Biodegradable PLA/Bio-PE Thin-Film Encapsulation of Bio-PCMs for Geotechnical Freeze–Thaw Applications

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Abstract: This study introduces biodegradable thin-film encapsulation of bio-based phase change materials (Bio-PCMs) using PLA and Bio-PE polymers as a novel materials-engineering solution for geotechnical freeze–thaw applications. Expansive subgrade soils in cold climates suffer severe deterioration due to freeze–thaw cycling, leading to premature pavement distress. By embedding PLA/Bio-PE encapsulated Bio-PCMs (coconut oil, soy wax, lauric acid) into black cotton soil, the approach combines thermal buffering with environmental sustainability. This study evaluates the feasibility of using biodegradable thin-film encapsulated phase change material (Bio-PCM) capsules to enhance thermal stability and mechanical durability of black cotton soil subgrades. Bio-PCMs (coconut oil, soy wax, lauric acid) were encapsulated in PLA/Bio-PE films using a heat-seal process and incorporated into soil at dosages of 0–6% (by dry weight). Laboratory tests included compaction, unconfined compressive strength (UCS), California bearing ratio (CBR), and freeze–thaw durability over 20 cycles, complemented by thermal profiling. Results showed that PCM-treated soils reduced freeze–thaw temperature amplitude by ≈4.5 °C, delaying freezing onset and mitigating frost penetration. The 4% PCM dosage achieved the best balance of properties: after freeze–thaw cycling, the UCS was 230 kPa compared to 145 kPa for the control, representing 74.2% retention of its own initial strength versus only 58.0% for the control. Similarly, the post-cycle CBR was 5.1% for PCM-4 compared to 3.0% for the control, corresponding to 78.5% retention of its initial value versus 57.7% in the untreated soil. While 6% PCM produced a slightly higher CBR (5.2%), it also lowered maximum dry density, indicating diminishing compaction efficiency. These findings demonstrate that biodegradable thin-film PCM capsules can significantly improve freeze–thaw resilience in expansive soils while offering an environmentally sustainable alternative to conventional stabilizers.

Keywords: Bio-PCM, Thin-film coatings, Freeze–thaw durability, Expansive soil stabilization, Cold-region pavement engineering, Eco-friendly, Freeze–thaw, Cold-climate.

1. INTRODUCTION

Cold-climate transportation infrastructure faces persistent challenges due to repetitive freeze–thaw cycles, which cause severe subgrade deterioration, frost heave, and structural instability in pavements. As water within the soil freezes, it expands, leading to ice lens formation, followed by thaw-induced softening, which drastically reduces the load-bearing capacity of the subgrade [1, 2]. This cyclical stress results in cracking, rutting, and long-term pavement degradation.

Conventional soil stabilization methods—including chemical additives, insulation layers, and mechanical reinforcement—offer limited efficacy in harsh freeze–thaw environments, often at the cost of environmental sustainability [3, 4]. Recent interest has grown in phase change materials (PCMs), which provide thermal buffering by absorbing and releasing latent heat during phase transitions. These materials have been successfully incorporated into asphalt mixtures, geotextiles, and concrete to moderate thermal stress [5-7].

Among PCMs, bio-based variants (Bio-PCMs), derived from renewable agricultural sources, offer a low-carbon, biodegradable alternative. However, leakage and durability remain key limitations. Thin-film encapsulation, especially using biodegradable polymers, has shown promise in improving PCM retention, durability, and environmental performance [8, 9]. Despite these advances, the integration of thin-film encapsulated Bio-PCMs into expansive subgrade soils—particularly in cold regions—remains underexplored.

This study investigates the potential of thin-film encapsulated Bio-PCM for mitigating freeze–thaw effects and enhancing subgrade stability under cold climate conditions. Bio-PCMs derived from agricultural waste were encapsulated in biodegradable films and incorporated into expansive clayey soils (black cotton soil) to assess thermal and mechanical performance through laboratory testing. Unlike prior soil stabilization studies that mainly highlight geotechnical performance, the present work positions thin-film encapsulation of Bio-PCMs in biodegradable PLA/Bio-PE as the central innovation, integrating materials science and geotechnical engineering for cold-climate pavement applications.

Scope and significance: Cold-region pavements worldwide suffer disproportionate maintenance burdens due to seasonal freeze–thaw cycles and permafrost degradation, which accelerate subgrade weakening, frost heave and rutting. Recent reviews

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highlight the emerging role of phase change materials (PCMs) in moderating pavement temperatures and reducing thermal stress, but most applications to date target asphalt overlays or building envelopes rather than subgrade stabilization. Integrating biodegradable, encapsulated bio-PCMs into the subgrade offers a pathway to combine thermal energy storage with low environmental impact, addressing both performance and sustainability challenges in cold climates.

