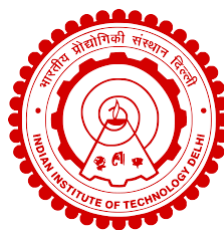


**PHYSICAL, MECHANICAL AND INTERFACE
CHARACTERISATION OF GEOFOAM FOR ITS USE AS
FILL MATERIAL FOR ROAD WIDENING IN HILLY
TERRAIN**

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**DEPARTMENT OF CIVIL ENGINEERING
INDIAN INSTITUTE OF TECHNOLOGY DELHI
JULY 2024**

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Parvathi G. S.

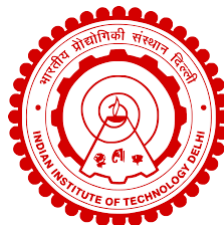
Department of Civil Engineering

submitted

in fulfilment of the requirements of the degree of

Doctor of Philosophy

to the



INDIAN INSTITUTE OF TECHNOLOGY DELHI

JULY 2024

Dedicated to My Son

Naricharan Sahu

CERTIFICATE

This is to certify that the thesis entitled - **“PHYSICAL, MECHANICAL AND INTERFACE CHARACTERISATION OF GEOFOAM FOR ITS USE AS FILL MATERIAL FOR ROAD WIDENING IN HILLY TERRAIN”**, being submitted by **Ms. Parvathi G. S.** to the Indian Institute of Technology Delhi is a record of bonafide research work carried out by her under my supervision and guidance. The thesis work, in my opinion, has reached the standard, fulfilling the requirements for the **DOCTOR OF PHILOSOPHY** degree. The research report and results presented in this thesis have not been submitted, in part or full, to any University or Institute for the award of any degree or diploma.

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-Parvathi G. S.

ABSTRACT

The widening of roads in hilly terrains is a time-consuming process that presents significant geotechnical and financial challenges. It typically involves hill cutting or valley-side filling, both of which can potentially induce slope instability due to steepening or increased loading/driving forces. This research focuses on the use of expanded polystyrene (EPS) geofoam, a material that is significantly lighter (20-100 times) than conventional fill materials, as an effective solution for embankment filling on valley sides to mitigate these risks. Extensive investigation into the physical, mechanical, and interface properties of EPS geofoam for road widening applications is carried out in this research.

The initial phase involves a detailed physical characterisation of various geofoam grades, encompassing image-based microstructural analysis (cell size, void fraction, cell population density), homogeneity assessments, and variations in density, surface roughness, and hardness properties. The mechanical characteristics such as compression, flexural strength, and monoblock shear resistance are evaluated with the aid of 2D digital image correlation (DIC) analysis to study strain distribution and concentrations within the geofoam.

The study reveals that compressive behaviour is significantly influenced by homogeneity, which is manifested by the changes in microstructure and apparent density of the geofoam. The cell size, void fraction, and homogeneity decrease with increasing geofoam density. Moreover, image analysis provides insights into failure patterns and strain localisation, enhancing understanding of the complex behaviour of geofoam. Poisson's ratio and their variations across different strain levels and grades of geofoam are also explored thoroughly.

A parametric evaluation of the primary design parameters from compression tests shows that apparent density, size, and ambient temperature critically control the compressive stresses of geofoam. Additionally, machine learning models, including Artificial Neural Networks (ANN)

and Extreme Gradient Boosting (XGBoost), are employed to develop predictive models of geofoam behaviour, with XGBoost demonstrating superior accuracy.

Interface tests are conducted to understand the shearing mechanisms at various geofoam interfaces relevant to embankment construction, such as geofoam-sand, geofoam-geofoam, and geofoam-concrete. The effects of the density of the geofoam, particle size of the sand, applied normal stress, and sand saturation are evaluated during the interface tests. Apart from the inherent variation of the geofoam roughness with density, the roughness is altered by providing ledges on the geofoam of varying sizes and shapes. These tests lead to empirical correlations for predicting friction coefficients based on interface roughness characteristics. The DIC technique is utilised to analyse strain distribution and failure patterns during interface shearing.

The concluding part of the study involves simulating a geofoam embankment for valley-side road widening using finite element software, incorporating the material and interface characteristics derived from the experimental studies of this thesis. Road widening using geofoam blocks improved the slope stability factor of safety by 25% compared to conventional soil fills. The simulation results suggest that stresses and deformations within the geofoam embankment are similar to those in traditional fills. The interface stresses of geofoam at varying depth levels are also evaluated to assess the critical interface. Finally, a quick-selection chart for geofoam grades and related material cost estimation for various slope angles in hilly terrains are also derived to provide a preliminary insight into the economic implications. This research provides essential guidance for design engineers in selecting the appropriate grade of geofoam and its design parameters for road widening projects in hilly terrains.

