Kochi Chapter

Indian Geotechnical Conference
IGC 2022
15th – 17th December, 2022, Kochi

Biopolymer stabilization of highly plastic silty soil for rammed earth construction materials

Deepak Patwa[1][0000-0002-7163-4014], Anant Aishwarya Dubey[1,2][0000-0002-9890-9583], K. Ravi[1][0000-0002-3152-1533], S. Sreedeep[1][0000-0003-2566-6901]

[1] Indian Institute of Technology Guwahati, Guwahati, Assam 781039, India
[2] Curtin University, Perth, Western Australia 6102, Australia
deepak21@iitg.ac.in

Abstract. Earthen construction materials (ECM) have been used in India since ancient times in the form of rammed earth blocks and mud house walls. The subsoil is often stabilized with lime/cement to improve its performance and durability. The use of lime/cement promotes the carbon footprint due to their high embodied energy. On the other hand, soil stabilization with biopolymers such as Xanthan Gum (XG) has demonstrated promising results in strength enhancement and negligible ecological risks. The ECM is expected to have a high Unconfined Compressive Strength (UCS) along with low erodibility and thermal conductivity. The current study investigates the influence of biopolymer amendment varying from 0.5% to 1.5% by weight of soil on the UCS, erodibility, and thermal characteristics of an abundantly available highly plastic silty soil in the Brahmaputra valley of the Assam region of India. The study reveals that the increment in biopolymer content results in a four-fold increment in the UCS of bare soil with no practical variation in the thermal conductivity, implying their potential to provide thermal comfort as a building unit. However, the pocket erosion test revealed that although the biopolymer treatment drastically enhances the erosion resistance of untreated soil, the proposed ECM remains in medium erodibility class, limiting its applicability in infrastructures designed for the long term. Nonetheless, the proposed ECM can be utilized effectively as a building unit for the rapid construction of temporary infrastructure, specifically for armed forces and highway engineers that are required to stay at a workstation transiently.

Keywords: Earthen Construction Materials, Biopolymer, Xanthan Gum, Thermal Conductivity, Erosion, Unconfined Compressive Strength (UCS).

1 Introduction

Earthen construction materials (ECM) have been an integral part of ancient construction practices in India [1, 2]. In recent times, there has been a reawakened interest in ECM for sustainable construction due to low embodied energy, low carbon footprint, and recyclability [3]. Their manufacturing is convenient due to the abundant availability of raw materials and simple preparation techniques. However, the ECM must be reinvented to fulfill the modern construction requirements to function as a structural component that possesses high mechanical strength, low erodibility, and low thermal conductivity. The above-discussed characteristics are desired to achieve durable and weather-adaptive thermally comfortable building units for sustainable housing.

An ECM consisting of locally available well-graded soil is prepared by compressing it at a high density. Such ECM is often termed as rammed or compressed earth blocks. Due to their molding at high density, such blocks are heavy and difficult to transport. There are a limited number of studies that have considered blending the local soil with clay, lime, cement, and biocement to improve the strength characteristics of the compressed earth blocks [3–5]. However, the application of chemical stabilizers like cement and lime to earthen materials might lead to an increase in the embodied energy and carbon footprint, contrary to the principles of sustainable infrastructure [6, 7]. It would also adversely affect its operational energy and recyclability. Additionally, these materials must be able to protect the blocks against environmental deterioration, such as moisture/rainfall-induced erosion. Therefore, finding a sustainable alternative to improve the strength of ECM is of utmost importance.

Recent studies reported that the addition of biopolymers such as Xanthan Gum (XG) to soil could improve the strength and erosion resistance significantly [8–17]. However, the application of biopolymers in view of preparing an ECM has not been well explored yet. The thermal characteristics of such biopolymer-based ECM have not been reported in the literature hitherto. Therefore, within the framework of the discussed gaps in the literature, this study investigates the applicability of biopolymers in preparing ECM that has high strength, low thermal conductivity, and negligible erodibility. For this purpose, the locally available highly plastic clayey soil is amended with different proportions of XG varying in the range of 0.5% to 1.5%. The prepared specimens are investigated via unconfined compressive strength (UCS), thermal conductivity (K), and pocket erosion test (PET). The microstructure of the treated specimen is also investigated via Field-Emission Scanning Electron Microscopy (FESEM). An experimental summary is demonstrated in Fig.1.