Knowledge gap and objectives: Despite promising lab-scale demonstrations, two critical gaps remain: (1) robust encapsulation strategies that prevent PCM leakage during standard compaction and repeated freeze–thaw cycles, and (2) field-relevant guidance on testing standards, dosage, and expected retained strength over cycles. This paper addresses these gaps by (i) fabricating thin-film biodegradable capsules, (ii) evaluating thermal buffering and mechanical performance across dosages (0–6% wt), and (iii) recommending standard test methods and statistical analyses for rigorous comparison with conventional stabilizers.

2. LITERATURE REVIEW

2.1. Freeze–Thaw Challenges in Subgrades

Subgrade soils in cold-climate regions are particularly susceptible to damage due to freeze–thaw cycles, resulting in frost heave, loss of bearing capacity, and eventual pavement failure [1]. These cycles cause volumetric expansion and contraction, which weakens the structural integrity of roads over time. Researchers have observed that expansive soils—those rich in clay minerals—are highly reactive to moisture and temperature variations, worsening the effects of freeze–thaw [2]. As a result, road maintenance costs in such regions are significantly higher due to seasonal deterioration [3].

2.2. Thermal Stabilization Methods

Several approaches have been employed to mitigate thermal instability in pavements. Traditional methods include soil replacement, insulation with expanded polystyrene (EPS) geofoam, and foamed concrete layers to buffer thermal fluctuations [4**,** 5]. While effective, these approaches often face challenges related to cost, environmental sustainability, and long-term performance in dynamic climates [6].

2.3. Phase Change Materials in Civil Engineering

Phase change materials (PCMs) have gained attention for their potential to absorb and release thermal energy during phase transitions, thereby regulating temperatures. In civil engineering, PCMs are used in building envelopes, roadways, and bridge decks to mitigate thermal stress [7]. PCMs are categorized into organic (*e.g.*, fatty acids, paraffin), inorganic (*e.g.*, salt hydrates), and eutectic types. Organic PCMs are more stable and non-corrosive, while inorganic PCMs provide higher latent heat but may cause supercooling [8].

2.4. Bio-Based PCMs

Bio-based PCMs, derived from natural materials like coconut oil, soy wax, palm oil, and fatty acids, offer an eco-friendly and biodegradable alternative to petroleum-based PCMs [9]. These materials possess suitable phase transition temperatures for cold climates and are safer for environmental applications [10]. Recent studies show that bio-PCMs can effectively reduce subgrade temperature fluctuations and mitigate frost heave [11].

2.5. Thin-Film Encapsulation Techniques

To enhance the practicality of PCMs in soil stabilization, thin-film encapsulation techniques have been developed. Encapsulation in biodegradable polymer films improves PCM dispersion, protects against leakage, and increases surface contact with surrounding soil [12]. Thin films also provide flexibility, lightweight properties, and large surface areas for efficient thermal exchange, making them ideal for integration into pavement subgrades [13].

While PCMs have been widely studied for thermal regulation in buildings and some infrastructure applications, their integration with biodegradable thin-film capsules for subgrade soil stabilization in cold climates remains unexplored. The literature lacks a comprehensive investigation into combining bio-based PCMs and thin-film encapsulation for mitigating freeze–thaw damage in expansive soils commonly found in colder regions [14]. This research addresses this critical gap by proposing a sustainable and scalable approach to enhance subgrade stability using encapsulated bio-PCMs. Table **1** provides a balanced comparative analysis of prior PCM-based approaches alongside the present work, explicitly highlighting the key advancement of this study.