सार

पहाड़ी इलाकों में सड़कों को चौड़ा करना एक समय लेने वाली प्रक्रिया है जो महत्वपूर्ण भू-तकनीकी और वित्तीय चुनौतियों को प्रस्तुत करती है। इसमें आम तौर पर पहाड़ी काटना या घाटी के किनारे भरना शामिल होता है, दोनों ही संभावित रूप से ढलान में अस्थिरता पैदा कर सकते हैं क्योंकि ढलान में ढलान या लोडिंग/ड्राइविंग बलों में वृद्धि हो सकती है। यह शोध विस्तारित पॉलीस्टाइनिन (EPS) जियोफोम के उपयोग पर केंद्रित है, जो एक ऐसी सामग्री है जो पारंपरिक भराव सामग्री की तुलना में काफी हल्की (20-100 गुना) है, जो इन जोखिमों को कम करने के लिए घाटी के किनारों पर तटबंध भरने के लिए एक प्रभावी समाधान है। इस शोध में सड़क चौड़ीकरण अनुप्रयोगों के लिए EPS जियोफोम के भौतिक, यांत्रिक और इंटरफ़ेस गुणों की व्यापक जांच की गई है।

प्रारंभिक चरण में विभिन्न जियोफोम ग्रेडों का विस्तृत भौतिक लक्षण वर्णन शामिल है, जिसमें छवि-आधारित माइक्रोस्ट्रक्चरल विश्लेषण (कोशिका आकार, शून्य अंश, कोशिका जनसंख्या घनत्व), समरूपता आकलन और घनत्व, सतह खुरदरापन और कठोरता गुणों में भिन्नता शामिल है। जियोफोम के भीतर तनाव वितरण और सांद्रता का अध्ययन करने के लिए 2D डिजिटल इमेज कोरिलेशन (DIC) विश्लेषण की सहायता से संपीड़न, फ्लेक्सुरल ताकत और मोनोब्लॉक कतरनी प्रतिरोध जैसी यांत्रिक विशेषताओं का मूल्यांकन किया जाता है। अध्ययन से पता चलता है कि संपीड़न व्यवहार समरूपता से काफी प्रभावित होता है, जो जियोफोम की सूक्ष्म

संरचना और स्पष्ट घनत्व में परिवर्तन से प्रकट होता है। सेल का आकार, शून्य अंश और समरूपता जियोफोम घनत्व में वृद्धि के साथ कम हो जाती है। इसके अलावा, छवि विश्लेषण विफलता पैटर्न और तनाव स्थानीयकरण में अंतर्दृष्टि प्रदान करता है, जो जियोफोम के जटिल व्यवहार की समझ को बढ़ाता है। जियोफोम के विभिन्न तनाव स्तरों और ग्रेडों में पॉइसन अनुपात और उनकी विविधताओं का भी गहनता से पता लगाया जाता है। संपीड़न परीक्षणों से प्राथमिक डिज़ाइन मापदंडों का एक पैरामीट्रिक मूल्यांकन दिखाता है कि स्पष्ट घनत्व, आकार और परिवेश का तापमान जियोफोम के संपीड़न तनावों को महत्वपूर्ण रूप से नियंत्रित करता है। इसके अतिरिक्त, आर्टिफिशियल न्यूरल नेटवर्क (ANN) और एक्सट्रीम ग्रेडिएंट बूस्टिंग (XGBoost) सहित मशीन लर्निंग मॉडल, जियोफोम व्यवहार के पूर्वानुमानित मॉडल विकसित करने के लिए नियोजित किए जाते हैं, जिसमें XGBoost बेहतर सटीकता प्रदर्शित करता है। तटबंध निर्माण से संबंधित विभिन्न जियोफोम इंटरफेस जैसे जियोफोम-रेत, जियोफोम-जियोफोम और जियोफोम-कंक्रीट पर कतरनी तंत्र को समझने के लिए इंटरफेस परीक्षण किए जाते हैं। इंटरफेस परीक्षणों के दौरान जियोफोम के घनत्व, रेत के कण आकार, लागू सामान्य तनाव और रेत संतृप्ति के प्रभावों का मूल्यांकन किया जाता है। घनत्व के साथ जियोफोम खुरदरापन की अंतर्निहित भिन्नता के अलावा, अलग-अलग आकार और आकृतियों के जियोफोम पर लेज प्रदान करके खुरदरापन बदल दिया जाता है। ये परीक्षण इंटरफेस खुरदरापन विशेषताओं के आधार पर घर्षण गुणांक की भविष्यवाणी करने के लिए अनुभवजन्य सहसंबंधों की ओर ले जाते हैं।

