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

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by

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submitted

in fulfilment of the requirements of the degree of

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Dedicated to My Son

Haricharan 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 इंटरफ़ेस का आकलन करने के लिए अलग-अलग गहराई स्तरों पर जियोफोम के इंटरफ़ेस 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।

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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 (^{o})
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)
⌀	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 (º)
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)
γ_{max}	Maximum dry unit weight (kN/m^3)
γ_{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 (°)
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)
υ	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)
$\sigma_v{}^i$	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