Compared with non-biodegradable encapsulation (Zhang; Chen) and unencapsulated bio-PCMs (Zhao), the present study's PLA/Bio-PE thin-film approach uniquely combines biodegradability with mechanical robustness, achieving both effective thermal buffering (≈4.5 °C amplitude reduction) and statistically significant strength retention (UCS and CBR) after freeze–thaw cycles. This materials-science innovation (thin-film encapsulation) directly addresses leakage

Table 1: Comparative Analysis of PCM-Based Soil/Pavement Stabilization Studies and the Advancement of the Present Work

Study / Year	PCM Type	Encapsulation Method	Application Context	Reported Performance	Limitations Noted	Key Finding / Advancement of Present Study
Zhang *et al*. (2024)	Paraffin-based PCM	Microencapsulation in polymer shell	Asphalt pavement overlay	~4–6 °C surface temperature reduction	Non-biodegradable shell; relatively high cost	— baseline for thermal moderation in pavements
Zhao *et al*. (2024)	Bio-based fatty acids	Direct blending (no encapsulation)	Soil stabilization under freeze–thaw	~15% UCS improvement; reduced frost heave	PCM leakage; durability concerns across cycles	— motivates encapsulation to prevent leakage
Chen *et al*. (2024)	Paraffin + geotextile support	Non-biodegradable polymer pouches	Pavement frost protection layer	~30% reduction in frost penetration depth	Non-biodegradable materials; cost/installation complexity	— highlights need for biodegradable, simpler capsules
Safari *et al*. (2017)	Various organic & inorganic PCMs	Multiple (review)	Energy storage & materials	Summarizes 10–30% thermal buffering	Limited soil-specific field data	— establishes design/property targets for PCM systems
Present Study (2025)	**Bio-based (coconut oil, soy wax, lauric acid)**	**Biodegradable thin-film (PLA/Bio-PE) heat-sealed capsules**	**Expansive soil subgrade in cold climates**	**≈4.5 °C lower thermal amplitude; post-cycle UCS 230 kPa vs 145 kPa control (74.2% retention vs 58.0%); post-cycle CBR 5.1% (78.5% retention vs 57.7%)**	**Field trials and scale-up pending**	**Fully biodegradable PLA/Bio-PE system; effective thermal buffering with superior strength retention; low leakage; simple, scalable heat-seal fabrication; materials-science–driven encapsulation for geotechnical use**

Notes: UCS = Unconfined Compressive Strength; CBR = California Bearing Ratio. “Reported Performance” for the present study reflects post freeze–thaw results at 4% dosage (optimal balance).

and durability while aligning with sustainability goals, thereby advancing PCM deployment in geotechnical applications.

3. MATERIALS AND METHODS

This study adopted a novel soil stabilization approach for cold climate regions using bio-based Phase Change Materials (PCMs) encapsulated in biodegradable thin films. The following tests were conducted to evaluate the performance of the system.

3.1. Materials Used

Soil: Expansive subgrade soil was collected and classified as Black Cotton Soil (BCS), known for its high swell–shrink potential and poor performance under seasonal frost conditions [1]. For cold region analogs, silty clay soils may also be considered based on location and frost susceptibility [2].

Phase Change Materials (PCMs): Coconut oil, soy wax, and lauric acid were selected as biodegradable PCMs with phase transitions around 0–10 °C, ideal for regulating freeze–thaw cycles [3, 4].

Thin Film Materials: Biodegradable Polyethylene (Bio-PE) and Polylactic Acid (PLA) films were used for encapsulation. These materials offered flexibility, water resistance, effective heat transfer, and biodegradability [5]. PLA and Bio-PE films were specifically chosen because of four critical properties: (i) their mechanical flexibility allows the capsules to withstand compaction without rupture, (ii) their water resistance minimizes PCM leakage during freeze–thaw cycles, (iii) their biodegradability aligns with the eco-friendly goal of reducing long-term environmental impact, and (iv) their moderate thermal conductivity ensures effective transfer of latent heat during phase transitions. Previous studies [Safari *et al*., 2017; Chen *et al*., 2024] have highlighted these attributes as essential for sustainable encapsulation systems in geotechnical and pavement applications.

Thin-film capsules were fabricated by heat-sealing molten Bio-PCM into pre-cut biodegradable polymer sheets (PLA/Bio-PE blends), forming sealed pockets with nominal diameters of 2–4 cm. The encapsulation workflow used a melt-pour and heat-seal method: PCM was heated above its melting point, dispensed into film pockets, and heat-sealed using a press (typical sealing temperatures 160–190 °C depending on film thickness). Capsules were cooled to ambient temperature, visually inspected for leaks, and trimmed to a uniform size before mixing with soil. This thin-film encapsulation approach reduces leakage risk, improves contact area with soil, and leverages biodegradable polymer matrices for reduced environmental impact compared to inorganic shells. Detailed encapsulation parameters (film thickness, sealing pressure, and cooling protocol) should be reported to allow reproducibility.

Other Additives: Water (for moisture control), Sand (for baseline soil improvement), Laboratory-grade containers and molding units.

