCTION	229
10.2	MECHANISTIC-EMPIRICAL DESIGN METHODOLOGY	230

10.2.1	Criteria for Rutting of Subgrade	231
10.2.2	Criteria for Fatigue Cracking of Bituminous Layer	232
10.3	DESIGN OF FLEXIBLE PAVEMENT	233
10.3.1	Design of Unreinforced Flexible Pavement	233
10.3.2	Design of Geosynthetic-Reinforced Flexible Pavement	234
10.4	RESULTS AND DISCUSSION	235
10.4.1	CBR Response of Unreinforced and Reinforced Soil Combinations	236
10.4.2	Thickness Evaluation of Pavement Resting on Present Materials as Subgrade	242
10.5	SUMMARY	246
 <b>CHAPTER- XI</b>		
	<b>CONCLUSIONS AND FUTURE SCOPE</b>	<b>247</b>
11.1	SUMMARY AND CONCLUSIONS	247
11.1.1	Chemical Analysis Test Results	248
11.1.2	Geotechnical Characterization Test Results	248
11.1.3	Shear Strength Characteristics	249
11.1.4	Dynamic Shear Modulus and Liquefaction Assessment	250
11.1.5	Damping Characteristics	251
11.1.6	Maximum Shear Modulus and Correlation Studies	252
11.1.7	Performance of Stratified Soil-Ash Deposit as a Pavement Material	252
11.2	LIMITATIONS AND SCOPE FOR FUTURE WORK	253
11.2.1	Limitations	253
11.2.2	Scope for Future Work	254
	 <b>REFERENCES</b>	 <b>255</b>
	 <b>LIST OF PUBLICATIONS</b>	 <b>313</b>

# LIST OF FIGURES

---

<b>Figure No.</b>	<b>Description</b>	<b>Page No.</b>
1.1	The contribution of different source of energy in the world's total primary energy consumption. (Source: Statistics review of world energy 2021)	3
1.2	Typical representation of (a) coal production growth, and (b) share of various sources in the electricity production of top fossil fuel consumer countries. (Source: World development indicators 2021)	4
1.3	Contribution of various sources in the installed power generation capacity in India. (Source: CAE 2020)	8
1.4	Demonstration of fly ash utilization and non-utilization during 25-years duration. (Source: CEA 2022)	9
1.5	Schematic representation of complete process involved in the thermal power plants. (Source: Tennessee Valley Authority 2023)	10
1.6	Typical cross-sectional demonstration of Pneumatic ash handling system. (Courtesy: VAC-U-MAX)	12
1.7	Hydraulic ash handling system, (a) Low velocity system, and (b) High velocity system. (Courtesy: Thermal Power Tech)	13
1.8	Illustration of mechanical ash handling system. (Courtesy: Thermal Power Tech)	14
2.1	Illustration of cyclic shear strain range of various dynamic tests in normalized modulus reduction curve	47
3.1	Flowchart of the experimental and analytical evaluation of present soil combinations under different phases	62
3.2	Site locations of the considered materials	64
3.3	Pictorial illustration of cyclic triaxial test apparatus	74
3.4	Illustration of sample preparation, (a) sample preparation mold, (b) compaction of first layer of local soil, (c) compaction of second layer, (d) final compacted form of local soil, (e) final compacted form of fly ash, (f) final compacted form of stratified soil-ash deposit	78
3.5	(a) Hysteretic stress–strain relationship for cyclic loading (Sitharam et al. 2004) and (b) Travel time determination using	81