इंटरफेस कतरनी के दौरान तनाव वितरण और विफलता पैटर्न का विश्लेषण करने के लिए डीआईसी तकनीक का उपयोग किया जाता है। अध्ययन के समापन भाग में इस थीसिस के प्रायोगिक अध्ययनों से प्राप्त सामग्री और इंटरफेस विशेषताओं को शामिल करते हुए परिमित तत्व सॉफ्टवेयर का उपयोग करके घाटी के किनारे सड़क चौड़ीकरण के लिए जियोफोम तटबंध का अनुकरण करना शामिल है। जियोफोम ब्लॉक का उपयोग करके सड़क चौड़ीकरण ने पारंपरिक मिट्टी भराव की तुलना में सुरक्षा के ढलान स्थिरता कारक में 25% तक सुधार किया। सिमुलेशन के परिणाम बताते हैं कि जियोफोम तटबंध के भीतर तनाव और विकृतियाँ पारंपरिक भरावों के समान हैं। महत्वपूर्ण इंटरफेस का आकलन करने के लिए अलग-अलग गहराई स्तरों पर जियोफोम के इंटरफेस तनावों का भी मूल्यांकन किया जाता है। अंत में, पहाड़ी इलाकों में विभिन्न ढलान कोणों के लिए जियोफोम ग्रेड और संबंधित सामग्री लागत अनुमान के लिए एक त्वरित-चयन चार्ट भी आर्थिक निहितार्थों में प्रारंभिक अंतर्दृष्टि प्रदान करने के लिए तैयार किया गया है। यह शोध पहाड़ी इलाकों में सड़क चौड़ीकरण परियोजनाओं के लिए जियोफोम के उपयुक्त ग्रेड और इसके डिजाइन मापदंडों का चयन करने में डिजाइन इंजीनियरों के लिए आवश्यक मार्गदर्शन प्रदान करता है।

TABLE OF CONTENTS

CERTIFICATE	i
ACKNOWLEDGEMENTS	ii
ABSTRACT	iv
संक्षेप	vi
TABLE OF CONTENTS	ix
LIST OF FIGURES	xiv
LIST OF TABLES	xx
LIST OF NOTATIONS	xxii
LIST OF ABBREVIATIONS	xxvii
CHAPTER 1: INTRODUCTION	1
1.1. BACKGROUND	1
1.2. ORGANIZATION OF THE THESIS	6
CHAPTER 2: LITERATURE REVIEW	9
2.1. INTRODUCTION	9
2.2. GEOTECHNICAL APPLICATIONS OF THE MATERIAL	11
2.3. PRODUCTION OF GEOFOAM	14
2.4. PHYSICAL CHARACTERISATION	16
2.5. MECHANICAL CHARACTERISATION	20
2.5.1. Compressive Behaviour	21
2.5.2. Parametric Studies	24
2.5.3. Poisson's Ratio	31
2.5.4. Flexural Behaviour	32
2.5.5. Monoblock Shear Behaviour	33
2.5.6. Imaging Techniques	34

2.6.	INTERFACE CHARACTERISATION.....	36
2.6.1.	Interface Test Configuration.....	37
2.6.2.	Effect of Surface Properties on Interface Behaviour.....	41
2.6.3.	Geofoam-Sand Interface.....	42
2.6.4.	Geofoam-Geofoam Interface.....	44
2.6.5.	Geofoam-Concrete Interface.....	45
2.7.	NUMERICAL SIMULATION.....	47
2.8.	GAPS IDENTIFIED IN THE LITERATURE.....	51
2.9.	OBJECTIVE AND SCOPE OF THE STUDY.....	52
2.10.	METHODOLOGY.....	53
CHAPTER 3:	PHYSICAL CHARACTERISTICS.....	57
3.1.	INTRODUCTION.....	57
3.2.	MATERIAL COLLECTION.....	57
3.3.	TESTING PROGRAM.....	58
3.4.	MORPHOLOGY.....	58
3.4.1.	Expanded EPS Beads.....	59
3.4.2.	Geofoam.....	60
3.5.	HOMOGENEITY.....	63
3.6.	NOMINAL DENSITY Vs. APPARENT DENSITY.....	64
3.7.	ROUGHNESS.....	66
3.8.	HARDNESS.....	68
3.9.	SUMMARY.....	69
CHAPTER 4:	MECHANICAL CHARACTERISTICS.....	71
4.1.	INTRODUCTION.....	71
4.2.	METHODS.....	72