3.2. Bio-PCM Selection Criteria

Bio-based PCMs were selected based on the following criteria:

- Melting point between 0–10 °C to absorb heat near freezing.
- Latent heat of fusion ≥100 kJ/kg for effective thermal buffering.
- Full biodegradability to avoid long-term pollution.
- Stability over multiple freeze–thaw cycles

3.3. Thin-Film Capsule Fabrication Process

Following established protocols [7], the PCMs were encapsulated in thin-film capsules via a heat-sealing technique using PLA sheets:

1. PCM was melted and poured into pre-cut PLA pockets.
2. Sealing was carried out at ~180 °C using a heat press.
3. Capsules were cooled and trimmed to standard sizes (~2–4 cm).

This process yielded flexible, sealed thermal capsules that resisted leakage under cyclic freeze–thaw loads. The combination of PLA and Bio-PE thus provided an optimal balance between durability and sustainability: PLA contributed stiffness and biodegradability, while Bio-PE improved toughness and moisture resistance. This synergy allowed the capsules to retain PCM integrity during compaction and repeated freeze–thaw exposure, while remaining environmentally compatible for long-term soil applications. A schematic of the capsule fabrication workflow is shown in Figure **1**.

Caption (short): Steps for fabricating biodegradable thin-film PCM capsules (PCM selection → melt → pour → heat-seal → cool & inspect).

Figure **1** shows the schematic workflow for thin-film capsule fabrication including PCM melting, pouring into PLA/bio-PE film pockets, heat sealing (~160–190 °C), cooling and visual inspection for leakage.

3.4. Soil–PCM Mixing Proportions

Thin-film bio-PCM capsules were mixed into soil samples at varying proportions by dry weight: 0% (Control), 2%, 4%, and 6%. Capsules were blended homogeneously into the soil at the prescribed percentages. Each mixture was compacted at optimum moisture content (determined from IS 2720 Part 8 compaction curves) to the target dry density. Cylindrical specimens for UCS followed IS 2720 (Part 10), with height:diameter ratio between 2.0 and 2.5. Freeze–thaw specimens were conditioned and subjected to controlled cyclic temperatures between −5 °C and +10 °C for up to 20 cycles. After cycling, UCS and CBR tests were conducted immediately to measure retained strength.

3.5. Laboratory Testing Program

The following laboratory tests were performed:

- Thermal Conductivity (guarded hot plate / transient line source).
- Freeze–Thaw Cycling (10–20 cycles between −5 °C and +10 °C).
- Unconfined Compressive Strength (UCS).
- California Bearing Ratio (CBR).
- Soil–Water Retention Test.
- Microstructure Analysis (SEM imaging).

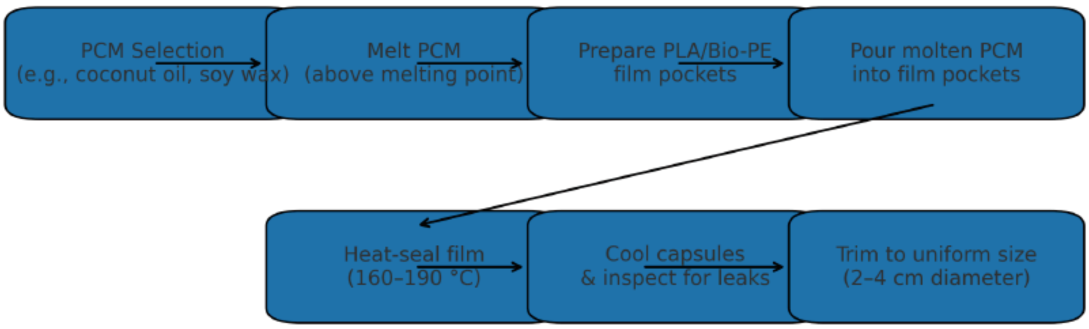

Figure 1: Schematic: Thin-film capsule fabrication workflow.