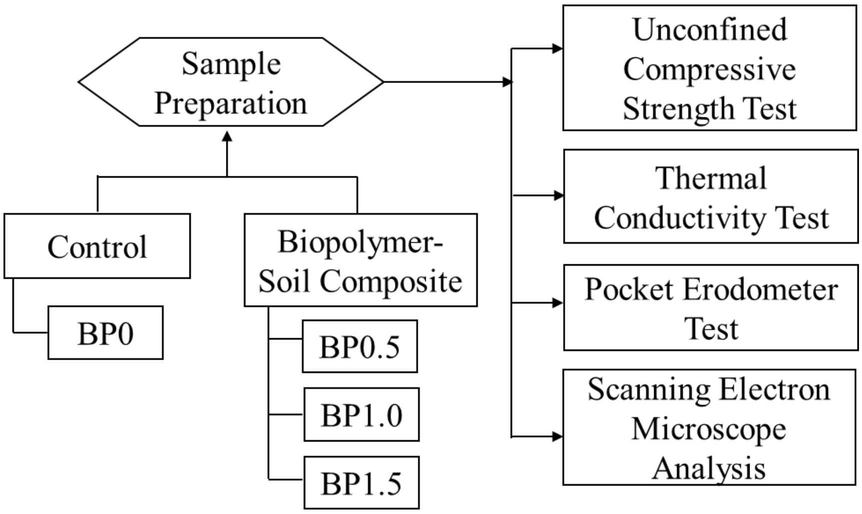

Fig. 1. Experimental summary of current study

2 Materials and Methods

2.1 Soil and Biopolymer

A locally available soil was collected from the Indian Institute of Technology Guwahati campus. The soil was physically cleaned of vegetation and then sieved through a 4.75 mm sieve. The sieved soil was then evaluated for its grain size distribution and index properties in accordance with ASTM standards and presented in Fig. 2 and Table 1. According to the unified soil classification system (USCS), the soil is characterized as highly plastic silt (MH).

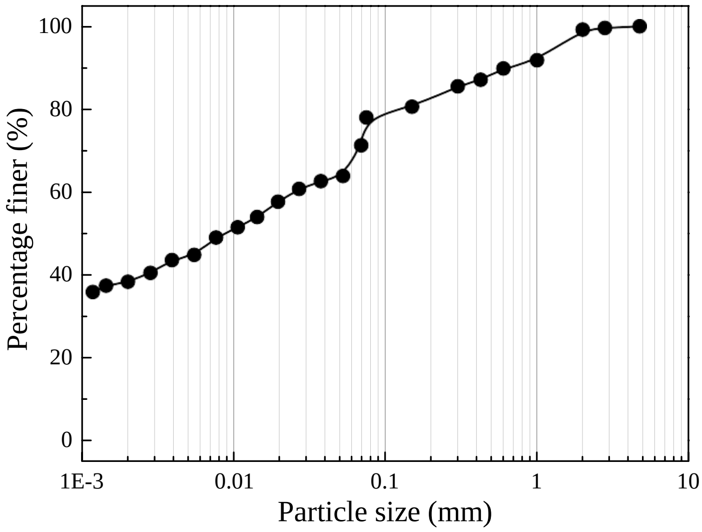

Fig. 2. Particle size gradation of used soil

Table 1. Index and geotechnical properties of the soil [18]

Properties	Values	Standards
Specific gravity (Gs)	2.71±0.011	ASTM D854 (2010)
Particle size fraction (%)		ASTM D422 (2007)
Coarse grain sand (4.75–2 mm)	0.80	
Medium grain sand (2–0.425 mm)	12.08	
Fine grain sand (0.425–0.075 mm)	9.12	
Silt content (0.075-0.002mm)	39.72	
Clay content (less than 0.002 mm)	38.28	
Consistency limits (%)		ASTM D4318 (2010)
LL (W_L)	54.41	
PL (W_L)	35.23	
Compaction parameter		ASTM D698 (2012)
OMC (%)	22.72	
MDD (g/cc)	1.58	
USCS classification	MH	ASTM D2487 (2011)
BET surface area (m^2/g)	41.35	BET Analysis

This type of soil is selected due to its clay-rich content. The clay particles are reported to form highly stable cationic and hydrogen bonds with the carboxylic group of XG [9]. A commercially accessible biopolymer (xanthan gum, XG) used in this study was procured from Himedia Laboratories Pvt. Ltd, India.