	time domain technique. (Kawaguchi et al. 2016)	
3.6	Pictures showing various stages in sample preparation for cyclic triaxial test: (a) Fly ash sample (b) Prepared specimen (c) Specimen with rubber membrane (d) Specimen with top piston assembly (e) Specimen with triaxial cell assembly and (f) Specimen subjected to confining pressure	82
3.7	Pictures showing various stages in sample preparation for bender element test: (a) Fly ash sample (b) Mould for sample preparation (c) Extracted specimen (d) Top and bottom groove of bender element (e) Bender element without specimen (f) Specimen kept on bottom element (g) Mounted specimen and (h) Mounted specimen with confining pressure	85
3.8	Schematic description of testing program for the cyclic triaxial and bender element test.	88
4.1	Scanning electron microscope analysis of fly ash sample under different magnification	92
4.2	Scanning electron microscope analysis of local soil sample under different magnification	93
4.3	Selected location of fly ash specimen for the EDX analysis	94
4.4	Graphical representation of the elemental composition of fly ash at four locations	96
4.5	Selected location of local soil specimen for the EDX analysis	96
4.6	Energy dispersive X-ray analysis of local soil at five locations	98
4.7	Mineralogical analysis of fly ash using the XRD analysis	99
4.8	Mineralogical analysis of local soil using the XRD analysis	100
4.9	Graphical representation of percentage of compound present in fly ash	101
5.1	Comparison of specific gravity of fly ash with past studies. (FA1, BA, PA: Sridharan et al. 1998; FA2: Sridharan et al. 2001; FA3: Pandian 2004; FA4, FA5: Moghal and Sivapullaiah 2011; FA6: Kumar et al. 2014; FA7: Rajak et al. 2017; FA8: Present study) (FA: Fly ash, BA: Bottom ash, PA: Pond ash).	109
5.2	Grain size distribution of local soil and fly ash using sieve and hydrometer analysis	111

5.3	Pictorial presentation of different particle size retained on various size of sieve in particle size distribution analysis, (a) fly ash, and (b) local soil.	112
5.4	Flow curve of local soil for the determination of liquid limit	114
5.5	Penetration of cone under different water content for non-plastic soil (fly ash)	114
5.6	Compaction plot of local soil and fly ash determined by standard Proctor test	117
5.7	Demonstration of MDD and OMC of fly ash with past studies. (FA1, BA, PA: Sridharan et al. 1998; FA2: Sridharan et al. 2001; FA3: Pandian 2004; FA4, FA5: Moghal and Sivapullaiah 2011; FA6: Kumar et al. 2014; FA7: Rajak et al. 2017; FA8: Present study) (FA: Fly ash, BA: Bottom ash, PA: Pond ash).	117
5.8	Graphical representation of the unsoaked CBR of homogeneous and stratified soil-ash deposit.	121
5.9	Graphical representation of soaked CBR of homogeneous and stratified soil-ash deposit	122
6.1	Prepared cylindrical specimen of homogeneous and stratified soil-ash deposit	129
6.2	Deviator stress versus axial strain plot of fly ash (FA), local soil (LS), and 2 layered soil-ash deposit (2L) under (a) Unconsolidated undrained, (b) Consolidated undrained, and (c) Consolidated drained conditions subjected to different confining pressure	133
6.3	Graphical representation of cohesion and angle of internal friction of fly ash (FA), local soil (LS), and 2 layered soil-ash deposit (2L) under UU, CU, and CD conditions	133
6.4	Failure pattern analysis of unconsolidated undrained triaxial test of all the specimen combinations	137
6.5	Strip footing used for the assessment of ultimate bearing capacity	142
7.1	Fundamental hysteresis loop of energy dissipation/stored mechanism (Green 2001)	149
7.2	Dynamic shear modulus illustration of fly ash and local soil considering each influencing parameter	154

7.3	Graphical representation of dynamic shear modulus of the stratified soil-ash deposit considering each influencing parameter	157
7.4	Typical plot of the variation of dissipated energy and its cumulative energy with number of cycles for liquefaction in the case of fly ash	160
7.5	Variation of cumulative dissipated energy of (a) fly ash, (b) local soil, and (c) stratified soil-ash deposit with cyclic shear strain	162
7.6	Comparison of the shear modulus of various soil prepared under different densities. ( <sup>1</sup> : Dammala et al. 2017, <sup>2</sup> : Kumar et al. 2017, <sup>3</sup> : Li et al. 2020, <sup>4</sup> : Ravishankar et al. 2005, <sup>5</sup> : Gao et al. 2021 (Lightweight expanded clay aggregate), <sup>6,7,&amp;8</sup> : Fly ash, Local soil, and Stratified soil (present study))	166
7.7	Comparison of the shear modulus of various soil loaded under different frequencies of loading. ( <sup>1</sup> : Das and Chakraborty 2022, <sup>2</sup> : Ravishankar et al. 2005, <sup>3</sup> : Reddy et al. 2021, <sup>4,5,&amp;6</sup> : Fly ash, Local soil, and Stratified soil (present study))	167
7.8	Comparison of the shear modulus of various soil consolidated under different effective confining pressure. ( <sup>1</sup> : Chattaraj and Sengupta 2017, <sup>2</sup> : Dammala et al. 2019, <sup>3</sup> : Jaya et al. 2012, <sup>4</sup> : Kumar et al. 2017, <sup>5,6,&amp;7</sup> : Fly ash, Local soil, and Stratified soil (present study))	168
8.1	Graphical illustration of various method such as (a) symmetrical hysteresis loop, (b) asymmetric hysteresis loop, (c) modified ASTM method for the estimation of damping ratio. (Das and Chakraborty (2022))	176
8.2	Systematic experimental outline of testing program	177
8.3	The distribution of grains by size in the soil and ash samples used in this investigation	179
8.4	Effect of various parameters on the damping ratio of fly ash (Ram and Mohanty 2021) and local soil for large strain	183
8.5	Variation of damping ratio of stratified soil-ash samples considering all influencing parameters	186
8.6	Graphical representation of damping ratio of fly ash and local soil evaluated using SHL, ASHL, and ASTM methods	190
8.7	Graphical representation of damping ratio of stratified soil-ash samples evaluated using SHL, ASHL, and ASTM methods	192