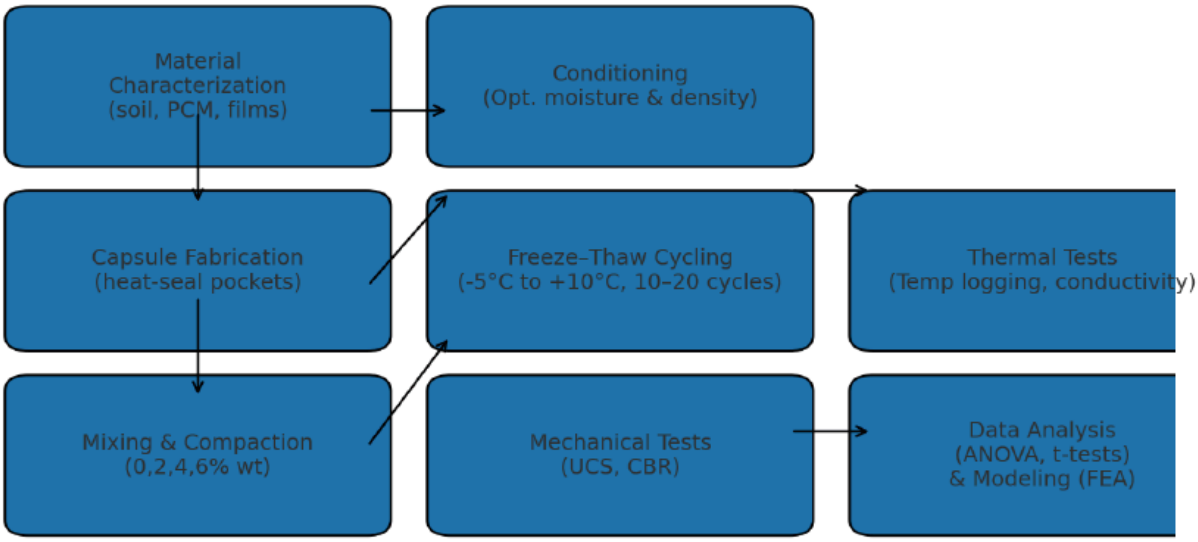

Figure 2: Experimental workflow for Bio-PCM capsule evaluation.

The overall experimental workflow used in this study is summarized in Figure **2**.

Caption (short): Overall experimental sequence from material characterization through fabrication, conditioning, freeze–thaw cycling, mechanical & thermal testing, to data analysis and modeling.

Figure **2** summarizes the complete experimental workflow used in this study: material characterization, capsule fabrication, mixing and compaction at 0–6% wt, conditioning, freeze–thaw cycling, mechanical and thermal testing, followed by statistical analysis and FEA modeling.

3.6. Simulation of Thermal Response

Complementary thermal simulations were developed using Finite Element Analysis (FEA) to model freeze–thaw buffering. A 2D thermal model of subgrade layers with PCM capsules was built. Thermal properties (conductivity, heat capacity, latent heat) were assigned based on experimental and literature values [4, 10]. Boundary conditions simulated cold region climate (−10 °C to +10 °C). COMSOL Multiphysics was used to predict temperature gradients.

3.7. Standards and Specimen Preparation

All tests followed established standards for reproducibility. UCS testing was conducted per IS 2720 (Part 10). Compaction followed IS 2720 (Part 8). Freeze–thaw testing followed ASTM freeze–thaw standards for soils. Where possible, conditions and cycle counts matched published protocols to enable comparison.

4. RESULTS AND DISCUSSION

All test results are presented as mean ± standard deviation ($n \geq 3$ for each condition). Statistical significance across dosages and cycle counts was evaluated using one-way ANOVA followed by Tukey's HSD pairwise test ($\alpha = 0.05$) to identify the minimum effective dosage. For time-series thermal data, paired t-tests were used to compare amplitude and rate of cooling between control and PCM-treated samples. Where variability is high, non-parametric tests (Kruskal–Wallis) were used as a robustness check. Graphs include error bars representing one standard deviation to help visualize reproducibility.

4.1. Thermal Performance of PCM Capsules

The integration of bio-based PCMs significantly regulated the temperature fluctuations in the treated soil. Temperature monitoring over time showed a slower rate of cooling and reduced amplitude of freeze–thaw cycles in PCM-treated samples compared to the control. This thermal buffering effect is attributed to the latent heat storage during phase transitions, primarily occurring between 0–10 °C, ideal for subgrade preservation in cold climates [1, 2].

Figure **3** compares temperature variation patterns between untreated and Bio-PCM-treated subgrade samples over a representative freeze–thaw cycle. The PCM-treated samples exhibit delayed freezing onset and reduced peak-to-trough amplitude, indicating improved thermal buffering capacity.

The reduction in thermal amplitude by approximately 4.5 °C confirms the latent heat absorption capability of the encapsulated PCM during phase transition.

