Freeze-Thaw Durability and Bearing Performance of Polypropylene Fiber-Reinforced Himalayan Subgrade Soil from Sela Pass

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ABSTRACT

This study evaluates the compaction characteristics and California Bearing Ratio (CBR) performance of polypropylene (PP) fiber-reinforced soil obtained from the high-altitude Sela Pass region of the Eastern Himalayas, with particular emphasis on freeze-thaw (F-T) induced strength degradation. Fiber contents ranging from 0% to 0.5% (by dry weight) were incorporated, and Standard Proctor compaction and CBR tests were conducted before and after four controlled F-T cycles. Fiber inclusion resulted in a systematic reduction in maximum dry density (MDD) from 1.83 g/cm³ (untreated) to 1.70 g/cm³ at 0.5% fiber, accompanied by an increase in optimum moisture content (OMC) from 13.2% to 15.72%, indicating the formation of a slightly less dense but more ductile soil-fiber matrix. CBR values improved consistently with fiber addition, reaching optimum performance at 0.4% fiber. Under soaked conditions, CBR increased from 14% to 23.73%, while unsoaked CBR rose from 22% to 33.70%. Following four F-T cycles, untreated soil exhibited significant strength loss; however, fiber-reinforced specimens retained substantially higher residual capacity. At 0.4% fiber content, soaked and unsoaked CBR values remained at 18.77% and 29.38%, respectively, compared to 9.3% and 16.63% for untreated soil. The results demonstrate that low-dosage PP fiber reinforcement markedly enhances frost durability and load-bearing performance, identifying 0.4% as the optimum content for improving cold-region subgrade soils. These findings support fiber stabilization as a practical strategy for high-altitude highway infrastructure development.

Keywords: California Bearing Ratio (CBR), Compaction, Freeze-Thaw Cycles, Polypropylene Fiber-Reinforced Soil, Polypropylene Fiber.

1. INTRODUCTION

The California Bearing Ratio (CBR) remains a primary index for evaluating subgrade load-bearing performance in flexible pavement design. A substantial body of literature demonstrates that discrete polypropylene (PP) fiber inclusion significantly enhances CBR performance when applied at optimum dosages, while excessive fiber content leads to strength reduction due to agglomeration and reduced soil-soil contact.

For granular and sandy subgrades, moderate improvements are consistently reported. [1] observed CBR enhancements of 22 to 41% at 0.5-1.0% fiber content in SC-SM soils, with strength reduction beyond the optimum dosage. Similar trends were reported by [2], confirming the sensitivity of CBR performance to fiber dispersion quality. [3] further demonstrated 10 to 25% improvement in lime-fly ash modified lightweight soils reinforced with 0.1% PP fiber, highlighting that even low dosages can be effective when combined with cementitious matrices. For non-plastic sands and ash-based materials, the relative improvement tends to be higher. [4] reported a 75% increase in CBR for pond ash stabilized with cement kiln dust and reinforced with 1% PP fiber. [5] documented CBR improvements ranging from 82% to 136% in fly ash mixtures containing 0.2- 0.3% PP fiber. [6] similarly observed bearing capacity improvements of 110 to 430% in cement-activated fly ash systems, underscoring the synergistic interaction between fiber reinforcement and chemical stabilization. In cohesive and expansive soils, where baseline CBR values are typically low, the proportional benefits of PP fiber are more pronounced. [7] reported an increase in soaked CBR from 1.93% to 8.8%, which is around 350% increase at 0.3% fiber content in alkali-activated black cotton soil. [8] observed a 225% increase in soaked CBR in clayey soil reinforced with 1% PP fiber. More substantial improvements have been reported in hybrid stabilization systems [9] achieved over a 1000% CBR improvement in cement-stabilized expansive clay with fiber inclusion, while [10] reported a 770% increase in lime-rice husk ash (RHA) stabilized silty soil reinforced with plastic waste fibers. [11] documented approximately 600% improvement in lime kiln dust-volcanic ash-stabilized kaolin reinforced with recycled PP fiber. Natural fiber systems exhibit similar enhancement mechanisms. [12] reported up to 2400% soaked CBR improvement in bottom ash-cement stabilized soil reinforced with areca fiber, while [13] demonstrated a 670% increase in lime-RHA stabilized clay reinforced with coir fiber. These findings confirm that discrete fiber reinforcement, when properly dispersed, enhances tensile resistance, interlocking, and crack bridging within the soil matrix. A systematic review by [14] concluded that unsoaked CBR typically increases by 40-80%, while soaked CBR improves by 20-50% at optimum PP fiber contents ranging from 0.25% to 0.75%. Beyond the optimum dosage, strength reduction is commonly observed due to fiber clustering and reduced compaction efficiency. In addition to PP fiber reinforcement, several recent studies have explored alternative materials and reinforcement systems for improving the CBR of sandy and subgrade soils. [15] investigated the use of cement-coated textile waste (CCTW) in poorly graded sand and reported a significant increase in CBR, with optimum performance observed at approximately 4% inclusion, beyond which strength reduction occurred due to excessive material content. Similarly, [16] demonstrated that cement-coated geotextile reinforcement improved the CBR of sandy soil by up to 3.25 times compared to unreinforced conditions, outperforming the conventional geotextile reinforcement, which showed an improvement of about 1.68 times. Furthermore, [17] evaluated the use of sustainable waste materials such as palm tree pruning waste has also been shown to enhance CBR performance. With results indicating comparable or even superior behaviour relative to geotextile reinforcement in sandy subgrades. These findings highlight that reinforcement efficiency is strongly governed by material type, dosage, and soil-reinforcement interaction mechanisms. However, most of these investigations are limited to conventional sandy soils under normal environmental conditions and do not consider the combined effects of reinforcement and F-T cycling in high-altitude Himalayan soils, which remains insufficiently explored. Collectively, these studies confirm that PP fiber reinforcement is highly dosage-sensitive and most effective when combined with appropriate stabilization or compaction control.