8.8	Asymmetry of hysteresis loop at 0th cycle position under different cyclic shear strain for homogeneous and stratified soil-ash samples	195
8.9	Asymmetry of hysteresis loop at 1st cycle position under different cyclic shear strain for homogeneous and stratified soil-ash samples	196
8.10	Bar distribution of area of hysteresis loop plotted against 0 <sup>th</sup> and 1 <sup>st</sup> cycle position	196
8.11	Assessment of damping characteristics of present study results with different types of soil considering the effect of relative compaction and confining pressure. ( <sup>1</sup> : Kumar et al. (2014); <sup>2</sup> : RaviShankar et al. (2012); <sup>3</sup> : Mog and Anbazhagan (2022); <sup>4</sup> : Present study; <sup>5</sup> : Li et al. (2020))	200
8.12	Assessment of damping ratio of present study results with different types of soil under the influence of frequency of loading. ( <sup>1</sup> : Das and Chakraborty (2021); <sup>2</sup> : Aghaeiraei et al. (2012); <sup>3</sup> : RaviShankar et al. (2012); <sup>4</sup> : Present study)	201
8.13	Comparison of damping ratio of present study results with different types of soil. ( <sup>1</sup> : Amir-Faryar et al. (2017); <sup>2</sup> : Chehat et al. (2018); <sup>3</sup> : Vucetic and Dobry (1991); <sup>4</sup> : Kokusho (1980); <sup>5</sup> : Hanumantharao and Ramana (2008); <sup>6</sup> : Chattaraj and Sengupta (2016); <sup>7</sup> : Matasovic and Vucetic (1994); <sup>8</sup> : Kiku and Yoshida (2000); <sup>9</sup> : Chiaradonna et al. (2015); <sup>10</sup> : Pagliaroli et al. (2018); <sup>11</sup> : Kumar et al. 2014; <sup>12</sup> : Govindaraju et al. 2012; <sup>13</sup> : Li et al. 2020; <sup>14,15,16</sup> : Present study)	202
9.1	Bender element vibration mechanism (Source: VJ tech).	207
9.2	Bender element complete setup, (a) amplifier, (b) waveform generator, (c) oscilloscope, and (d) triaxial setup equipped with bender element	207
9.3	Variation of shear wave velocity of fly ash determined through various available methods such as Peak to Peak, Start to Start, and Trough to Trough. (MDD:- 99%)	209
9.4	Variation of shear wave velocity of local soil determined through various available methods such as Peak to Peak, Start to Start, and Trough to Trough. (MDD :- 99%)	210
9.5	Variation of shear wave velocity of Layered soil determined through various available methods such as Peak to Peak, Start to Start, and Trough to Trough. (MDD :- 95%)	210

