PHYSICAL MODELLING OF ENCASED STONE COLUMNS WITH TIRE-DERIVED AGGREGATES: MODEL AND FIELD EXPERIMENTS

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DEDICATED

TO

MY BELOVED PARENTS

&

In the memory of my Late friend TAMMU MAHESH

CERTIFICATE

This is to certify that the thesis entitled **"PHYSICAL MODELLING OF ENCASED STONE COLUMNS WITH TIRE-DERIVED AGGREGATES: MODEL AND FIELD EXPERIMENTS"** submitted by **Mr. UPENDRA MODALAVALASA** to the Indian Institute of Technology Delhi, is a record of the bonafide research work carried out by him under our supervision and guidance. This thesis work, in our opinion, has reached the standard, fulfilling the requirements for **DOCTOR OF PHILOSOPHY** degree. The research report and the results presented in this thesis have not been submitted, in part or full, to any other university or institute, for the award of any degree or diploma.

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ABSTRACT

With the expansion of industrialization, the need for land with sufficient load-bearing capacity—especially soft soils—has grown to accommodate infrastructure such as heavy buildings, machinery, runways, port facilities, embankments, and oil storage tanks. However, the rising consumption of natural resources like stone aggregates, commonly used in stone columns for ground improvement, has led to the search for sustainable alternatives. This study focuses on shredded tire chips, known as Tire Derived Aggregate (TDA), as a potential replacement for stone aggregates in stone column applications. Discarded tires, which are difficult to dispose of due to their slow decomposition and landfill limitations, present a significant environmental issue. Recent developments in geotechnical engineering have highlighted the feasibility of using scrap tires as economical and eco-friendly materials. This research examines the performance of stone columns made with various combinations of stone aggregates and TDA, in accordance with ASTM D6270 guidelines for the use of scrap tires in civil engineering projects.

A comprehensive series of 170 element tests were conducted using large-scale triaxial tests to analyze the stress-strain response of stone columns with different TDA sizes and varying mix proportions with stone aggregates (SA). The results indicated that increasing the proportion of TDA reduces the failure deviatoric stress, decreases the angle of shearing resistance, and increases the apparent cohesion. Attempts were made to compensate the loss in shear strength of stone aggregates due to the inclusion of TDA by various reinforcing methods. Element tests were performed on SA+TDA mix proportions by horizontally reinforcement; encasement; horizontally reinforcement and encasement. The performance of the stone columns made up with SA+TDA mix proportions are compared to that of OSC made of 100% SA as a benchmark. The results indicated that with the help of encasement about 65% of SA can be replaced with TDA by volume.

To further evaluate the performance of TDA-based stone columns, 20 single-column and 4 group-column model tests were conducted on geogrid encased stone columns with a length of 660 mm and a diameter of 110 mm. Two types of geogrids with different tensile strengths were used to assess the influence of tensile strength on the load-carrying capacity and bulging behaviour of the columns. Strain gauges were placed along the geogrid encasement to monitor the bulging behaviour of the columns. The model tests results are accessed with the help of efficiency of stone columns made of SA+TDA with that of OSC_100SA. The results from model tests indicated that with the help of encasement about 70% of SA can be replaced with TDA by volume.

To validate the findings from the model tests, six full-scale field studies were conducted in Madurai, Tamil Nadu, on encased stone columns with different proportions of stone aggregates and TDA. The field columns, measuring 300 mm in diameter and 4.5 m in depth, were installed in strata comprising 4 m of clay followed by 2 m of silt. Borehole investigations were carried out prior to field testing, and plate load tests were performed on the installed columns using a reaction arrangement. The results obtained from the field tests closely aligned with the outcomes of the model tests, confirming that encased stone columns with TDA aggregates perform comparably to conventional stone columns.

Following the successful completion of field tests, numerical analysis was performed using PLAXIS 3D software to simulate the behaviour of encased stone columns with varying proportions of TDA and stone aggregates. The simulations were conducted to analyse the load-settlement behaviour, stress distribution, and deformation characteristics of the columns. The results obtained from the PLAXIS 3D analysis further validated the experimental and field findings, providing deeper insights into the interaction between the encasement, stone aggregates, and TDA. Parametric study is also conducted on stone columns made of 70SA+30TDA mix proportions to quantify the improvement ratios by varying the stiffness of geogrid, diameter of column, undrained shear strength of clay.

The findings of this study demonstrate that TDA can serve as a viable and sustainable alternative to stone aggregates in stone columns. The use of TDA not only reduces dependency on natural resources but also provides an environmentally responsible solution for the disposal of non-biodegradable waste. Encased stone columns with TDA can effectively stabilize soft ground, reduce settlement, and maintain load-carrying capacity. The results from the comprehensive study done through triaxial tests, model tests, field tests and numerical analysis confirms that TDA-based stone columns perform similarly to conventional stone columns, making them a promising solution for sustainable ground improvement.