The incorporation of PP fiber moderately alters compaction behavior. Most studies report a slight reduction in maximum dry density (MDD) and a marginal increase in optimum moisture content (OMC), attributed to the low specific gravity and bulky morphology of fibers. [1] observed a 6 to 8% reduction in MDD with negligible OMC variation in sandy soils reinforced with waste tire textile fibers. [18] reported a 7.8% decrease in MDD and increased OMC in lime-stabilized marine clay with PP fiber inclusion. [19] documented a reduction in MDD from 18.3 to 17.2 g/cm³ and an increase in OMC from 13% to 14.2% in cement-treated clayey sand containing up to 2% PP fiber. [14] synthesized prior findings and reported MDD reductions of 2-5% and OMC increases of 5-10%. Although fiber inclusion slightly reduces compaction efficiency, the resulting soil structure demonstrates enhanced ductility, post-peak resistance, and improved load transfer capacity. [6] emphasized that compaction energy and moisture control remain critical factors in fiber-stabilized systems.

F-T cycles severely degrade subgrade strength by increasing void ratio, inducing frost heave, and disrupting particle bonding. [20] reported that untreated subgrades experienced CBR reductions of 70 to 85% after F-T cycles. [21] observed CBR losses of 35 to 85% in fine-grained soils due to repeated freezing and thawing. [22] documented a 42% CBR reduction after 15 F-T cycles in untreated clayey soil. [23] further demonstrated 25-53% strength reductions in recycled pavement materials under F-T exposure. Importantly, several researchers have highlighted that initial CBR is not a reliable indicator of long-term durability under cyclic freezing conditions [19, 20].

PP reinforcement has shown potential to mitigate F-T-induced degradation by restraining crack propagation and maintaining structural integrity during thaw softening. [20] reported that 0.6% PP fiber reduced frost heave by 55 to 60% and improved post-thaw CBR by approximately 180%. [20] Further demonstrated post-thaw CBR improvements of 400 to 600% relative to untreated soil at optimum fiber dosage. [24] observed 20 to 35% higher post-thaw CBR in clayey sand reinforced with 1% PP fiber compared to unreinforced soil.

Although previous studies have demonstrated the effectiveness of PP fiber reinforcement in enhancing the strength and ductility of various soils, most investigations have focused on laboratory prepared soils, chemically stabilized materials, or soils from relatively moderate climate regions. Similarly, several studies have examined the deterioration of subgrade strength under F-T cycles, however, the combined effect of fiber reinforcement and F-T exposure on natural high-altitude soils remains insufficiently explored. This limitation is particularly significant for Himalayan subgrades, where repeated F-T action and severe environmental conditions often lead to rapid deterioration of pavement support layers. In particular, no systematic investigation has been reported on the compaction behaviour and CBR performance of PP fiber-reinforced soil obtained from Sela Pass region of the Eastern Himalayan soils under F-T cycles. Understanding the interaction between PP fibers and native Himalayan soil under cyclic freezing conditions is therefore essential for improving the durability and load-bearing capacity of subgrade in cold mountainous regions. To address this gap, the present study experimentally evaluates the compaction characteristics and the CBR performance of PP fiber-reinforced Sela Pass soil subjected to controlled F-T cycles, with the objective of identifying the optimum fiber content for enhancing subgrades performance in cold-region infrastructure. This study represents one of the first systematic investigations on the coupled influence of PP fiber reinforcement and F-T cycling on natural high-altitude Eastern Himalayan soil (Sela Pass). Unlike previous studies that primarily focus on laboratory prepared or moderate climate soils, this work specially evaluates compaction-CBR interaction and identifies optimum fiber dosage under realistic cold-region conditions.

2. MATERIALS AND METHODOLOGY

2.1 Site description and soil sampling

The soil investigated in this study was collected from a frost-susceptible side slope along National Highway 13 near Sela Pass, Tawang district, Arunachal Pradesh, India (27.50519890° N, 92.10466340° E), at an elevation exceeding 4000 m above mean sea level. The study site is presented in Figure 1. The region experiences prolonged sub-zero winter temperatures, intense seasonal F-T cycling, heavy snowfall, and recurrent slope instability, making it representative of cold-region subgrade conditions. To obtain representative in-situ material, an open pit excavation was carried out after removing the organic surface layer. Soil samples were collected from a depth of approximately 1.5 m below ground level to minimize the influence of vegetation, weathering, and seasonal moisture variations. This approach ensured that the collected soil reflects the native subgrade material governing mechanical response under F-T conditions.

Fig. 1 Study site at Sela Pass, Eastern Himalaya

2.2 Physical characterization of soil

The physical and index properties of the soil were determined in accordance with IS: 2720 (1985). The measured parameters, including grain size distribution and consistency limits, are summarized in Table 1. Based on the Unified Soil Classification System (USCS), the soil is classified as well-graded sand with silt (SW-SM). The presence of a well-graded sandy framework with an appreciable silt fraction is particularly significant in cold-region geotechnics, as such soils are susceptible to moisture migration, pore ice formation, and microstructural alteration under repeated F-T cycles. These characteristics make the selected soil suitable for evaluating F-T induced strength degradation and the effectiveness of PP fiber reinforcement.

Table 1.

Index and compaction properties of the soil sample.

Properties	**Values**
Specific Gravity	2.683
Gravel (%)	11.60
Sand (%)	79.21
Silt (%)	5.12
Clay (%)	4.06
Uniformity Coefficient (C_u)	7.11
Coefficient of Curvature (C_c)	1.03

Maximum dry density, MDD (g/cm^3)	1.83
Optimum moisture content, OMC (%)	13.2

2.3 Polypropylene fibers

PP fiber was used as discrete reinforcement to evaluate its influence on compaction characteristics and CBR performance of the Eastern Himalayan soil under F-T conditions. Polypropylene is a synthetic thermoplastic polymer characterized by low density, high tensile strength, chemical inertness, and negligible water absorption, making it well-suited for cold-region geotechnical applications where cyclic freezing governs soil degradation. In this study, PP fibers of 12 mm nominal length and specific gravity of 0.92 were adopted to promote effective crack bridging and tensile stress transfer within the soil matrix during F-T cycling. Fiber contents of 0%, 0.1%, 0.2%, 0.3%, 0.4%, and 0.5% by dry weight of soil were selected. The fibers were dry-mixed with air-dried soil to ensure uniform dispersion prior to compaction at the corresponding optimum moisture content. The physical and mechanical properties of the fibers are summarized in Table 2 and the appearance of the PP fiber used in this study is shown in Figure 2.