9.6	Maximum shear modulus illustration of fly ash considering (a) all conditions and (b) under confinement without saturation	212
9.7	Maximum shear modulus illustration of local soil considering (a) all conditions and (b) under confinement without saturation	213
9.8	Maximum shear modulus illustration of stratified soil-ash deposit considering (a) all conditions and (b) under confinement without saturation	214
9.9	Normalized shear modulus plot of homogeneous and stratified soil-ash deposit	216
9.10	Hyperbolic model fitting for modulus reduction curve of (a) fly ash, (b) local soil, and (c) stratified soil-ash deposit	217
9.11	Damping response of the homogeneous and stratified soil-ash deposits	220
9.12	Hyperbolic model fitting of damping response of fly ash, local soil, and stratified soil-ash deposits	221
9.13	The graphical illustration between excess pore pressure ratio and strain energy ratio for a particular density, frequency, and confining pressure for fly ash	224
9.14	The graphical illustration between excess pore pressure ratio and strain energy ratio for a particular density, frequency, and confining pressure for local soil	224
9.15	The graphical illustration between excess pore pressure ratio and strain energy ratio for a particular density, frequency, and confining pressure for the stratified soil-ash deposit	225
9.16	Range of coefficients of pore pressure model obtained from the cyclic triaxial test conducted on the, (a) fly ash, (b) local soil, and (c) stratified soil-ash deposit	226
10.1	The schematic diagram of flexible pavement with various layers illustrating critical strains (IRC-37-2018)	231
10.2	Pictorial illustration of different types of reinforcements, (a) Geonet 121, (b) Geonet 131, (c) Geonet 153, (d) Biaxial geogrid, and (e) PRPP (4 mm)	238
10.3	Schematic diagram of CBR testing sample having equally distributed fly ash and local soil with reinforcement placed at center	239
10.4	California Bearing Ratio of all the soil combinations under, (a) soaked condition, and (b) unsoaked condition	241
10.5	Evaluation of the pavement thickness for local soil and layered soil-ash arrangements	244
10.6	Assessment of the pavement thickness for layered soil-ash	244

arrangements with various reinforcements

10.7	Typical representation of the flexible pavement thickness considering various reinforcement under different conditions	245
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# LIST OF TABLES

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<b>Table No.</b>	<b>Description</b>	<b>Page No.</b>
1.1	Past reported failure case study of ash deposits between 2019 to 2021 (Kapoor and Raheja 2021)	17
2.1	Impact of toxic elements in all parts of the human body (Health Energy Initiative - 2020)	28
2.2	Tabular representation of geotechnical characterization of coal ash	31
2.3	Summary of past literature on soil stabilization using coal ash	36
2.4	Demonstration of dosage/proportion of fly ash in different areas of application	39
2.5	Systematic literature about the fundamental studies on the stratified soil deposit	44
2.6	Summary of the past literature associated with stratified/layered deposit	53
4.1	Percentage contribution of various compound present in fly ash	102
4.2	Chemical alteration of fly ash tested from different states in India	103
4.3	Typical range of pH of fly ash for the acidic and basic classification. (Kolbe et al. 2011)	104
5.1	Basic geotechnical properties of fly ash from various power plants in India	118
6.1	Layout of laboratory experiments for shear strength determination	129
6.2	Comparisons of the shear strength parameters of the present study with the past reported studies	134
6.3	Failure description of all the samples under different triaxial conditions (UU, CU, and CD)	138
6.4	Variation of elastic modulus of all the samples represented by initial tangent and secant modulus	140
6.5	Ultimate bearing capacity of strip foundation resting on the considered soil and soil-ash deposit under all triaxial conditions	143
7.1	Laboratory experimental program of the cyclic triaxial test	150

8.1	Expressions that estimate the dynamic characteristics using various methodologies	175
10.1	Physical and mechanical properties of Geonet considered in the present study	238
10.2	Physical and mechanical properties of Geogrid in machine direction (MD) and cross-machine direction (CD) considered in the present study	240
10.3	Physical and mechanical properties of Petrosshield rock protection padding mesh considered in the present study	240
10.4	Tabular presentation of soaked and unsoaked CBR of various combinations of soil with and without reinforcement	242

# NOMENCLATURE

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$\varepsilon$  - Axial strain

