

Polypropylene Fiber-Reinforced Himalayan Subgrade Soil: Enhancing Strength, Permeability, and Freeze-Thaw Durability for Cold-Region Infrastructure

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Abstract

Freeze-thaw (FT) cycling is a critical factor governing the degradation of strength, hydraulic stability, and durability of frost-susceptible soils in high-altitude Eastern Himalayan regions, posing major challenges for subgrades, embankments, and slope stability. This study investigates the mechanical behavior, permeability response, and microstructural evolution of polypropylene (PP) fiber-reinforced natural Himalayan soil subjected to laboratory conditioning and repeated FT cycles. Experimental evaluation was performed using unconfined compressive strength (UCS) testing, constant-head permeability testing, scanning electron microscopy (SEM), and SEM-EDS analysis. For UCS durability assessment, the untreated soil was evaluated under an extended FT program up to 90 cycles, whereas the PP fiber-reinforced soil was evaluated up to 28 FT cycles. The untreated soil showed a time-dependent increase in UCS from 45.0 kPa initially to 69.7 kPa after 28 days of laboratory conditioning. The fiber content producing the highest measured zero-day UCS was determined from the fiber-dosage series. A maximum UCS of 125.67 kPa was obtained at 0.75% PP fiber content, and this value was subsequently adopted as the baseline for evaluating conditioning-related strength development and FT-induced strength degradation. Under FT exposure, the reinforced specimens exhibited nonlinear degradation, with rapid initial strength loss followed by gradual stabilization. After 28 FT cycles, the UCS decreased to 81.4 kPa, indicating effective residual strength retention. Permeability results showed that PP fiber inclusion also altered the hydraulic response. Before FT exposure, the mean coefficient of permeability decreased from 4.30×10^{-5} cm/s for untreated soil to 2.63×10^{-5} cm/s at 0.5% PP fiber content. After 4 FT cycles, permeability increased in all mixtures; however, reinforced specimens retained lower permeability than untreated soil, with the lowest post-FT value of 2.97×10^{-5} cm/s observed at 0.6% PP fiber content. These distinct mechanical and hydraulic response optima indicate that fiber dosage should be selected according to the governing performance requirement rather than on the basis of UCS alone. SEM observations revealed porous fabric, weak interparticle contacts, microvoids, and localized crack-like features, while SEM-EDS indicated relatively low calcium content and did not indicate a calcium-rich composition suggestive of cementitious products. These observations are consistent with, but do not independently establish, a predominantly physical reinforcement mechanism. Overall, PP

fibers improved the measured laboratory strength, hydraulic response, and FT resistance, indicating potential for further evaluation in cold-region geotechnical applications.

Keywords: Polypropylene fiber-reinforced soil, freeze-thaw cycles, ground improvement, Himalayan subgrade, unconfined compressive strength, hydraulic conductivity, microstructural characterization, cold-region geotechnics.

Introduction

In cold and mountainous regions, repeated FT cycles represent one of the most severe environmental actions affecting near-surface soils. During freezing, pore water transforms into ice and expands by approximately 9%, promoting ice-lens formation, pore-volume increase, crack initiation, and disruption of interparticle contacts. During thawing, ice melting weakens particle bonding, redistributes moisture, increases porosity, and rearranges the soil fabric [1-4]. These processes progressively reduce the strength, stiffness, bearing capacity, hydraulic stability, and long-term durability of soils used in subgrades, embankments, slopes, and pavement-supporting layers [5-8]. High-altitude areas of the Eastern Himalaya are particularly vulnerable to FT-induced deterioration because of pronounced seasonal and diurnal temperature fluctuations, prolonged sub-zero periods, high moisture availability from snowmelt and rainfall, and complex slope-subgrade interactions. These conditions promote frequent freezing and thawing, shallow frost penetration, moisture migration, microstructural disturbance, and progressive weakening of soil deposits, ultimately contributing to pavement distress, subgrade failure, slope instability, and premature deterioration of cold-region infrastructure. Therefore, understanding the coupled mechanical and hydraulic response of Eastern Himalayan soils under FT action is essential for reliable and region-specific geotechnical design.

Previous studies have consistently shown that FT cycling degrades untreated and stabilized soils, although the rate and magnitude of deterioration depend strongly on soil type, moisture condition, stabilizer type, freezing temperature, and number of cycles. Fine-grained and frost-susceptible soils are particularly sensitive because ice segregation and thaw weakening alter volume, fabric, pore structure, and strength [1, 5, 6]. Ding et al. [2] reported a sharp reduction in UCS during the early FT cycles in cement-treated and polypropylene (PP) fiber-cement-stabilized clay, followed by a slower rate of degradation in later cycles. Similar early-stage damage followed by gradual stabilization has been reported for lime-treated, lignosulfonate-treated, calcium sulfoaluminate cement (CSA)-treated, and geopolymer-stabilized soils [3, 9-11]. Studies on landslide-prone and pavement-supporting soils have also demonstrated that FT action reduces strength, stiffness, California bearing ratio, and serviceability of subgrade systems [8, 12-14]. These findings confirm that FT-induced degradation is a major durability concern; however, the response is highly material- and region-dependent, requiring direct evaluation of locally available soils exposed to site-specific environmental conditions.