2.2 Samples preparation

In this study, the biopolymer content was selected as 0.5 %, 1.0 %, and 1.5 % by dry weight of soil. The XG solution was prepared by mixing the desired quantity of XG powder with the required quantity of distilled water, which is equal to the OMC (optimum moisture content). To avoid agglomeration, the mixing of biopolymer in distilled water was carried out on a warm plate at 60°C with continuous stirring with a magnetic stirrer. The dry soil and produced xanthan gum solution were manually mixed in an aluminum tray.

2.3 Unconfined compressive strength (UCS)

The UCS tests were carried out according to ASTM D2166 (ASTM 2006). A cylindrical sample with dimensions of 3.8 cm in diameter and 7.6 cm in length was created in a cylinder-shaped sampler mold. Previous studies revealed that a curing temperature of 60°C for seven days improved strength to the greatest extent possible [9, 15, 19]. Therefore, the sample was cured at a temperature of 60 °C for seven days to allow the hardening of the xanthan gum. The compressive load was applied to the sample at a constant strain rate of 1.25 mm/min, and the corresponding stress-strain responses were created for each sample. The plots were used to derive the secant modulus of elasticity (E_{50}) and unconfined compressive strength. The secant modulus at half of the peak stress is known as E_{50}. For each test condition, three replicate samples were examined to assess the repeatability of the UCS data. The average peak stress value of these samples was then reported as the UCS value.

2.4 Thermal conductivity measurement

The sample preparation procedure was the same as for the UCS test. For thermal conductivity measurement, the sample was poured into the transparent plastic mold (acrylic) having an inside diameter of 8 cm and a sample height of 6 cm and then compacted in a three-layer to MDD by a static compression loading apparatus. Thereafter, the sample was extracted using the sample extruder and cured at a temperature of 60 °C for seven days. The thermal conductivity was measured using an SH-1 thermal probe sensor [18]. For measuring thermal conductivity (K), a steel needle with a sharp edge that was slightly smaller in diameter than the actual probe was used to make a dummy hole that would make it simpler to put the needle probe into the cured sample. Thereafter, the thermal probe was put into the center of the samples. Before conducting measurements, a 15-minute waiting period was required for the probe and soil samples to attain an equilibrium temperature.

2.5 Pocket Erodometer Test (PET)

A replicate of biopolymer-treated soil specimens of dimension 35 mm × 60 mm× 60 mm was prepared to evaluate the erosion resistance by a modified protocol for the pocket erodometer test prescribed by Briaud et al. [20]. A water impulse with a velocity of 8±0.5 m/sec was fired on the test specimen for 20 times. The eroded depth (PET depth) was measured using a Vernier caliper. It must be noted that the pocket erodometer is a brute way to compare the erodibility of soil in comparison to the sophisticated Erosion Function Apparatus (EFA). However, it is a convenient method to compare the erosion resistance of the geomaterials [21].

3 Results and discussion

3.1 Influence of biopolymer amendment on UCS and Secant Modulus

Fig.3 illustrates the stress-strain response of the soil samples stabilized with distinct biopolymer content after curing. The untreated soil (BP0) exhibited lower peak stress of 1.25 MPa. The addition of biopolymer to bare soil increases the peak stress and peak strain at failure conditions of soil samples. The failure strain of soil sample was observed to be increase by 17% in sample BP0.5. This shows the development of a cohesive bond between soil particles. A consistent increase in peak stress was observed with an increase in biopolymer content. A four-fold increase in the peak stress value was noted for treated sample BP1.5 (5.35 MPa) in comparison to untreated soil BP0 (1.25 MPa).