Table 2

Polypropylene Fiber Properties.

Properties	**Value**
Specific Gravity	0.92 g/cm^3
Fiber length (mm)	12
Fiber diameter (mm or µm)	0.030 or 30
Aspect ratio (L/D)	400
Tensile strength (MPa)	600-700 MPa (manufacturer specification)
Elastic modulus (GPa)	3.7
Water absorption	Negligible
Fiber content (% dry soil weight)	0.0 to 0.5%

Fig.2 Discrete PP fibers used for soil reinforcement

2.4 Compaction testing

Standard Proctor compaction tests were conducted in accordance with IS: 2720 (Part 7)-1980. Soil-fiber mixtures were compacted in a standard mould using specified compactive effort to determine MDD and OMC. The compaction characteristics were evaluated for both untreated and PP fiber-reinforced soils. Compaction tests were initially performed prior to F-T exposure to establish baseline properties. Post F-T compaction characteristics were determined using separately prepared replicate sample specimens subjected to 4 F-T cycles, in order to assess changes in densification behavior and structural integrity resulting from thermal degradation. The specimens used for post F-T testing were not derived from previously compacted samples.

2.5 Freeze-Thaw procedure

Four F-T cycles were adopted to simulate the critical early-stage deterioration of subgrades soil, as most of the reduction in strength and CBR value occurs within the initial few cycles. This also ensures a practical balance between realistic field simulation and laboratory testing time, as reported in [25]. Each cycle consisted of a freezing phase at -15 ^{0}C for 12 hours, followed by a thawing phase at +20 ^{0}C (room temperature) for 12 hours. The selected freezing temperature reflects the minimum winter temperature recorded in the Sela Pass region, ensuring realistic thermal exposure consistent with in-situ conditions. Moisture conditions were carefully maintained throughout the cycling process to replicate field-relevant frost action and thaw softening mechanisms. Immediately after completion of the prescribed F-T cycles, specimens were tested for compaction characteristics and CBR to capture F-T induced deterioration in mechanical performance. The adopted F-T protocol follows established experimental methodologies reported in the literature [26-28], ensuring methodological consistency and comparability with prior cold-region geotechnical investigations.

2.6 California bearing ratio (CBR) testing

CBR tests were conducted in accordance with IS: 2720 (Part 16)-1987 under both unsoaked and soaked conditions. Load-penetration responses were recorded at penetrations of 2.5 mm and 5.0 mm, and the higher corresponding CBR value was adopted for analysis. Tests were performed on specimens both before and after F-T exposure to evaluate strength degradation and to assess the effectiveness of PP fiber reinforcement under simulated cold-region conditions. Figure 3 illustrates the soaked CBR specimen during the freezing phase, while Figure 4 shows the specimen during the thawing phase. The soil sample was initially air-dried and sieved through a 4.75 mm sieve to remove oversized particles and to ensure uniformity. Although IS: 2720 (Part 16) permits the use of particles up to 20 mm, a finer fraction was adopted in this study to facilitate uniform mixing and distribution of polypropylene fibers within the soil matrix. Polypropylene fibers were then added to the dry soil at predetermined contents (0%, 0.2%, 0.4%, and 0.5% by dry weight of soil) and thoroughly mixed to achieve homogeneity. Subsequently, water corresponding to the Optimum Moisture Content (OMC), determined from the Standard Proctor test, was added and mixed uniformly. The prepared mixture was compacted into a standard CBR mould (150 mm diameter and 175 mm height) in three equal layers, each compacted with 56 blows using a standard rammer to achieve the MDD. The top surface was levelled, and surcharge weights were applied in accordance with standard testing procedures.

For unsoaked conditions, CBR values were determined immediately after specimen preparation (0 days) and were compared with replicate specimens subjected to 4 F-T cycles. For soaked conditions, specimens were fully immersed in water for 96 hours prior to testing, and the corresponding CBR values were compared with replicate-soaked specimens that were subsequently subjected to 4 F-T cycles. The CBR tests were conducted at a constant penetration rate of 1.25 mm/min. Each test was conducted on three replicate specimens, and the reported values correspond to the mean of the three measurements to ensure reliability. The variability of the results is expressed using standard deviation, and error bars are included in the corresponding figures.

Fig.3 CBR sample in soaked condition under freezing process

Fig.4 CBR sample in soaked condition under thawing process

3. RESULTS AND DISCUSSION

3.1 Compaction behaviour

The compaction behavior of untreated and PP fiber-reinforced soils was evaluated using the Standard Proctor test in accordance with IS: 2720 (Part 7)-1980. The results indicate a systematic decrease in MDD and a corresponding increase in OMC with increasing fiber content. The untreated soil exhibited an MDD of 1.83 g/cm³ at an OMC of 13.2%. The water content-dry density relationship for the untreated (natural) soil is presented in Table 3, while the corresponding compaction curve is illustrated in Figure 5. With progressive fiber inclusion, MDD decreased gradually to 1.70 g/cm³ at 0.5% fiber, representing an overall reduction of approximately 7.1% relative to the untreated soil. Concurrently, OMC increased from 13.2% to 15.72%, corresponding to an increase of nearly 19%. The compaction characteristics of soil reinforced with different PP fiber contents are summarized in Table 4. The variation of MDD with PP fiber content is shown in Figure 6, whereas the effect of PP fiber content on OMC is illustrated in Figure 7. This trend can be attributed to the low specific gravity and bulky morphology of PP fibers, which reduce the overall unit weight of the soil-fiber matrix and increase the void ratio. The increase in OMC reflects the additional moisture required to facilitate lubrication and uniform fiber dispersion within the soil matrix. Similar reductions in MDD (2 to 8%) and marginal increases in OMC have been widely reported for PP fiber-reinforced soils [1, 14, and 18].