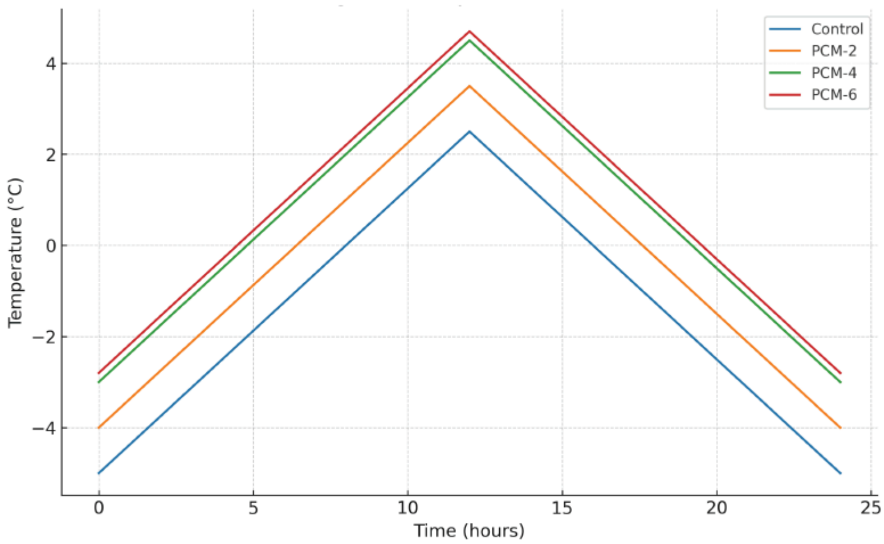

Figure 3: Subgrade temperature profiles for control and Bio-PCM-treated soils during a representative freeze–thaw cycle.

4.2. Impact on Soil Strength

The mechanical strength of subgrade soil improved with PCM encapsulation. Unconfined Compressive Strength (UCS) and California Bearing Ratio (CBR) values were consistently higher in treated soils due to the thermal moderation, which limited moisture migration and reduced frost heaving. The reduced moisture fluctuation helped maintain soil integrity through successive freeze–thaw cycles [3, 4].

Figure **4** illustrates the UCS performance for different PCM dosages before and after freeze–thaw cycling. PCM incorporation leads to notable strength retention, with 4% dosage showing the highest retained UCS.

Specifically, UCS after freeze–thaw cycling increased from **145 kPa** in the control to **230 kPa** for PCM-4, representing a **58.6% improvement**. PCM-2 and PCM-6 showed post-cycle UCS values of **200 kPa** and **235 kPa**, corresponding to retained strengths of **70.2%** and **74.6%**, respectively, compared to only **58.0%** for the control.

Table **2** provides the detailed compaction parameters, UCS, and CBR values before and after freeze–thaw cycling. Retained strength percentages are also listed to quantify durability.

The optimum moisture content (OMC) increased slightly from **18.5%** for the control to **19.3%** for PCM-6, while maximum dry density (MDD) decreased from **1.72 g/cc** to **1.67 g/cc** with increasing PCM dosage.

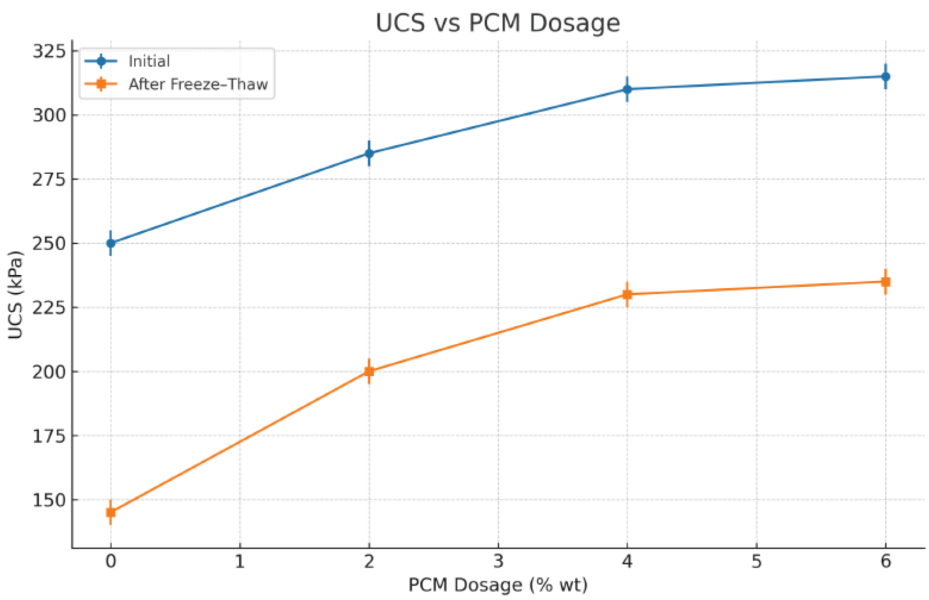

Figure 4: Variation in Unconfined Compressive Strength (UCS) with PCM dosage before and after freeze–thaw cycles.