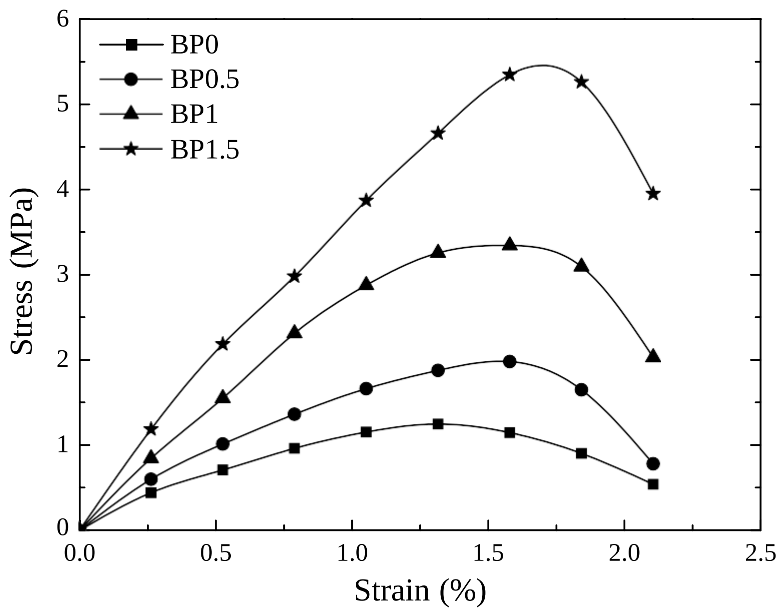

Fig. 3. Stress-strain response of biopolymer-stabilized soil

The UCS and secant modulus of elasticity (E_{50}) of soil stabilized with various biopolymer contents are shown in Fig. 4. E_{50} is defined as the secant modulus at half of the peak stress. The UCS of soil was found to be increase by 59%, 168%, and 328%. Similarly, the E_{50} of soil was noted to be increased by 27%, 100%, and 160%. The increase in strength of the biopolymer-stabilized soil sample is credited to the development of bridges between the soil particles, hydrogen bonds, and the formation of cohesive forces between xanthan gum and electrically charged clay particles [9, 22]. This result is also supported by micrographic analysis, which revealed the mechanism of biopolymer stabilization of soil at the microscale.

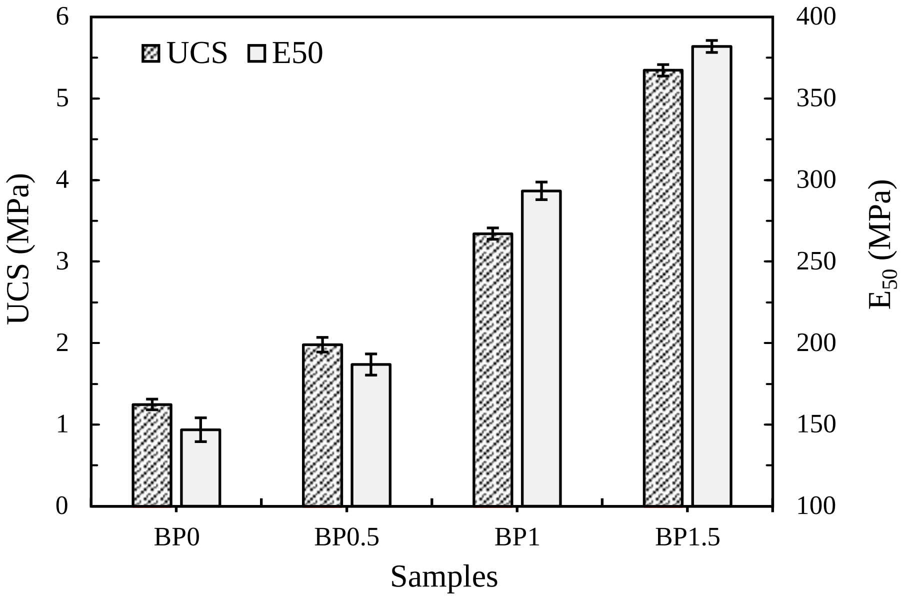

Fig. 4. UCS and E_{50} of biopolymer stabilized soil

To reveal the stabilization mechanism, a sample was extracted from the biopolymer stabilized sample, and FESEM analysis was carried out. Fig.5 shows the SEM micrograph of the biopolymer stabilized sample, which illustrates the coating of the biopolymer layer on the soil particles and the development of bridging between the soil particles. During loading, the biopolymer sheets between soil particles get stretched, which creates cohesion between the soil particles. Thus, the biopolymer-stabilized sample can sustain much more compressive stress and strain before failure.