सार

औद्योगीकरण के विस्तार के साथ, भारी इमारतों, मशीनरी, रनवे, बंदरगाह सुविधाओं, तटबंधों और तेल भंडारण टैंकों जैसे बुनियादी ढाँचे के लिए पर्याप्त भार वहन क्षमता वाली भूमि–विशेषकर नरम मिट्टी–की आवश्यकता बढ़ गई है। हालाँकि, प्राकृतिक संसाधनों जैसे पत्थर के समुच्चय, जिनका उपयोग आमतौर पर भूमि सुधार के लिए पत्थर के स्तंभों में किया जाता है, की बढ़ती खपत ने स्थायी विकल्पों की खोज को जन्म दिया है। यह अध्ययन टायर व्युत्पन्न समुच्चय (TDA) के रूप में जाने जाने वाले कटे हुए टायर चिप्स पर केंद्रित है, जो पत्थर के स्तंभ अनुप्रयोगों में पत्थर के समुच्चय के संभावित प्रतिस्थापन के रूप में है। त्यागे गए टायर, जिनका उनके धीमे अपघटन और लैंडफिल सीमाओं के कारण निपटान करना मुश्किल होता है, एक गंभीर पर्यावरणीय समस्या प्रस्तुत करते हैं। भू-तकनीकी इंजीनियरिंग में हाल के विकासों ने स्क्रैप टायरों को किफायती और पर्यावरण-अनुकूल सामग्री के रूप में उपयोग करने की व्यवहार्यता पर प्रकाश डाला है। यह शोध सिविल इंजीनियरिंग परियोजनाओं में स्क्रैप टायरों के उपयोग के लिए ASTM D6270 दिशानिर्देशों के अनुसार, पत्थर के समुच्चय और TDA के विभिन्न संयोजनों से बने पत्थर के स्तंभों के प्रदर्शन की जाँच करता है।

विभिन्न TDA आकारों और भिन्न मिश्रण अनुपात वाले पत्थर के स्तंभों के प्रतिबल-विकृति अनुक्रिया का विश्लेषण करने के लिए बड़े पैमाने पर त्रिअक्षीय परीक्षणों का उपयोग करते हुए 170 तत्व परीक्षणों की एक व्यापक श्रृंखला आयोजित की गई, जिसमें पत्थर समुच्चयों (SA) के साथ उनका विश्लेषण किया गया। परिणामों से संकेत मिला कि TDA का अनुपात बढ़ाने से विफलता विचलन प्रतिबल कम होता है, कतरनी प्रतिरोध का कोण घटता है, और स्पष्ट संसंजकता बढ़ती है। TDA के समावेश के कारण पत्थर समुच्चयों की कतरनी शक्ति में हुई हानि की विभिन्न सुदृढ़ीकरण विधियों द्वारा क्षतिपूर्ति करने का प्रयास किया गया। SA+TDA मिश्रण अनुपातों पर क्षैतिज सुदृढ़ीकरण; आवरण; क्षैतिज सुदृढ़ीकरण और आवरण द्वारा तत्व परीक्षण किए गए। SA+TDA मिश्रण अनुपातों से बने पत्थर के स्तंभों के प्रदर्शन की तुलना बेंचमार्क के रूप में 100% SA से बने OSC से की गई।

परिणामों से संकेत मिला कि आवरण की सहायता से लगभग 65% SA को आयतन के हिसाब से TDA से प्रतिस्थापित किया जा सकता है। टीडीए-आधारित पत्थर के स्तंभों के प्रदर्शन का और अधिक मूल्यांकन करने के लिए, 660 मिमी लंबाई और 110 मिमी व्यास वाले जियोग्रिड आवरण वाले पत्थर के स्तंभों पर 20 एकल-स्तंभ और 4 समूह-स्तंभ मॉडल परीक्षण किए गए। स्तंभों की भार वहन क्षमता और उभार व्यवहार पर तन्य शक्ति के प्रभाव का आकलन करने के लिए विभिन्न तन्य शक्तियों वाले दो प्रकार के जियोग्रिड का उपयोग किया गया। स्तंभों के उभार व्यवहार की निगरानी के लिए जियोग्रिड आवरण के साथ तनाव गेज लगाए गए थे। मॉडल परीक्षण के परिणाम SA+TDA से बने पत्थर के स्तंभों की दक्षता का OSC_100SA से तुलना करके प्राप्त किए गए हैं। मॉडल परीक्षणों के परिणामों से संकेत मिलता है कि आवरण की सहायता से लगभग 70% SA को आयतन के हिसाब से TDA से बदला जा सकता है।