Discrete fiber reinforcement has emerged as a practical method for improving the mechanical behavior of soils under adverse loading and environmental conditions. PP fibers are particularly attractive for cold-region applications because of their low density, hydrophobic nature, chemical inertness, high tensile strength, resistance to degradation, and ease of mixing with soil. Unlike chemical stabilizers, PP fibers primarily improve soil behavior through physical mechanisms, including tensile resistance, fiber-soil interlocking, crack bridging, restraint of deformation, and stress redistribution. Malekzadeh and Bilsel [15] showed that PP fibers can reduce accumulated permanent strain under cyclic loading, while [16-18] demonstrated the role of fibers in improving tensile resistance and limiting crack development in soil and pavement-related materials. Recent studies have also reported improved ductility and post-peak behavior in fiber-reinforced soils and stabilized geomaterials [19, 20]. These characteristics make PP fibers a promising reinforcement option for subgrade soils subjected to cyclic freezing and thawing.

A substantial body of literature confirms that PP fiber inclusion can improve UCS and ductility of soils. Zaimoglu [5] reported that the UCS of fine-grained soil subjected to FT cycles increased with PP fiber content, while [21] showed that PP fiber addition increased UCS before and after FT exposure and reduced frost heave. Strength improvement due to PP fiber inclusion has also been reported in cement-treated, lignosulfonate-treated, CSA-treated, geopolymer-stabilized, loess, and residual soil systems [2, 22, 23]. However, these studies also indicate that fiber reinforcement is not linearly beneficial at all dosages. Beyond an optimum fiber content, clustering, poor dispersion, increased void ratio, weak fiber-soil interfaces, reduced soil-soil contact, and lower compaction efficiency may reduce strength and durability [11, 18, 22, 24]. Therefore, identifying the fiber dosage associated with the desired mechanical response for a specific regional soil is necessary before evaluating its FT durability.

Under FT exposure, fiber-reinforced soils generally retain higher residual strength than unreinforced soils. Ghazavi and Roustaie [21] observed improved UCS before and after FT cycling with PP fiber addition, while [25] reported that reinforcement reduced strength loss from 43% in unreinforced soil to 32% in reinforced soil. Similar improvements in post-FT strength retention and ductility have been reported for PP fiber-reinforced soils and PP fiber-binder systems [1-3, 26]. Lignosulfonate-, CSA-, biopolymer-, and alkali-activated systems further indicate that fibers can reduce damage accumulation and improve residual strength after repeated FT cycling [4, 9, 10, 27]. Studies using other fibers or composite fiber-stabilizer systems support the broader conclusion that discrete reinforcement limits crack growth, redistributes stress, and helps preserve internal structural integrity under cyclic freezing and thawing [7, 13, 28, 29].

In addition to strength degradation, permeability is a critical hydraulic response governing drainage capacity, pore-water migration, frost susceptibility, and long-term serviceability of subgrade soils in cold regions. FT cycling can enlarge pores, increase macropore volume, promote microcrack formation, and develop connected seepage pathways, leading to higher hydraulic conductivity and greater hydraulic vulnerability [30-32]. PP fibers may alter the permeability response by modifying soil fabric, pore continuity, and crack propagation

mechanisms. At appropriate dosages, randomly distributed PP fibers can restrict crack development and reduce the connectivity of preferential flow paths, whereas excessive fiber inclusion may disturb particle packing, increase voids, and generate weak fiber-soil interfaces that enhance pore interconnection [33-35]. Therefore, permeability should not be treated as a secondary response in cold-region reinforced soils. Instead, it must be evaluated together with strength because FT-induced pore expansion and crack connectivity can directly control both hydraulic stability and mechanical durability.

Microstructural investigations using scanning electron microscopy (SEM) provide direct evidence for the mechanisms controlling strength improvement, hydraulic response, and FT degradation. Roustaei et al. [25] observed that FT cycling increased large pores and reduced cohesion between soil particles and PP fibers, while fibers acted as tensile elements that limited strength loss. Liu et al. [36] reported that FT cycles loosened the soil surrounding fibers and reduced interfacial contact; nevertheless, the spatial stress network formed by discrete fibers continued to redistribute load. Kravchenko et al. [37] showed that PP fibers retained their geometry after FT exposure and dynamic loading, supporting their durability in cold-region soils. In binder-treated systems, SEM studies have shown that hydration products, fiber-matrix contact, pore filling, and interlocking improve matrix integrity [3, 22, 23, 38]. Other SEM-based studies have highlighted the importance of fiber distribution, crack bridging, interfacial friction, pore refinement, and matrix cracking in controlling strength and ductility under FT exposure [4, 11, 16, 24]. However, most microstructural studies have focused on controlled clay, silt, loess, residual soil, or binder-treated systems, while natural Himalayan subgrade soils remain insufficiently investigated.