It is to be noted that the biopolymer-stabilized soil might lose strength if the soil is cohesionless [9]. The strength of the biopolymer-treated soil tends to be less influenced by the presence of moisture when the clay content increases, as the hydroxyl group (-OH) of clays and the carboxyl group of Xanthan Gum (-COOH) make cation and hydrogen bonding.

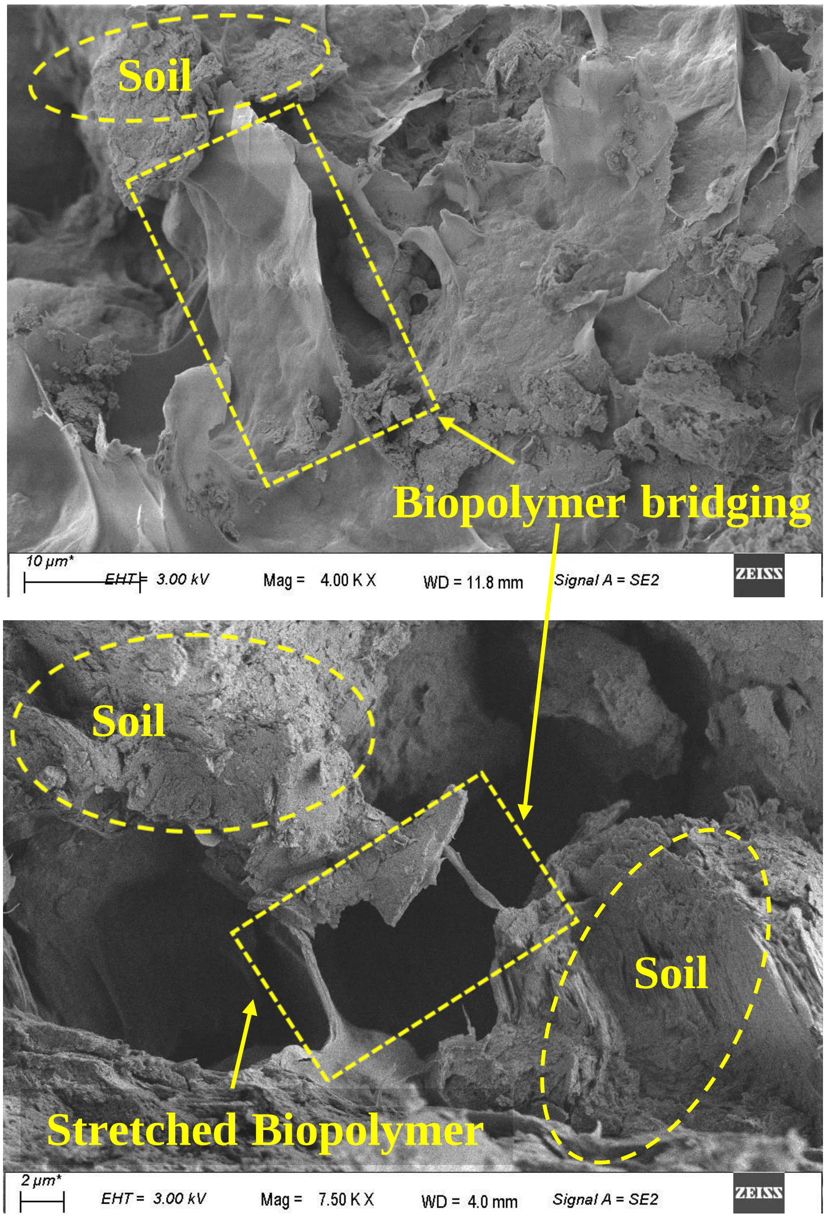

Fig. 5. UCS and E_{50} of biopolymer stabilized soil

3.2 Influence of biopolymer amendment on thermal conductivity

Fig.6 presents the thermal conductivity (*K*) of the soil stabilized with various biopolymer content. The thermal conductivity value was noted to be marginally increased with the addition of bipolymer content. This is attributed to an increase in the bonding of soil particles, which occurs when the soil particles get closer during the xanthan gum's hardening process. However, the observed variation in thermal conductivity is practically insignificant with biopolymer addition.