$\rho$  - Bulk mass density

$\nu$  - Poisson's ratio

$\eta$  - Porosity

$\lambda$  - Wavelength

$^{\circ}\text{C}$  – Degree Celsius

$\gamma_d$  – Dry unit weight

$^{\circ}\text{F}$  – Fahrenheit

$\mu\text{m}$  – micrometre

$\Delta W$  – Dissipated energy

3D – Three dimensional

$\text{\AA}$  – Angstrom

AASHTO- American association of state highway and transportation officials

$A_L$  - Area of hysteresis loop

$\text{Al}_2\text{O}_3$  – Aluminum oxide

AMD – Arithmetic mean diameter

ASHL - Asymmetric hysteresis loop

ASTM - American Society for Testing and Materials

B – Width

B - Skempton's pore pressure parameter

BA – Bottom ash

BC – Bituminous course

BE- Bender element

$c'$  – Effective cohesion

$c$  - Cohesion

CBR - California bearing ratio test

CC – Cross correlation

CD - Consolidated drained

CIF – Central instrumental facility

CO<sub>2</sub> – Carbon dioxide

CP – Confining pressure

CPT- Cone penetration test

CSH – Calcium silicate hydrate

CSIR- IMMT - Institute of Minerals and Materials Technology Council of Scientific  
and Industrial Research

CSM – Cement stabilized macadam

Cu – Coefficient of uniformity

CU - Consolidated undrained

D – Damping ratio

D – Depth

DBM – Dense bound macadam

E – East

E – Young's modulus

EDX - Energy dispersive x-ray

$E_{eq}$  – Equivalent modulus

$E_i$  - Initial tangent modulus

$E_s$  – Secant modulus

ESP - Electrostatic precipitator

f – frequency

FA – Fly ash

FAM – Fly ash mission

$Fe_2O_3$  – Iron oxide

FVD – Free vibration decay

G – Dynamic shear modulus

g/cc – Gram per cubic centimetre

$G/G_{max}$  – Normalized shear modulus

GG – Geogrid

GGBFS – Ground granulated blast furnace slag

$G_{\max}$  – Maximum shear modulus

GN – Geonet

$G_s$  – Specific gravity

$G_{\text{sec}}$  – Secant shear modulus

Ha – Hectare

HEI – Health energy initiative

HR-SEM – High resolution scanning electron microscope

Hz – Hertz

IRC – Indian road congress

IS- Indian standard

JCPDS - Joint committee on powder diffraction standards

$k$  – Coefficient of permeability

kg – Kilogram

kHz – Kilohertz

$\text{km}^2$  – Square kilometre

kN – Kilo newton

kPa – Kilo Pascal

kV – Kilo volt

$L_{iv}$  – Volumetric binder content

LS – Local soil

M1, M2, & M3 – Method one, two, and three

M<sup>3</sup> – Cubic metre

MASW - Multichannel analysis of surface wave

MDD- Maximum dry density

ml – Millilitre

mm – Millimetre

MPa – Mega Pascal

M<sub>R</sub> – Resilient modulus

MSA – Million standard axle

MSW – Municipal solid waste

MT – Million tonnes

M<sub>w</sub> – Moment magnitude

N – North

NO<sub>x</sub> – Oxides of Nitrogen

OMC- Optimum moisture content

PA – Pond ash

PAHS - Pneumatic ash handling system

pH – Power of hydrogen

PI – Plasticity index

PP – Peak to peak

PRPP - Petroshield rock protection padding mesh

$q_{ul}$  – Ultimate bearing capacity

$q_u$  – Unconfined compressive strength

RAP – Reclaimed asphalt pavement

RC – Relative compaction

RDSO - Research Designs and Standards Organisation

$r_u$  – Excess pore pressure ratio

SASW - Spectral analysis of surface waves

SCC – Self compacting concrete

SEM - Scanning electron microscope

SHL – Symmetric hysteresis loop

SiO<sub>2</sub> – Silicon dioxide

SO<sub>2</sub> – Sulfur dioxide

SPT – Standard penetration test

SS – Start to start

SSA – Specific surface area

SSV – Steady state vibration

$t$  – thickness

TPS – Thermal power station

UCS- Unconfined compression strength

US EPA – United states environmental protection agency

UU - Unconsolidated undrained

$V_s$  – Shear wave velocity

$W/W_{Liq}$  – Strain energy ratio

XR – X-Ray

XRD- X-ray diffraction

XRF- X-ray fluorescence

$\Delta u$  - Change in pore pressure

$\Delta \sigma_c$  - Change in confining pressure

$\Phi'$  – Effective angle of friction

$\phi$  - Internal friction/ Angle of friction

$\gamma$  - Shear strain

$\sigma'_c$  - Effective confining pressure

$\sigma_c$ - Confining pressure

$\sigma_d$ - Deviator stress