300 मिमी व्यास और 4.5 मीटर गहराई वाले क्षेत्र स्तंभों को 4 मीटर मिट्टी और उसके बाद 2 मीटर गाद वाले स्तर पर स्थापित किया गया था। क्षेत्र परीक्षण से पहले बोरहोल जांच की गई और प्रतिक्रिया व्यवस्था का उपयोग करके स्थापित स्तंभों पर प्लेट लोड परीक्षण किए गए। क्षेत्र परीक्षणों से प्राप्त परिणाम मॉडल परीक्षणों के परिणामों के काफी हद तक अनुरूप थे, जिससे पुष्टि हुई कि टीडीए समुच्चय वाले आवरणयुक्त पत्थर के स्तंभ पारंपरिक पत्थर के स्तंभों के समान ही प्रदर्शन करते हैं।

क्षेत्र परीक्षणों के सफल समापन के बाद, टीडीए और पत्थर के समुच्चय के अलग-अलग अनुपातों वाले आवरणयुक्त पत्थर के स्तंभों के व्यवहार का अनुकरण करने के लिए PLAXIS 3D सॉफ्टवेयर का उपयोग करके संख्यात्मक विश्लेषण किया गया। स्तंभों के भार-निपटान व्यवहार, प्रतिबल वितरण और विरूपण विशेषताओं का विश्लेषण करने के लिए सिमुलेशन आयोजित किए गए। PLAXIS 3D विश्लेषण से प्राप्त परिणामों ने प्रयोगात्मक और क्षेत्र निष्कर्षों को और अधिक मान्य किया, जिससे आवरण, पत्थर के समुच्चय और टीडीए के बीच परस्पर क्रिया के बारे में गहन

जानकारी मिली। 70SA+30TDA मिश्रण अनुपात से बने पत्थर के स्तंभों पर भी पैरामीट्रिक अध्ययन किया गया है ताकि जियोग्रिड की कठोरता, स्तंभ का व्यास, मिट्टी की अपरदन शक्ति को बदलकर सुधार अनुपातों को मापा जा सके।

इस अध्ययन के निष्कर्ष दर्शाते हैं कि TDA पत्थर के स्तंभों में पत्थर के समुच्चय के लिए एक व्यवहार्य और टिकाऊ विकल्प के रूप में काम कर सकता है। TDA का उपयोग न केवल प्राकृतिक संसाधनों पर निर्भरता को कम करता है, बल्कि गैर-जैवनिम्नीकरणीय कचरे के निपटान के लिए एक पर्यावरणीय रूप से जिम्मेदार समाधान भी प्रदान करता है। TDA के साथ संलग्न पत्थर के स्तंभ प्रभावी रूप से नरम जमीन को स्थिर कर सकते हैं, निपटान को कम कर सकते हैं, और भार वहन क्षमता बनाए रख सकते हैं। त्रिअक्षीय परीक्षणों, मॉडल परीक्षणों, क्षेत्र परीक्षणों और संख्यात्मक विश्लेषण के माध्यम से किए गए व्यापक अध्ययन के परिणाम इस बात की पुष्टि करते हैं

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c	Apparent cohesion
S_u	undrained shear strength of kaolinite clay
N	Number of blows
ϕ	angle of internal friction
υ	Poisson's ratio
τ	shear stress
σ_3 and σ_c	Confining pressure
φ_s	Sphericity
σ	Normal stress
σ_1	Triaxial compressive strength
ε	Axial strain
ε_h	Hoop strain
p	Mean principle stress
q	Mean shear stress
$\Delta\ \sigma_f$	Failure deviatoric stress
d and D	diameter of the column
d_s	size of aggregates
d_{smax}	maximum size of aggregates
E_{50}	Secant modulus of elasticity
h	Height of the specimen
L	length of the column

n	prototype stone column diameter/model test column diameter
$1/n^3$	scale factor for force (for 1g laboratory)
U_x	Lateral displacement
IS	Indian Standard
HRG	Horizontal Reinforced Geogrid layer
SPT	Standard Penetration Test
SA	Stone Aggregates
TDA	Tire Derived Aggregates
MP	Mix Proportions
GG	Geogrid
100SA	100% Stone Aggregates
70SA+30TDA	70% Stone Aggregates + 30% Tire Derived Aggregates
50SA+50TDA	50% Stone Aggregates + 50% Tire Derived Aggregates
30SA+70TDA	30% Stone Aggregates + 70% Tire Derived Aggregates
100TDA	100% Tire Derived Aggregates
OSC	Ordinary Stone Columns
ESC	Encased Stone Columns
HROSC	Horizontally reinforced Ordinary Stone Column
HRESC	Horizontally reinforced Encased Stone Column
MSC	Mix proportion ordinary Stone Column
GMSC	Geogrid encased MSC