There are alternate techniques that can either increase the strength of soil or reduce the thermal conductivity of the soil. The soil treatment method which can impart both characteristics to the soil is scarce. Such as, the amendment of soil with biochar and fibers reduces the thermal conductivity of soil [3, 18, 23, 24]. However, the negative effect of this amendment is the diminution in the strength of soil [18]. On the other hand, trending eco-friendly techniques such as bio-cementation can also improve the strength of soil, but it also undesirably increases the thermal conductivity of soil [9, 25]. Therefore, the biopolymer treatment of soil in the case of ECM is one of the most suitable techniques that not only improves the strength of soil but also maintains low thermal conductivity.

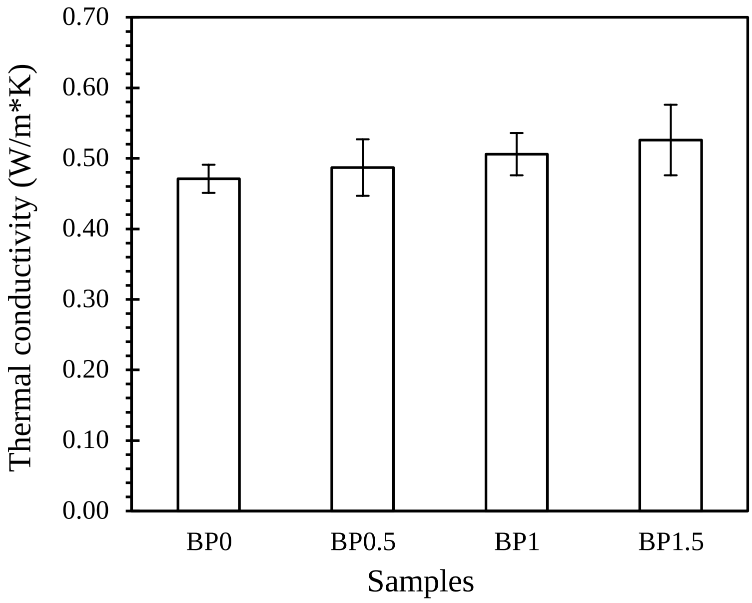

Fig. 6. Influence of biopolymer amendment on thermal conductivity of soil

3.3 Influence of biopolymer amendment on erosion resistance

Fig.7 presents the PET depth of the soil stabilized with various biopolymer content. The PET depth of erosion was noted to be reduced by 42%, 58%, and 67%, with the amendment of 0.5%, 1%, and 1.5% biopolymer content. This is credited to the increase in the bonding of soil particles which happens when the soil particles get closer during the xanthan gum's hardening process. The finding of this test revealed that although the biopolymer treatment drastically enhances the erosion resistance of the untreated soil, the treated soil remains in the medium erodibility class. This limits its applicability in designing the infrastructures in the vicinity of rivers, coasts, and heavy-rainfall areas such as North-East India.

In previous studies, it has been established that the biopolymer treatment for sandy soil is not suitable due to the hydrophilic nature of XG and the lack of the chance of formation of stable cationic bonds due to the scarcity of clay particles [9, 12, 24]. However, studies on fine-grained soils have established that the clayey soils treated with XG are substantially more stable [8, 16, 17, 26].