Despite the reduction in MDD, fiber inclusion enhances ductility and tensile resistance, which compensates for the slight loss in compaction efficiency. The observed behavior confirms that while PP fibers moderately alter densification characteristics, the changes remain within acceptable limits for field compaction practices. Overall, the compaction results demonstrate a predictable and dosage-dependent modification of soil structure, consistent with established findings in fiber-reinforced geotechnical systems.

Table 3

Variation of maximum dry density (MDD) with water content.

Water Content (%)	**MDD (g/cm^3)**
7.256	1.659
8.431	1.707
11.021	1.774
13.165	1.809
14.899	1.764
16.962	1.719
18.507	1.680

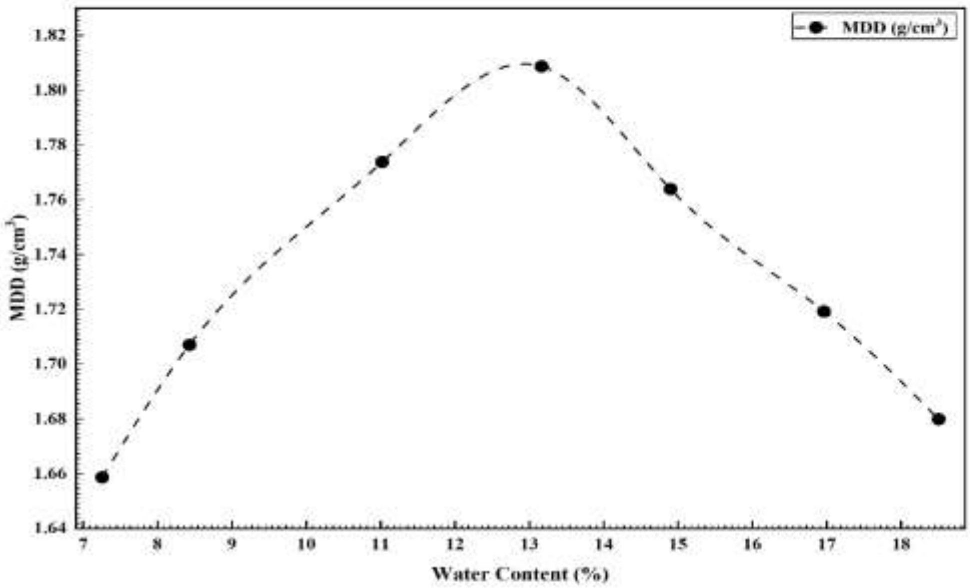

Fig.5 Compaction curve showing variation of MDD with water content of natural soil

Table 4

Compaction characteristics of soil reinforced with different polypropylene fiber contents.

Fiber Content (%)	MDD (g/cm3)	OMC (%)
Base 0.0	1.83	13.2
0.1	1.81	13.71
0.2	1.78	14.13
0.3	1.76	14.68
0.4	1.73	15.14
0.5	1.7	15.72