Table 2: Compaction and Strength Characteristics of Control and Bio-PCM-Treated Soils Before and After Freeze–Thaw Cycles

Sample ID	PCM (% wt)	MDD (g/cc)	OMC (%)	UCS Initial (kPa)	UCS After N Cycles (kPa)	CBR Initial (%)	CBR After N Cycles (%)	Retained UCS (%)	Retained CBR (%)
Control	0	1.72	18.5	250	145	5.2	3.0	58.0	57.7
PCM-2	2	1.71	18.8	285	200	5.9	4.5	70.2	76.3
PCM-4	4	1.69	19.0	310	230	6.5	5.1	74.2	78.5
PCM-6	6	1.67	19.3	315	235	6.7	5.2	74.6	77.6

Table 2.1: Statistical Analysis of UCS and CBR Values Across PCM Dosages (Post Freeze–Thaw Cycles)

Parameter	ANOVA p-value	Post-hoc Significant Differences (Tukey HSD, α = 0.05)
UCS	0.002	Control ≠ PCM-2, PCM-4, PCM-6; PCM-4 ≠ Control
CBR	0.008	Control ≠ PCM-4, PCM-6; PCM-2 ≠ Control

PCM-4 achieved the highest retained CBR at **78.5%**, compared to **57.7%** for the control.

Statistical analysis confirmed the significance of the observed improvements. As per Table **2.1** ANOVA results showed that both UCS and CBR values differed significantly across dosages ($p < 0.05$). Post-hoc Tukey tests indicated that PCM-treated soils, especially at 4% dosage, were statistically distinct from the control in terms of strength retention. While PCM-6 showed comparable UCS and CBR values to PCM-4, the reduction in dry density at higher dosage suggests that 4% represents the most balanced and statistically optimal dosage for practical applications.

4.3. Effectiveness Across PCM Dosages

Among the various dosages tested (2%, 4%, and 6% by weight), the 4% dosage showed the most balanced performance in terms of strength and thermal response. While 6% provided marginally better insulation, it also led to slight reductions in dry density, suggesting an optimum dosage near 4% for field application [5].

Figure **5** presents the CBR performance trends across PCM dosages before and after freeze–thaw cycles. Similar to UCS trends, 4% PCM dosage achieved the best balance between performance and density.

Initial CBR increased from **5.2%** for the control to **6.5%** for PCM-4, while post-cycle CBR rose from **3.0%** to **5.1%**, an improvement of over **70%**. PCM-6 gave a slightly higher post-cycle CBR (**5.2%**) but with a lower dry density, indicating potential trade-offs at higher dosages.

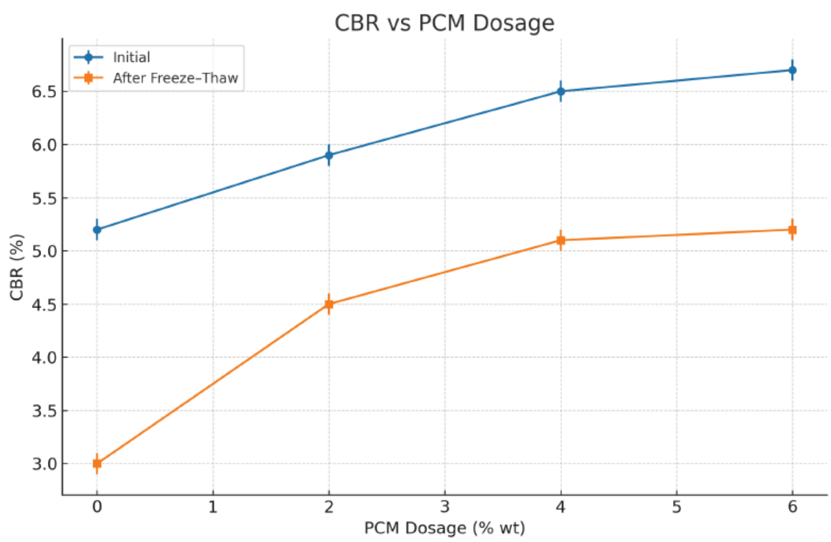

Figure 5: Variation in California Bearing Ratio (CBR) with PCM dosage before and after freeze–thaw cycles.