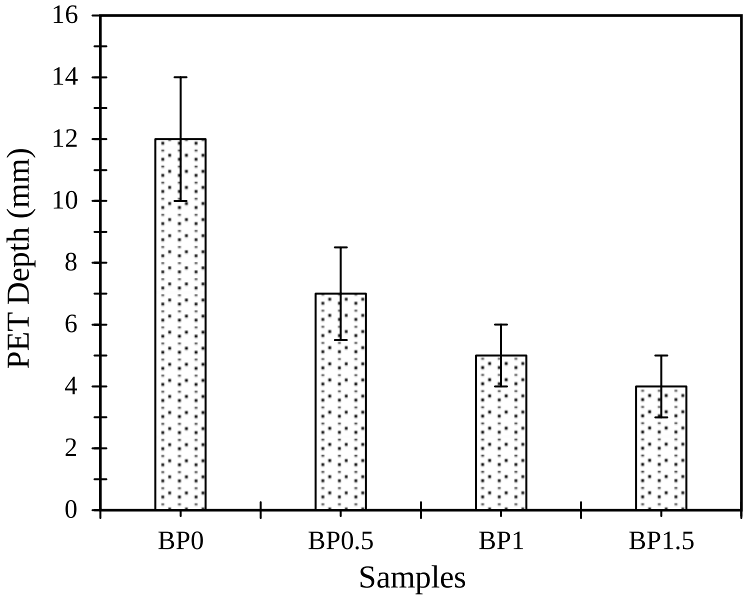

Fig. 7. Influence of biopolymer amendment on erodibility of soil

4 Conclusion

This study attempts to reinvent the earthen construction materials that can fulfill the demand of modern infrastructures by using a sustainable biopolymer binder. The current study is on the influence of biopolymer amendment (0.5%, 1%, and 1.5%) on unconfined compressive strength (UCS), thermal conductivity, and erosion resistance of a highly plastic silty soil for investigating its potential in developing an eco-friendly method to improve its applicability in the form of modern building units. This study finds positive outcomes regarding strength improvement, thermal, and erodibility performance. The addition of biopolymer in the soil increases the UCS by four-fold and reduces the erosion depth by three-fold while maintaining the thermal conductivity of the soil.

The finding of the study unravels the potential of xanthan gum biopolymers to replace lime/cement treatment for ECM. Therefore, the proposed ECM can be utilized effectively as a building unit for the rapid construction of temporary infrastructure, specifically for armed forces and construction/highway engineers that are required to stay at a workstation momentarily. This study will promote future investigations on earthen construction materials as they have shown potential to replace contemporary construction units due to their high mechanical strength, low thermal conductivity, negligible carbon footprint, low embodied energy, and convenient manufacturing process.

References

1. Chel A, Tiwari GN (2009) Thermal performance and embodied energy analysis of a passive house - Case study of vault roof mud-house in India. Appl Energy 86:1956–1969. https://doi.org/10.1016/j.apenergy.2008.12.033
2. Singh MK, Mahapatra S, Atreya SK (2011) Solar passive features in vernacular architecture of North-East India. Sol Energy 85:2011–2022. https://doi.org/10.1016/j.solener.2011.05.009
3. Karrech A, Strazzeri V, Elchalakani M (2021) Improved thermal insulance of cement stabilised rammed earth embedding lightweight aggregates. Constr Build Mater 268:121075. https://doi.org/10.1016/j.conbuildmat.2020.121075
4. Porter H, Blake J, Dhami NK, Mukherjee A (2018) Rammed earth blocks with improved multifunctional performance. Cem Concr Compos 92:36–46. https://doi.org/10.1016/j.cemconcomp.2018.04.013
5. Morel JC, Pkla A, Walker P (2007) Compressive strength testing of compressed earth blocks. Constr Build Mater 21:303–309. https://doi.org/10.1016/j.conbuildmat.2005.08.021
6. Maskell D, Heath A, Walker P (2014) Comparing the Environmental Impact of Stabilisers for Unfired Earth Construction. Key Eng Mater 600:132–143. https://doi.org/10.4028/www.scientific.net/KEM.600.132
7. Gallipoli D, Bruno AW, Perlot C, Mendes J (2017) A geotechnical perspective of raw earth building. Acta Geotech 12:463–478. https://doi.org/10.1007/s11440-016-0521-1
8. Muguda S, Lucas G, Hughes PN, et al (2020) Durability and hygroscopic behaviour of biopolymer stabilised earthen construction materials. Constr Build Mater 259:119725. https://doi.org/10.1016/j.conbuildmat.2020.119725
9. Ramachandran AL, Dubey AA, Dhami NK, Mukherjee A (2021) Multiscale Study of Soil Stabilization Using Bacterial Biopolymers. J Geotech Geoenvironmental Eng 147:1–16. https://doi.org/10.1061/(asce)gt.1943-5606.0002575
10. Devrani R, Dubey AA, Ravi K, Sahoo L (2021) Applications of bio-cementation and bio-polymerization for aeolian erosion control. J Arid Environ 187:104433. https://doi.org/10.1016/j.jaridenv.2020.104433
11. Dubey AA, Ravi K, Shahin MA, et al (2021) Bio-composites treatment for mitigation of current-induced riverbank soil erosion. Sci Total Environ 800:149513. https://doi.org/10.1016/j.scitotenv.2021.149513
12. Dubey AA, Hooper-Lewis J, Ravi K, et al (2022) Biopolymer-biocement composite treatment for stabilisation of soil against both current and wave erosion. Acta Geotech 2:. https://doi.org/10.1007/s11440-022-01536-2
13. Dubey AA, Dhami NK, Mukherjee A, et al (2021) Investigating the Potential of Xanthan Gum for Aeolian Erosion Mitigation. In: Sitharam TG, Parthasarathy CR, Kolathayar S (eds) Ground Improvement Techniques, Lecture Notes in Civil Engineering, Volume 118. Springer Singapore, pp 379–386
14. Seo S, Lee M, Im J, et al (2021) Site application of biopolymer-based soil treatment (BPST) for slope surface protection: in-situ wet-spraying method and strengthening effect verification. Constr Build Mater 307:124983. https://doi.org/10.1016/j.conbuildmat.2021.124983
15. Chang I, Lee M, Tran ATP, et al (2020) Review on biopolymer-based soil treatment (BPST) technology in geotechnical engineering practices. Transp Geotech 24:100385.