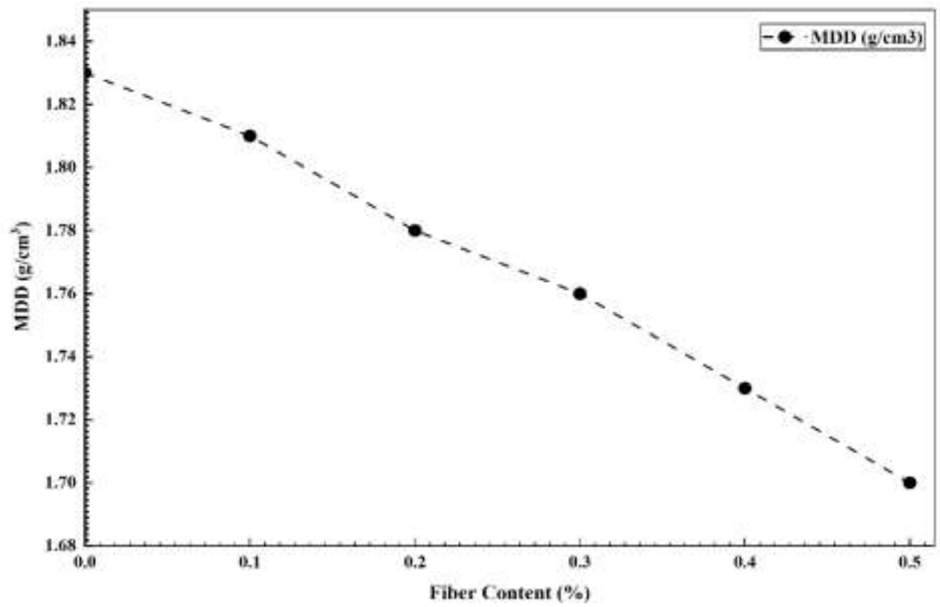

Fig.6 Effect of PP fiber content on MDD of soil

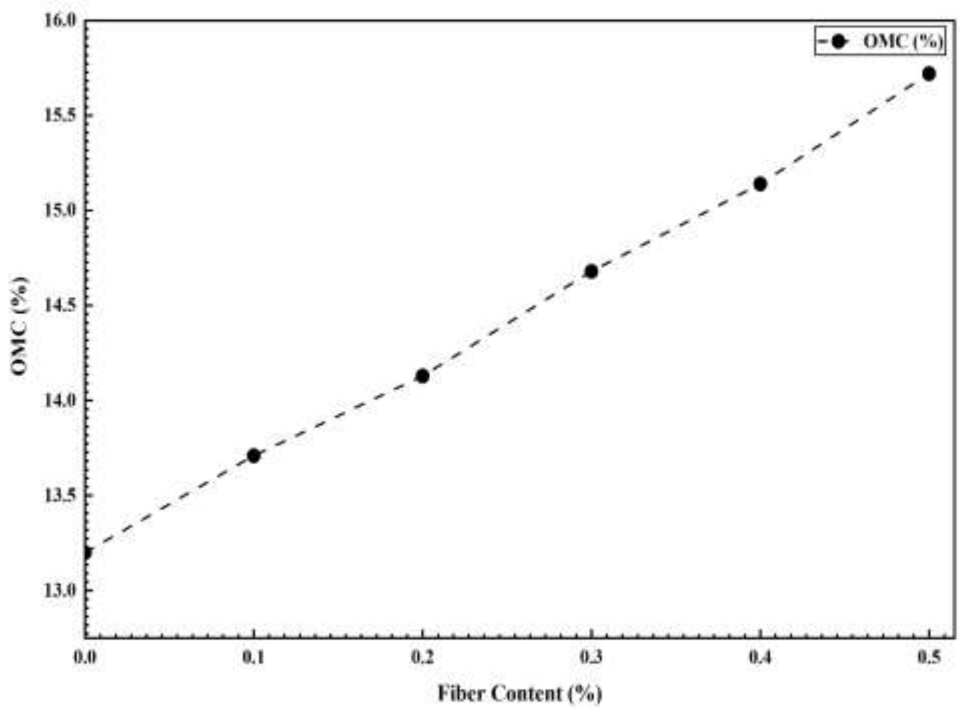

Fig.7 Effect of PP fiber content on OMC of soil sample

3.2 Compaction characteristics after F-T cycles

The compaction characteristics of untreated and PP fiber-reinforced soils were re-evaluated after subjecting four F-T cycles to quantify thermal degradation effects on densification behavior. The compaction characteristics of soil reinforced with different PP fiber contents after 4 F-T cycles are presented in Table 5. The untreated soil exhibited a reduction in MDD from 1.83 g/cm³ (pre-F-T) to 1.80 g/cm³ (post-F-T), corresponding to a decrease of approximately 1.6%, while the OMC increased from 13.2% to 13.99%. This shift indicates structural loosening and increased moisture demand due to freeze-induced particle rearrangement and micro-crack formation. Similar F-T induced reductions in compaction efficiency have been reported in cold-region soils [21, 23]. With increasing fiber content, MDD continued to decrease systematically after F-T exposure, reaching 1.684 g/cm³ at 0.5% fiber, while OMC increased to 16.71%. Compared to pre-F-T values, fiber-reinforced soils exhibited slightly lower post-F-T densities and marginally higher moisture requirements. The variation of MDD with PP fiber content before and after 4 F-T cycles is illustrated in Figure 8, while the variation of OMC with PP fiber content before and after 4 F-T cycles is shown in Figure 9. This behavior can be attributed to combined effects of fiber-induced voids and F-T driven fabric alteration. However, despite the reduction in MDD, the relative changes due to F-T cycling remained moderate across all fiber contents, indicating that PP fibers help maintain structural integrity during thermal cycling. The presence of discrete fibers likely restricts excessive particle displacement and limits frost-induced volumetric expansion, thereby reducing compaction degradation. Comparable observations have been reported in fiber-reinforced soils subjected to cyclic freezing [28]. Overall, the post-F-T compaction results suggests that while F-T cycling slightly reduces achievable dry density and increases moisture demand, PP fiber inclusion does not cause disproportionate deterioration. Instead, the soil-fiber matrix maintains stable compaction characteristics, supporting its suitability for cold-region subgrade applications.

Table 5

Compaction characteristics of soil reinforced with different PP fiber contents after 4 F-T cycles

Fiber Content (%)	MDD (g/cm3)	OMC (%)
Base 0.0	1.80	13.99
0.1	1.782	14.54
0.2	1.761	14.99
0.3	1.746	15.46
0.4	1.714	16.02
0.5	1.684	16.71