4.2.1.	Uniaxial Compression Tests	72
4.2.2.	Four-Point Flexural Tests	72
4.2.3.	Shear Tests of Monoblock	73
4.2.4.	Digital Image Correlation	74
4.3.	COMPRESSIVE BEHAVIOUR.....	77
4.3.1.	General Response.....	77
4.3.2.	Non-Destructive Testing and Correlation with Compressive Stresses	78
4.3.3.	Safety Factor	79
4.3.4.	Strain Field Maps	81
4.3.5.	Poisson's Ratio.....	83
4.4.	FLEXURAL BEHAVIOUR	85
4.4.1.	General Response.....	85
4.4.2.	Strain Field Maps	89
4.5.	SHEAR BEHAVIOUR	92
4.5.1.	General Response.....	92
4.5.2.	Strain Field Maps	95
4.6.	SUMMARY	96
CHAPTER 5: ANALYSIS AND PREDICTIVE MODELLING OF COMPRESSIVE CHARACTERISTICS.....		97
5.1.	INTRODUCTION.....	97
5.2.	PARAMETRIC STUDY	97
5.2.1.	Methodology	97
5.2.1.	Results.....	99
5.3.	DATA ANALYSIS	108
5.4.	CORRELATION ANALYSIS	108

5.5.	DEVELOPMENT OF MACHINE LEARNING MODELS.....	111
5.5.1.	Data Matrix Expansion	113
5.5.2.	Artificial Neural Network (ANN).....	115
5.5.3.	Extreme Gradient Boosting (XGBOOST).....	116
5.5.4.	Prediction Output	117
5.6.	SUMMARY	122
CHAPTER 6:	INTERFACE CHARACTERISTICS.....	125
6.1.	INTRODUCTION.....	125
6.2.	MATERIALS USED.....	125
6.2.1.	Geofoam.....	125
6.2.2.	Sand.....	125
6.2.3.	Concrete	129
6.3.	METHODOLOGY.....	130
6.3.1.	Interface Test Set-up	130
6.3.2.	Roughness Modification	133
6.4.	RESULTS.....	135
6.4.1.	Geofoam-Sand	135
6.4.2.	Geofoam-Geofoam	150
6.4.3.	Geofoam-Concrete.....	160
6.5.	SUMMARY	165
CHAPTER 7:	NUMERICAL SIMULATION OF TYPICAL GEOFOAM	
EMBANKMENT.....	167	
7.1.	INTRODUCTION.....	167
7.2.	NUMERICAL SIMULATION	167
7.2.1.	Geometric and Material Properties of the Model	169

7.2.2.	Interface and Meshing Details	170
7.2.3.	Loading Conditions.....	171
7.2.4.	Validation of the Model	176
7.2.5.	Results.....	178
7.3.	CONSTRUCTION ASPECTS	192
7.3.1.	Geofoam Volume Requirement	192
7.3.2.	Selection of Geofoam Grade.....	193
7.4.	SUMMARY	197
CHAPTER 8:	CONCLUSIONS	199
8.1.	MAJOR CONCLUSIONS OF THE STUDY	199
8.1.1.	Physical Characteristics	199
8.1.2.	Mechanical Characteristics	200
8.1.3.	Parametric Evaluation of Design Parameters	201
8.1.4.	Interface Characteristics.....	202
8.1.5.	Numerical Simulation	203
8.2.	LIMITATIONS OF THE PRESENT STUDY	205
8.3.	SUGGESTIONS FOR FURTHER RESEARCH.....	206
REFERENCES		207
LIST OF PUBLICATIONS FROM THE CURRENT STUDY		229
BIODATA		230

LIST OF FIGURES

Figure 1.1	Statistics on the length of National Highways under construction in hilly terrain by a) NHAI, b) NHIDCL (Collated from project planning and progress reports 1
Figure 1.2	Typical slip surface anticipated for widened road with (a) conventional soil fill and (b) geofoam fill.....4
Figure 1.3	Key interfaces of a typical road-widening embankment using vertical-sided geofoam blocks5
Figure 2.1	Manufacturing process of geofoam; a) Pre-expansion, b) Storage, c) Moulding, d) Finished full-sized geofoam block of size 2.0 m × 1.0 m × 0.6 m 15
Figure 2.2	(a) Microscopic image of geofoam and b) the variation of the size of the EPS beads within the geofoam, with density (Adapted from Vaitkus, 2006)..... 17
Figure 2.3	Variation of average cell size with apparent density (Adapted from Bureau & Gendron, 2003)..... 18
Figure 2.4	Variation of compression parameters with nominal density reported by various researchers22
Figure 2.5	Comparison of modulus of elasticity values reported in the literature23
Figure 2.6	Size effect on the compression behaviour reported in the literature27
Figure 2.7	Cubical and cylindrical specimen before and after testing (Adapted from Akis et al., 2022).....28
Figure 2.8	Poisson's ratio values reported in the literature32
Figure 2.9	Monoblock shear strength parameters reported by various researchers34
Figure 2.10	Deformation measurement principle of 2D-DIC35
Figure 2.11	Test setup of Configuration B (after Özer & Akay, 2016).....37
Figure 2.12	Comparison of geofoam-sand interface friction angles and friction coefficients for sands with varying angles of shear resistance, reported in the literature ...38
Figure 2.13	Graphical representation of a) Configuration A, b) Configuration B, c) Deformed geofoam blocks observed in Configuration B.....39
Figure 2.14	Bilinear failure envelope of geofoam-sand; a) (Adapted from Atmatzidis et al., 2001), b) (after Xenaki and Athanasopoulos, 2001)43
Figure 2.15	Three interaction phases of the sand-geofoam interface (after Xenaki and Athanasopoulos, 2001).....43
Figure 2.16	Summary of the reported geofoam-geofoam interface friction angles45