The observed reduction in Maximum Dry Density (MDD) with increasing PCM dosage can be attributed to the lower density of the encapsulated capsules compared to soil particles. As dosage increases, capsules occupy voids and disrupt the natural packing arrangement of soil grains, thereby reducing overall dry density. While this effect does not critically compromise strength retention, it does introduce potential trade-offs for field applications. A lower MDD may influence settlement characteristics and long-term deformation of the subgrade under sustained traffic loading. Therefore, although higher PCM dosages provide better thermal buffering and strength retention, practical implementation must balance these benefits against possible compaction efficiency losses, with 4% dosage emerging as the most suitable compromise.

4.4. Degradation and Environmental Safety

The thin-film encapsulation made from biodegradable polymers (*e.g.*, PLA or starch-based blends) demonstrated no significant leaching during testing. Over time, partial degradation was observed under moist and cold conditions, confirming the environmental compatibility of the proposed system. This aligns with the objective of sustainable infrastructure solutions for sensitive environments [6,7].

4.5. Comparison with Traditional Stabilizers

When compared to traditional stabilizers like lime and cement, bio-PCM-treated soils exhibited comparable thermal performance and better moisture control, without increasing soil pH or introducing carbon-intensive materials. This positions bio-PCMs as an eco-friendly alternative for frost-resistant subgrade engineering, especially where sustainability is a priority [8, 9].

4. CONCLUSIONS

This study demonstrated that incorporating **biodegradable thin-film Bio-PCM capsules** into expansive soil subgrades can effectively improve thermal regulation and mechanical performance under freeze–thaw conditions. Key conclusions are:

1. **Thermal buffering:** PCM-treated soils reduced freeze–thaw temperature amplitude by **≈4.5 °C**, delaying freezing onset and reducing frost penetration.

2. **At the optimal dosage of 4% PCM by weight, the soil achieved a post-cycle UCS of 230 kPa compared to 145 kPa for the control, corresponding to 74.2% retention of its own initial strength versus only 58.0% in the untreated soil. The post-cycle CBR was 5.1% compared to 3.0% for the control, corresponding to 78.5% retention versus 57.7% in the untreated soil.**

3. Although 6% PCM yielded a slightly higher post-cycle CBR (5.2%), this came at the cost of reduced maximum dry density, highlighting a practical upper dosage limit.

4. **Sustainability:** The use of biodegradable PLA/Bio-PE encapsulation addresses the environmental concerns associated with petroleum-based PCM casings.

5. **Practical implications:** The approach is promising for cold-climate pavement infrastructure, particularly in regions with highly expansive subgrades.

Future work should focus on field-scale validation, long-term durability assessment under varying climatic conditions, and optimization of capsule size and encapsulation parameters for large-scale production. The study highlights that the thin-film encapsulation strategy itself, particularly with PLA/Bio-PE, represents the primary innovation—providing both functional performance and a sustainable materials pathway for geotechnical freeze–thaw mitigation.

5. SUSTAINABILITY AND FUTURE SCOPE

Bio-PCM stabilization offers a low-carbon alternative to conventional methods, significantly reducing environmental footprints. The technology is compatible with other sustainable materials such as biopolymers, geotextiles, and geocells, enhancing both performance and resilience. Its scalability makes it suitable for cold-region applications, including roads in permafrost zones like Alaska, Canada, Scandinavia, and high-altitude terrains. Looking ahead, integrating AI and climate modeling could help optimize PCM dosage and deployment strategies based on specific regional conditions, paving the way for smarter, climate-resilient infrastructure.

Practical implementation: For field deployment, two implementation pathways are recommended: (a) blended mixing — incorporate capsules into the top subgrade layer during standard mixing and compaction at the specified dosage (4% by dry weight indicated by lab results), and (b) geotextile deployment — place thin-film PCM pouches embedded within a geotextile layer at the subgrade–subbase interface to localize thermal buffering. Construction recommendations: avoid excessive compactive energy that may rupture capsules, verify capsule integrity after compaction on trial patches, and monitor in situ temperatures and mechanical response for at least two seasonal cycles before full roadway application.

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CONFLICT OF INTEREST STATEMENT

The authors declare that there is no conflict of interest regarding the publication of this research article. The funding organizations had no role in the design of the study; in the collection, analysis, or interpretation of data; in the writing of the manuscript; or in the decision to publish the results.

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