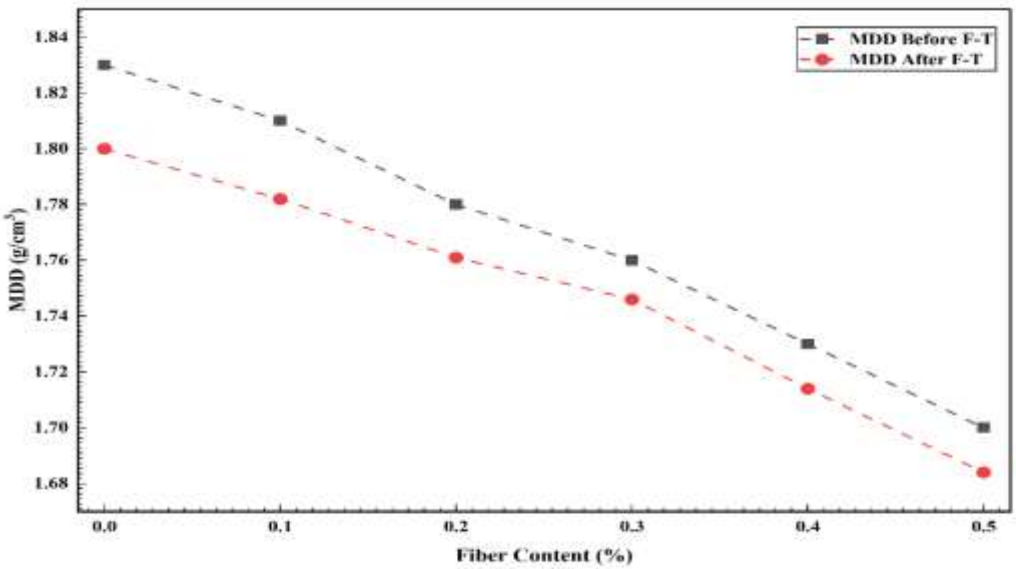

Fig.8 Variation of MDD with PP fiber content before and after 4 F-T cycles

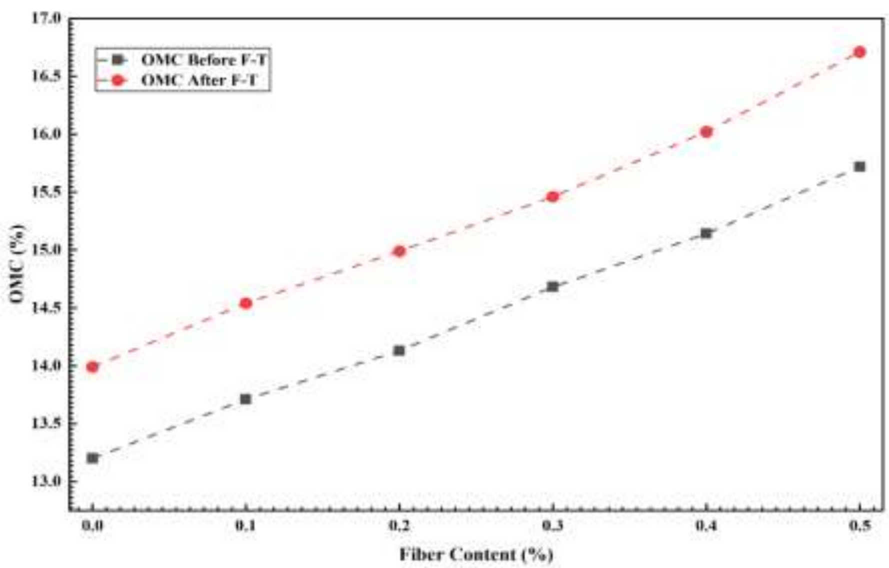

Fig.9 Variation of OMC with PP fiber content before and after 4 F-T cycles

3.3 CBR performance under unsoaked conditions

The presented CBR values represent the mean of three replicate tests, and the associated variability is illustrated using standard deviation in the form of error bars in Figure 10. The relatively small magnitude of standard deviation indicates good repeatability of the experimental results and testing procedure. Under unsoaked conditions, the untreated soil exhibited a CBR of 22.0%, which decreased to 16.63% after four F-T cycles, corresponding to a strength reduction of approximately 24.4%. The unsoaked CBR values presented in Table 6 represent the mean of three replicate tests, with variability quantified using standard deviation. Although the degradation is lower than that observed under soaked conditions, the reduction indicates that cyclic freezing likely disrupts soil fabric and weakens particle bonding even in the absence of prolonged water immersion. Similar F-T induced CBR losses (25-40%) have been reported for untreated granular and mixed soils [21, 28]. With PP fiber inclusion, a consistent increase in unsoaked CBR was observed prior to F-T exposure. The CBR increased progressively from 22.0% (untreated) to 33.7% at 0.4% fiber content, representing an improvement of approximately 53%. A slight reduction to 32.87% at 0.5% fiber indicates the onset of diminishing returns. The observed optimum performance at 0.4% fiber content may be attributed to an effective balance between fiber distribution and soil-fiber interaction. At this dosage, fibers are sufficiently dispersed to form a reinforcing network that enhances interparticle confinement and load transfer. However, at higher fiber content (0.5%), excessive fibers tend to overlap and form clusters, leading to reduced soil-to-soil interaction or contact, increased void ratio, and inefficient stress transfer, thereby causing a marginal reduction in CBR. The variation of unsoaked CBR with PP fiber content before and after 4 F-T cycles is illustrated in Figure 10. This dosage-dependent behavior is consistent with findings by [1, 14], who emphasized the existence of an optimum fiber content beyond which strength gains plateau or decline.

Following F-T cycling, fiber-reinforced specimens exhibited significantly higher retained strength compared to the untreated soil. The post-F-T CBR increased from 16.63% (untreated) to 29.38% at 0.4% fiber, corresponding to an enhancement of approximately 76.6% relative to the untreated post-F-T condition. Even at lower fiber contents (0.1-0.3%), substantial strength retention was observed, demonstrating the beneficial role of PP fibers in mitigating F-T damage by improving stress redistribution and restricting excessive particle displacement during F-T cycling. Moreover, the proportional strength loss due to F-T cycling decreased with fiber inclusion. While the untreated soil experienced a 24.4% reduction, the 0.4% fiber-reinforced specimen showed a comparatively smaller relative decline, indicating improved structural stability under thermal cycling. This improvement can be attributed to fiber-induced tensile resistance, crack-bridging action, and enhanced soil-fiber interlocking, which likely restrain thaw-softening and maintain load transfer capacity. Comparable F-T durability enhancement in PP fiber-reinforced soils has been documented by [21, 28]. From an engineering perspective, the improved unsoaked CBR and reduced strength degradation under F-T cycling indicate that PP fiber reinforcement can enhance the short-term and residual performance of subgrade soils in cold regions. The reduced sensitivity to F-T cycles suggests improved resistance to seasonal weakening, which is critical for maintaining pavement serviceability. However, the marginal reduction at higher content highlights the importance of optimizing fiber dosage to ensure field applicability and uniform compaction.

Overall, the results indicate that 0.4% PP fiber content yields the highest mean unsoaked CBR within the tested range. The observed differences between 0.4% and adjacent fiber contents exceed the corresponding standard deviation, indicating a consistent optimum trend rather than experimental scatter. These findings are consistent with established literature, which indicates that low to moderate fiber contents (0.25-0.75%) provide optimal reinforcement efficiency by balancing improved tensile resistance under both normal and cyclic freezing conditions.

Table 6

Unsoaked CBR values of PP fiber-reinforced soil before and after F-T cycles (mean ± standard deviation, n=3)

Fiber Content (%)	CBR Value (%)	CBR after 4 F-T Cycles
0	22.00 ± 0.87	16.63 ± 0.15
0.1	24.63 ± 1.00	20.71 ± 0.22
0.2	28.03 ± 1.06	22.56 ± 0.30
0.3	31.26 ± 1.41	26.47 ± 0.26
0.4	33.70 ± 0.76	29.38 ± 0.34
0.5	32.87 ± 1.2	27.96 ± 0.24