Figure 2.17	Comparison of the numerical model and field observed (a) compression responses and (c) differential settlement (Newman et al., 2010)	48
Figure 2.18	Comparison of the predicted and observed settlement response (Adapted from, Özer & Akinay, 2022)	49
Figure 3.1	Flow chart for physical characterisation of geofoam	58
Figure 3.2	Microstructure of a) Single EPS bead at magnification 100X, b) Surface pores on the EPS bead at a magnification 1000X, c) A set of EPS beads, d) Fused beads inside a geofoam (50X)	59
Figure 3.3	Microstructure of geofoam; a) Undisturbed structure, b) Saw-cut specimen, c) Hotwire-cut specimen	60
Figure 3.4	Variation of morphological parameters with nominal density	61
Figure 3.5	Comparison of the SEM images (500X) after compression; a) 15D, b) 30D geofoam grades	62
Figure 3.6	(a) Variation of P-wave velocity in different directions, (b) Standard deviation of velocity in different directions	64
Figure 3.7	Variation of apparent density with nominal density	65
Figure 3.8	(a) Sample counts of different size categories, (b) Contour plot of the apparent density variation with size	66
Figure 3.9	a) Stylus Profiler testing, b) Roughness profile of different geofoam grades ..	67
Figure 3.10	Hardness measurement using Shore A durometer with the details of the plunger (adapted from ASTM D2240-15, 2021)	68
Figure 4.1	Flow chart for mechanical characterisation of geofoam	71
Figure 4.2	Schematic diagram of the flexural test setup	73
Figure 4.3	Schematic diagram of the monoblock shear test	74
Figure 4.4	2D-DIC test set-up	75
Figure 4.5	Variation of DIC strain to nominal strain; a) uniaxial compression test, b) flexural test	76
Figure 4.6	Unconfined compressive stress-strain behaviour of geofoam; a) Typical stress-strain response, b) Repeatability with variation bands	78
Figure 4.7	Relationship between compressive stresses and UPV	79
Figure 4.8	Variation of safety factors with an apparent density; a) Permissible stress, b) Yield Stress	80

Figure 4.9	Strain field images at varying nominal axial strains for different geofoam grades	82
Figure 4.10	Variation of Poisson's ratio with axial strain for varying nominal density; a) 15D, b) 20D, c) 25D, d) 30D.....	84
Figure 4.11	Flexural test results.....	86
Figure 4.12	a) Location of failure plane, b) Microscopic image of the surface of the failure plane	86
Figure 4.13	Variation of flexural strength for different geofoam grades	87
Figure 4.14	Variation of flexural strength and modulus with respect to apparent density ..	88
Figure 4.15	Strain field maps.....	90
Figure 4.16	Histogram of strain distribution at failure	91
Figure 4.17	Variation of stress ratio with horizontal displacement.....	93
Figure 4.18	Failure envelopes of geofoam monoblock	94
Figure 4.19	Strain field images of geofoam monoblock at various horizontal strain levels	95
Figure 5.1	Compression test set up.....	98
Figure 5.2	Measured compressive behaviour of geofoam under varying a) strain rate, b) temperature, c) cube sizes and d) cylinder sizes	99
Figure 5.3	Scatter matrices of the test results for varying parameters a) Nominal density, b) Strain rate, c) Temperature, d) Size, e) Shape.....	100
Figure 5.4	Variation of modulus of elasticity with apparent density	102
Figure 5.5	Variation of (a) modulus of elasticity and (b) compressive stress at 10% strain with apparent density	103
Figure 5.6	Variation of compressive stresses with strain rate	104
Figure 5.7	Variation of compressive stresses with temperature	106
Figure 5.8	Variation of compressive stresses with geofoam size and shape	107
Figure 5.9	Heat map of correlation coefficients	110
Figure 5.10	Architecture of the ANN model	116
Figure 5.11	Plot between the observed and the predicted values for training and testing datasets for $\sigma_{1\%}$, $\sigma_{10\%}$, and σ_y	118
Figure 5.12	Residual Plots of the Models.....	120