https://doi.org/10.1016/j.trgeo.2020.100385
16. Kwon YM, Chang I, Lee M, Cho GC (2019) Geotechnical engineering behavior of biopolymer-treated soft marine soil. Geomech Eng 17:453–464. https://doi.org/10.12989/gae.2019.17.5.453
17. Kwon YM, Ham SM, Kwon TH, et al (2019) Surface-erosion behaviour of biopolymer-treated soils assessed by EFA. Geotech Lett 10:. https://doi.org/10.1680/jgele.19.00106
18. Patwa D, Chandra A, Ravi K, Sreedeep S (2021) Influence of Biochar Particle Size Fractions on Thermal and Mechanical Properties of Biochar-Amended Soil. J Mater Civ Eng 33:1–15. https://doi.org/10.1061/(asce)mt.1943-5533.0003915
19. Fatehi H, Abtahi SM, Hashemolhosseini H, Hejazi SM (2018) A novel study on using protein based biopolymers in soil strengthening. Constr Build Mater 167:813–821. https://doi.org/10.1016/j.conbuildmat.2018.02.028
20. Briaud J-L, Bernhardt M, Leclair M (2012) The Pocket Erodometer Test: Development and Preliminary Results. Geotech Test J 35:102889. https://doi.org/10.1520/GTJ102889
21. Chek A, Crowley R, Ellis TN, et al (2021) Evaluation of Factors Affecting Erodibility Improvement for MICP-Treated Beach Sand. J Geotech Geoenvironmental Eng 147:04021001. https://doi.org/10.1061/(ASCE)GT.1943-5606.0002481
22. Fatehi H, Ong DEL, Yu J, Chang I (2021) Biopolymers as green binders for soil improvement in geotechnical applications: A review. Geosci 11:1–39. https://doi.org/10.3390/geosciences11070291
23. Patwa D, Muigai HH, Ravi K, et al (2022) A Novel Application of Biochar Produced from Invasive Weeds and Industrial Waste in Thermal Backfill for Crude Oil Industries. Waste and Biomass Valorization 13:3025–3042. https://doi.org/10.1007/s12649-022-01694-0
24. Patwa D, Bordoloi U, Dubey AA, et al (2022) Energy-efficient biochar production for thermal backfill applications. Sci Total Environ 833:. https://doi.org/10.1016/j.scitotenv.2022.155253
25. Xiao Y, Tang Y, Ma G, et al (2021) Thermal Conductivity of Biocemented Graded Sands. J Geotech Geoenvironmental Eng 147:1–15. https://doi.org/10.1061/(asce)gt.1943-5606.0002621
26. Mahamaya M, Das SK, Reddy KR, Jain S (2021) Interaction of biopolymer with dispersive geomaterial and its characterization: An eco-friendly approach for erosion control. J Clean Prod 312:127778. https://doi.org/10.1016/j.jclepro.2021.127778