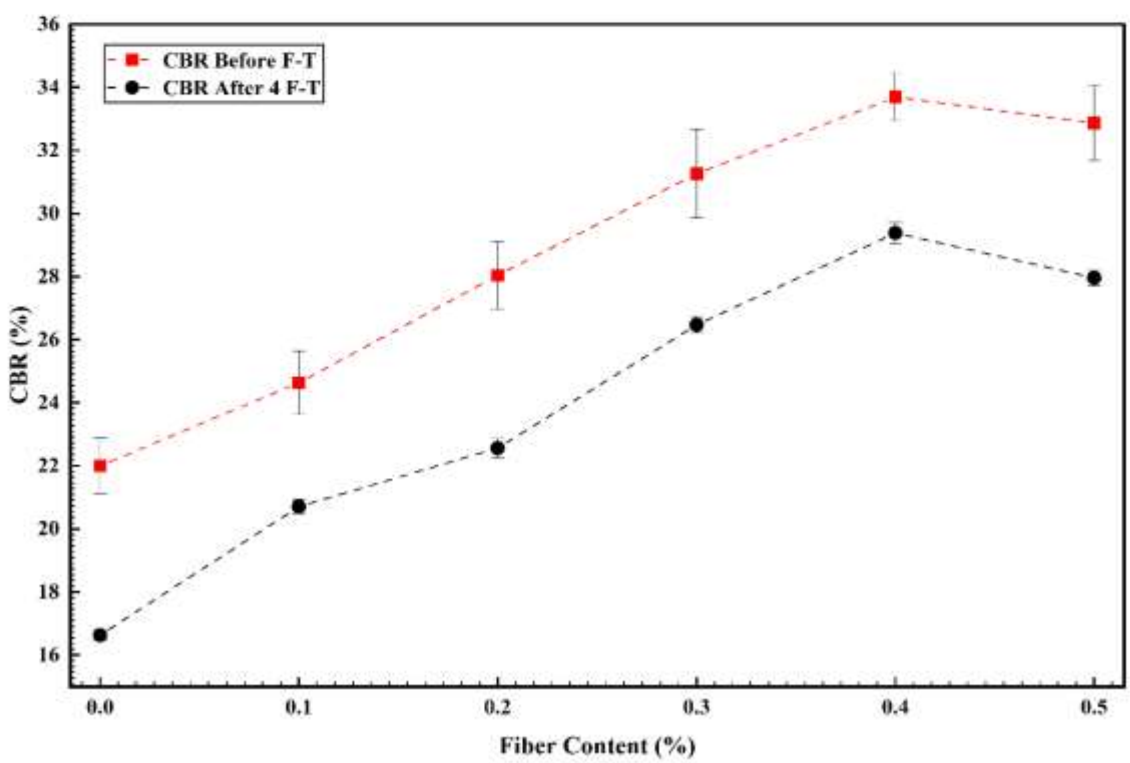

Fig.10 Variation of unsoaked CBR with PP fiber content before and after 4 F-T cycles. Error bars represent ±1 standard deviation based on three replicate tests (n=3).

3.4 CBR performance under soaked conditions

Similar to the unsoaked condition, the soaked CBR values represent the mean of three replicate tests, with variability quantified using standard deviation as shown in Figure 11. The relatively low dispersion of results indicates the reliability of the observed trends. The untreated soil exhibited a soaked CBR of 14.0%, which reduced to 9.30% after four F-T cycles, corresponding to a strength loss of approximately 33.6%. The soaked CBR values reported in Table 7 are expressed as mean values with corresponding standard deviation, indicating the consistency of the experimental results. The comparatively lower CBR values under soaked conditions, relative to unsoaked conditions, may be attributed to the loss of matric suction and reduction in effective stress due to saturation, which reduces interparticle friction and facilitates deformation under loading. This reduction is consistent with previously reported degradation trends in frost-susceptible soils, where repeated freezing likely induces moisture migration, ice lens formation, and microstructural disturbance, leading to significant bearing capacity loss [21-23]. The observed decline confirms the susceptibility of the SW-SM soil to thaw weakening under cyclic thermal loading. Upon incorporation of PP fiber, a progressive improvement in soaked CBR was observed under both pre and post F-T conditions. Under normal (pre-F-T) conditions, CBR increased from 14.0% (untreated) to 23.73% at 0.4% fiber content, representing an enhancement of approximately 69.5%. However, at 0.5% fiber dosage, CBR slightly decreased to 22.84%, indicating the onset of diminishing returns. The observed optimum performance at 0.4% fiber content under soaked conditions may be attributed to the combined effects of fiber reinforcement and moisture interaction within soil matrix. At this dosage, fibers likely improve resistance to pore water-induced softening by maintaining structural integrity and enhancing load transfer under saturated conditions. However, at higher fiber content of 0.5%, the increased void ratio and reduced compaction efficiency may become more pronounced in the presence of water, leading to greater susceptibility to deformation and a slight reduction in CBR. The variation of soaked CBR with PP fiber content before and after 4 F-T cycles is illustrated in Figure 11. This behavior aligns with the dosage-sensitive trends reported in the literature, where optimum fiber contents typically range between 0.25% and 0.75%, beyond which strength reduction may occur due to poor dispersion [1, 14]. After four F-T cycles, fiber-reinforced specimens consistently demonstrated higher retained strength compared to the untreated soil. The CBR increased from 9.30% (untreated post-F-T) to a maximum of 18.77% at 0.4% fiber, representing an improvement of approximately 102% relative to the untreated post-F-T condition. Even at lower dosages (0.2-0.3%), significant enhancement was observed, indicating that fiber inclusion contributes to mitigating F-T induced strength degradation by improving stress redistribution and limiting excessive particle displacement during cyclic thermal loading. Importantly, the percentage strength loss due to F-T cycling reduced with increasing fiber content. While the untreated soil experienced a 33.6% reduction, the 0.4% fiber-reinforced soil showed a comparatively smaller proportional decline. This suggests that PP fibers may enhance F-T durability by restraining crack propagation, maintaining interparticle contact, and improving tensile resistance during thaw softening. Similar mechanisms have been reported by [21], who observed substantial post-thaw CBR retention in PP fiber-reinforced soils, and by [28], who documented 20-35% higher post-thaw CBR in fiber-treated clayey sand. The results further demonstrate that 0.4% fiber content provides highest mean soaked CBR within investigated range. The improvement relative to adjacent fiber contents is greater than the associated standard deviation, supporting the identification of this dosage as the optimum. The slight reduction at 0.5% further confirms that the excessive fiber addition may adversely affect performance due to reduced compaction efficiency and increase void formation as previously noted by [14, 18]. The behaviour observed under soaked and F-T conditions represents a critical worst-case scenario for subgrade performance in cold regions. The improved CBR and reduced strength degradation indicate that PP fiber reinforcement can enhance the resistance of subgrade soils to moisture-induced softening and thaw weakening, which are primarily causes of pavement distress in high-altitude environments. This suggests that fiber-reinforced soils may provide improved stability during seasonal snowmelt and prolonged wet conditions. However, the reduction in performance at higher fiber content highlights the need for careful control of fiber dosage and field compaction practices to avoid excessive void formation under saturated conditions.