Figure 5.13	Relative importance of different input variables	122
Figure 6.1	SEM images (100X) of a) Sand 1 and b) Sand 2; c) Sequence of image analysis of a sand particle	126
Figure 6.2	Statistics of the morphological parameters of the sands	127
Figure 6.3	Grain size distribution curves of the sand	128
Figure 6.4	Direct shear test results of sands; a) Variation of stress-ratio with horizontal displacement, b) Failure envelopes	129
Figure 6.5	Interface test setup using modified configuration A	130
Figure 6.6	Test set-up for the interface testing	131
Figure 6.7	Summary of the interface testing program	132
Figure 6.8	Different patterns of geofoam ledges	133
Figure 6.9	Stress ratio variation with horizontal displacement for geofoam-sand planar interfaces and their failure envelopes	136
Figure 6.10	Microscopic images of the dry geofoam (a) before and (b) after the interface test	138
Figure 6.11	Variation of peak friction angle with a) density and b) surface hardness	139
Figure 6.12	SEM images of geofoam interface with dry sand; a) S ₁ 15, b) S ₁ 30.....	140
Figure 6.13	Variation of stress ratio and dilation angle with horizontal displacement for different geofoam-sand interfaces	141
Figure 6.14	Failure envelopes of geofoam-sand ledged interface	142
Figure 6.15	Variation of stress ratio with displacement for different sand types and geofoam grades	145
Figure 6.16	Variation of apparent friction coefficient with normal stress for varying a) sizes of ledges, b) shapes of ledges	146
Figure 6.17	Correlation plot of efficiency with the relative roughness	147
Figure 6.18	2D horizontal and vertical strain field at various stages of shearing	149
Figure 6.19	Variation of stress ratio and dilation angle with horizontal displacement	150
Figure 6.20	Failure envelopes of the geofoam-geofoam planar interfaces	151
Figure 6.21	Variation of stress ratio and dilation angle with horizontal displacement for varying densities geofoam-geofoam interfaces with different ledge sizes a) 2 mm; b) 4 mm	154

Figure 6.22	Failure envelopes and the variation of apparent friction coefficient and friction angle with ledge size	155
Figure 6.23	Variation of apparent friction coefficient and dilation angle with horizontal displacement for varying ledge shapes.....	157
Figure 6.24	2D horizontal strain field of geofoam-geofoam interfaces	159
Figure 6.25	Correlation plot of apparent friction coefficient with the geofoam roughness	160
Figure 6.26	Variation of friction coefficient with horizontal displacement for different concrete and geofoam grades and their failure envelopes.....	161
Figure 6.27	Variation of friction coefficient and friction angle with relative roughness ..	164
Figure 6.28	2D horizontal strain field of geofoam-concrete interface	165
Figure 7.1	Geometry of the model using geofoam	168
Figure 7.2	Finite element model including the flexible pavement layers.....	173
Figure 7.3	Variation of traffic load with time considered at a node for the FE simulation	174
Figure 7.4	Earthquake input motions of El Centro earthquake	175
Figure 7.5	Typical cross-section of geofoam embankment used for validation (after Newman et al., 2010)	176
Figure 7.6	Validation results.....	177
Figure 7.7	Plastic strain profile from the slope stability analysis.....	178
Figure 7.8	Results finite element simulation; a) Total displacement profile; b) Transverse displacement profile; c) Plastic strain profile.....	180
Figure 7.9	Vertical displacement and stress distribution along the depth of embankment	181
Figure 7.10	Variation of translational displacement profile with the depth; a) at the junction of existing and widened embankment, b) at the outer edge of the widened embankment	182
Figure 7.11	Variation of translational stresses at different geofoam interfaces for case B	183
Figure 7.12	Results finite element simulation of the steady seepage condition; a) Phreatic line; b) Pore pressure profile; c) Hydraulic gradient profile	184
Figure 7.13	a) Variation of pore pressure with depth behind the widened embankment; b) Factor of safety results from slope stability analysis	185

Figure 7.14	Results finite element simulation of the dynamic traffic loading condition; a) Total displacement profile; b) Transverse displacement profile; c) Shear stress profile	186
Figure 7.15	Variation of different output parameters with time for varying depths beneath the subgrade for case B	187
Figure 7.16	Variation of vertical displacement and stresses of the road surface; a) across the traffic direction; b) along the traffic direction.....	188
Figure 7.17	Response with time of widened embankment lane under earthquake: a) Acceleration; b) Horizontal displacement.....	189
Figure 7.18	Plastic strain profile.....	189
Figure 7.19	Variation of plastic strain with time of widened embankment lane under earthquake	190
Figure 7.20	Normal and shear stress range along various geofoam interfaces	191
Figure 7.21	Total volume requirement of hill road widening using geofoam blocks	193
Figure 7.22	Factors of safety with respect to geofoam layer number: a) Slope-sided embankment, b) vertical-facing embankment.....	196
Figure 7.23	Variation of geofoam material cost with slope angle.....	197

LIST OF TABLES

Table 2.1	Geofoam material properties investigated in the literature for various geotechnical applications	12
Table 2.2	Nominal densities and nomenclature of EPS geofoam manufactured in different countries	16
Table 2.3	Summary of the literature regarding the physical characteristics of geofoam	19
Table 2.4	Summary of the literature studies conducted regarding the compression behaviour of geofoam	24
Table 2.5	Summary of the studies conducted on the parametric evaluation of geofoam compression behaviour	30
Table 2.6	Summary of the literature on the flexural and monoblock shear behaviour of geofoam.....	34
Table 2.7	Summary of the geofoam interfaces literature studies.....	46
Table 2.8	Summary of the reported case studies of field monitoring and numerical simulation.....	50
Table 3.1	Analysis results of morphological parameters	62
Table 3.2	Morphological parameters after compression.....	63
Table 3.3	Statistical analysis results of apparent density measurement	65
Table 3.4	Roughness and hardness properties of geofoam	68
Table 4.1	Compression to tensile strain distribution at bending failure	91
Table 4.2	Comparison of monoblock shear results with the literature	94
Table 5.1	Specimen details and testing conditions	98
Table 5.2	Statistical analysis data from experiments conducted on 122 specimens....	109
Table 5.3	Interpretation of Spearman's rank correlation coefficient	111
Table 5.4	Statistical description of the compiled database	114
Table 5.5	Summary of comparison between various prediction models	119
Table 6.1	Physical and geotechnical properties of the sand	128
Table 6.2	Surface properties of concrete	129
Table 6.3	Specimen details and testing conditions	134

Table 6.4	Estimated average roughness of the ledged geofoam	134
Table 6.5	Comparison of geofoam-sand interface results with literature	137
Table 6.6	Interface shear strength parameters	143
Table 6.7	Comparison of geofoam-geofoam interface test results with literature	152
Table 6.8	Interface shear strength parameters of interlocked geofoams.....	158
Table 6.9	Comparison of geofoam-concrete interface test results with literature	163
Table 7.1	Material and Mesh Properties	170
Table 7.2	Interface properties	171
Table 7.3	Material and Mesh Properties of pavement layers.....	173

LIST OF NOTATIONS

A_i	Area of the SEM image (m ²)
M	Magnification factor for SEM image (dimensionless)
N	Number of cells in the SEM image (dimensionless)
N_f	Cell population density per unit volume (m ⁻³)
V	Ultrasonic pulse velocity (m/s)
V_f	Void fraction (%)
ρ_f	Apparent density of the geofoam (kg/m ³)
ρ_p	Unfoamed polymer density (kg/m ³)
$\sigma_{1\%}$	Compressive stress at 1% strain (kPa)
$\sigma_{5\%}$	Compressive stress at 5% strain (kPa)
σ_y	Yield stress (kPa)
$\sigma_{10\%}$	Compressive stress at 10% strain (kPa)
σ_h	Strain hardening stress (kPa)
c	Cohesion intercept (kPa)
ϕ	Angle of shearing resistance (°)
E_i	Modulus of elasticity of geofoam (MPa)
E_p	Young's modulus of solid polystyrene (MPa)
γ_p	Density of solid polystyrene (kg/m ³)
γ_f	Apparent density of geofoam (kg/m ³)
C	Correlation constant (dimensionless)
R	Rate of crosshead motion (mm/min)
Z	Strain rate of the outer fibre (min ⁻¹)

S	Maximum outer fibre stress (MPa)
ε	Maximum outer fibre strain (dimensionless)
E_f	Flexural modulus (MPa)
L	Length of the specimen (mm)
b	Breadth of the specimen (mm)
d	Depth of the specimen (mm)
P	Load (N)
F	Deflection at the load fixture position (mm)
I	Moment of inertia (mm ⁴)
D	Corrected deflection at the centre of the sample (mm)
$\varnothing$	Diameter of the cylinder (mm)
H	Height of the cylinder (mm)
r_s	Spearman's rank correlation coefficient(dimensionless)
X'_i	Rank of the independent variable (dimensionless)
Y'_i	Rank of the dependent variable (dimensionless)
y'	Predicted value (respective unit of the parameter)
y	Measured values (respective unit of the parameter)
i	Number of input parameters (dimensionless)
n	Number of datasets (dimensionless)
B	Size of the specimen (mm)