Overall, the findings indicate that PP fiber reinforcement significantly enhances both soaked CBR and F-T resistance of the Eastern Himalayan SW-SM soil. The improvement may be attributed to fiber-induced tensile reinforcement, crack bridging, and enhanced soil fiber interlocking, which collectively improve load transfer and reduce structural degradation under cyclic freezing conditions.

Table 7

Soaked CBR values of PP fiber-reinforced soil before and after 4 F-T cycles (mean ± standard deviation, n=3)

Fiber Content (%)	CBR (%)	CBR (%) after 4 F-T cycles
Base 0	14.00 ± 0.50	9.30 ± 0.10
0.1	15.86 ± 0.90	10.68 ± 0.17
0.2	19.00 ± 0.50	13.76 ± 0.30
0.3	21.47 ± 1.14	16.42 ± 0.33
0.4	23.73 ± 0.86	18.77 ± 0.31
0.5	22.84 ± 0.79	16.93 ± 0.25

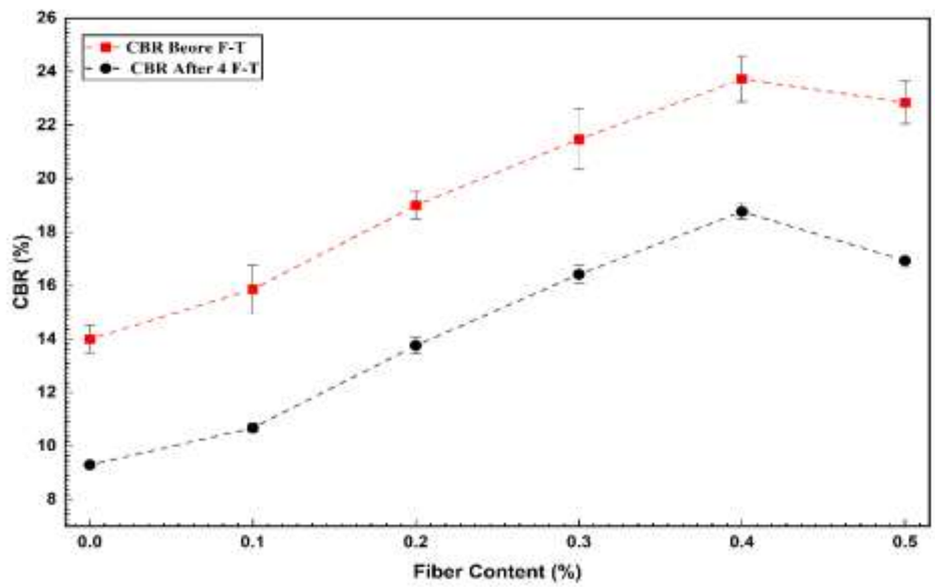

Fig.11 Variation of soaked CBR with PP fiber content before and after 4 F-T cycles. Error bars represent ±1 standard deviation based on three replicate tests (n=3).

4. CONCLUSIONS

This study evaluated the compaction characteristics and CBR performance of PP fiber-reinforced Eastern Himalayan soil subjected to F-T cycling. Based on the experimental results, the following conclusions can be drawn:

- The untreated SW-SM soil exhibited significant strength degradation after 4 F-T cycles, with soaked and unsoaked CBR values reducing by approximately 33.6% and 24.4% respectively. This behaviour indicates high susceptibility of the native soil to F-T induced weakening.
- The inclusion of PP fibers resulted in a consistent improvement in CBR under both soaked and unsoaked conditions. The optimum fiber content was observed at approximately 0.4%, at which soaked and unsoaked CBR values increased by about 69.5% and 53% respectively, compared to untreated soil. A slight reduction in strength at higher fiber content (0.5%) suggests diminishing returns beyond optimum dosage. The inclusion of statistical variability (standard deviation) further confirms the reliability of the observed fiber content.
- After F-T cycling, fiber-reinforced specimens retained significantly higher bearing capacity than untreated soil. At 0.4% fiber content, post-F-T soaked and unsoaked CBR values improved by approximately 102% and 76.6%, respectively,

relative to untreated post-F-T conditions, indicating improved resistance to F-T induced degradation.

- Fiber inclusion resulted in a gradual decrease in MDD and an increase in OMC due to the low specific gravity and bulky nature of PP fibers. However, despite the reduction in density, the overall strength improvement suggests that reinforcement effects play a more dominant role than densification in governing mechanical behaviour.
- The observed improvements in strength and durability may be attributed to enhanced tensile resistance, improved stress redistribution, and restriction of particle displacement within the soil fiber matrix during loading and F-T cycling.
- From an engineering perspective, the results indicate that low-percentage PP fiber reinforcement (approximately 0.4%) has the potential to improve the performance and durability of subgrade soils in cold region environments. The enhanced resistance to moisture induced weakening and F-T degradation suggests its applicability in high-altitude road construction, particularly under conditions of seasonal saturation and thaw softening.

Overall, the findings suggest that polypropylene fiber reinforcement can be an effective and practical approach for improving the mechanical performance and freeze-thaw resilience of frost susceptible subgrade soils, provided that appropriate fiber dosage and compaction control are maintained.

Limitation of present study

Although the present study provides valuable insights into the compaction behaviour and CBR performance of PP fiber-reinforced soil under freeze-thaw conditions, several limitations should be acknowledged:

- The experimental program was limited to four controlled F-T cycles, whereas natural cold-region environments may experience a significantly larger number of seasonal cycles.
- The investigation focused on a single soil type (SW-SM) collected from the Sela Pass region, and therefore the results may not be directly applicable to other soil types with different gradation or plasticity characteristics.
- The experiments were conducted under laboratory-controlled conditions, which may not fully capture complex field factors such as variable moisture regimes, traffic loading, and long-term environmental effects. Future studies incorporating a wider range of soil types, extended F-T cycles, and field-scale validation would further improve the understanding of fiber-reinforced soil performance in cold-region infrastructure applications.

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Conflict of Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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