AR	Aspect ratio of cylinder (dimensionless)
du	Horizontal displacement (mm)
dv	Vertical displacement (mm)
Q	Subset (pixels)
δ	Interface friction angle ($^{\circ}$)
A	Angularity (dimensionless)
C	Circularity (dimensionless)
R	Roundness (dimensionless)
P_c	Convex hull perimeter of the particle (mm)
P_e	Perimeter of the equivalent ellipse (mm)
L_e	Major axis length of the equivalent ellipse (mm)
A_p	Area of the particle projection profile (mm^2)
P_p	Perimeter of the particle projection profile (mm)
d_{50}	Average particle size (mm)
d_{10}	Particle size corresponding to 10 % finer (mm)
C_u	Uniformity coefficient (dimensionless)
C_c	Coefficients of curvature (dimensionless)
$\gamma_{\max}$	Maximum dry unit weight (kN/m^3)
$\gamma_{\min}$	Minimum dry unit weight (kN/m^3)
$e_{\max}$	Maximum void ratio (dimensionless)

$e_{\min}$	Minimum void ratio (dimensionless)
w	Shear box width (mm)
d	Shear box depth (mm)
h_l	Height of the ledge (mm)
σ_n	Normal stress (kPa)
$(R_a)_l$	Average surface roughness of the ledged geofoam (μm)
k	Width ratio of the ledge (dimensionless)
w_l	Width of the ledge (mm)
h_{avg}	Average height of the ledge (mm)
R_a	Average roughness (μm)
c_a	Adhesion intercept (kPa)
μ'	Apparent friction coefficient (dimensionless)
μ'^*	Average friction coefficient (dimensionless)
ψ	Dilation angle ($^\circ$)
μ'_p	Peak apparent friction coefficient (dimensionless)
e	Void ratio (dimensionless)
RD	Relative density (%)
R'	Relative roughness (dimensionless)
E_δ	Efficiency factor of the interface (dimensionless)
H_{disp}	Horizontal displacement (mm)

γ	Unit weight (kN/m ³)
E	Modulus of elasticity (MPa)
ν	Poisson's ratio (dimensionless)
K	Normal stiffness (MN/m ³)
G	Shear stiffness (MN/m ³)
P_o	Static wheel load (kN)
P	Load induced by the wheel traction (kN)
M_o	Momentum from the unsprung weight of the wheel (kN s ² /m)
$\mu_{w/r}(y)$	Road roughness function (m)
v	Speed of the vehicles (m/s)
L	Geometric curve wavelength of the pavement (m)
t	Duration of load (s)
σ_p	Static surcharge from the pavement (kPa)
γ_s	Density of side cover soil (kN/m ³)
t_s	Thickness of side cover soil (m)
h_b	height of geofoam blocks (m)
j	geofoam layer number from the embankment top (dimensionless)
m	total number of geofoam blocks in an embankment (dimensionless)
σ_t	Traffic surcharges (kPa)
σ_v^i	Total vertical stress acting at each layer (kPa)

LIST OF ABBREVIATIONS

MHA	Ministry of Home Affairs
NH	National Highways
NHIDCL	National Highways & Infrastructure Development Corporation Limited
NHAI	National Highway Authority of India
ASTM	American Society for Testing and Materials
IRC	Indian Roads Congress
IS	Indian Standard
FoS	Factor of Safety
CBR	California Bearing Ratio
DIC	Digital Image Correlation
EPS	Expanded Polystyrene
SEM	Scanning Electron Microscope
UPV	Ultrasonic Pulse Velocity
RMS	Root Mean Square
UTM	Universal Testing Machine
ROI	Region of Interest
SF	Safety Factor
ANN	Artificial Neural Network
XGBoost	Extreme gradient boosting

ML	Machine Learning
R^2	Coefficient of determination
CoV	Coefficient of Variance
MSE	Mean square error
RMSE	Root mean square error
MAE	Mean absolute error
MAPE	Mean absolute percent error
ELU	Exponential linear unit
ReLU	Rectified linear unit
SW	Well graded sand
SP	Poorly graded sand
NR	Not reported
LDS	Load distribution slab
FLAC	Fast Lagrangian Analysis of Continua
FEM	Finite Element Method
SRM	Strength Reduction Method
MSA	Million Standard Axles
PIB	Press Information Bureau