Despite these advances, a critical regional research gap remains. Existing studies on PP fiber-reinforced soils under FT conditions have been conducted mainly on clayey soils, silts, loess, cement-stabilized soils, geopolymer-stabilized soils, residual soils, or laboratory-controlled soil-binder systems. These materials do not fully represent the naturally occurring, weathered, well-graded sand with silt (SW-SM) soils encountered in high-altitude Eastern Himalayan corridors. In particular, frost-affected subgrade soils from the Sela Pass region of Arunachal Pradesh experience a distinctive combination of high elevation, severe seasonal freezing, snowmelt-driven moisture availability, steep terrain, weathered parent material, and infrastructure vulnerability along strategic mountain highways. However, these soils have not been systematically evaluated for PP fiber reinforcement under repeated FT cycles. This regional gap is significant because the performance of fiber-reinforced soil depends strongly on local gradation, fines content, mineralogy, compaction condition, moisture regime, and FT exposure environment. Consequently, design recommendations derived from non-Himalayan soils or chemically stabilized matrices may not be directly transferable to Eastern Himalayan subgrade conditions. A second gap concerns the limited integration of mechanical, hydraulic, and microstructural responses in natural cold-region soils. Many previous studies have examined UCS improvement or FT durability, while fewer have simultaneously assessed permeability

evolution, strength degradation, strength retention, SEM-based soil fabric changes, and SEM-EDS-based evidence to distinguish physical reinforcement from chemical stabilization. For natural PP fiber-reinforced Himalayan soil, the relationship among fiber dosage, FT-induced UCS degradation, permeability change, crack development, pore connectivity, and microstructural evolution remains poorly established. This lack of integrated understanding limits the ability to design reinforced subgrades that satisfy both mechanical stability and hydraulic durability requirements under cold-region service conditions.

Accordingly, the present study addresses this regional and scientific gap by experimentally investigating PP fiber-reinforced natural Himalayan subgrade soil collected from the Sela Pass region of Arunachal Pradesh, Eastern Himalaya. The specific objectives are to: (i) evaluate the time-dependent UCS response of untreated soil under laboratory conditioning; (ii) determine the PP fiber content producing the highest measured zero-day UCS within the investigated dosage range; (iii) assess the permeability response of untreated and PP fiber-reinforced soils before and after FT exposure; (iv) evaluate the conditioning-related strength development and FT-induced strength degradation of soil reinforced with the selected 0.75% PP fiber content; and (v) interpret the reinforcement and degradation mechanisms using SEM and SEM-EDS analyses. By integrating strength, permeability, and microstructural evidence, this study provides region-specific experimental insight into the performance of PP fiber-reinforced Eastern Himalayan subgrade soil. The findings provide laboratory-scale evidence relevant to further evaluation of PP fiber reinforcement for cold-region geotechnical applications in high-altitude Himalayan environments.

Materials

Soil

The SW-SM soil sample was collected from a frost-susceptible side slope along National Highway 13 in the high-altitude region of Arunachal Pradesh, Eastern Himalaya. The sampling location is situated near the Sela Pass in Tawang district (27.50519890° N, 92.10466340° E), at an elevation exceeding 4000 m above mean sea level. This region is characterized by prolonged sub-zero winter temperatures, significant seasonal FT cycling, and recurrent slope instability, making it representative of cold-region subgrade and slope materials. A representative view of the sampling site is shown in Figure 1 (a) and (b), illustrating the terrain conditions and physical features of the site. To obtain representative soil samples, an open pit excavation was carried out to a depth of approximately 1.5 m after removing the organic-rich topsoil layer. Sampling below the active organic horizon was adopted to minimize the influence of vegetation, surface weathering, and seasonal moisture variations. This approach ensures that the collected material adequately represents the in-situ soil governing mechanical behavior under FT conditions.

Physical Characterization of Soil

The physical and index properties of the soil were determined in accordance with Bureau of Indian Standard, IS: 2720. The measured properties, including grain size distribution and compaction characteristics, are summarized in Table 1. The grain size distribution curve of the soil is presented in Figure 2, which indicates a well-graded particle distribution with a dominant sand fraction and a minor proportion of fines. Based on the Unified Soil Classification System (USCS), the soil is classified as SW-SM. The presence of a well-graded sandy matrix combined with a non-negligible silt fraction is particularly significant in cold-region geotechnics, as such soils are susceptible to moisture migration, pore ice formation, and progressive fabric alteration under FT cycling. These characteristics make the selected soil suitable for investigating FT-induced strength degradation and evaluating the effectiveness of PP fiber reinforcement in improving UCS and durability under cold-region conditions.

Polypropylene Fiber

PP fiber was used as discrete reinforcement to enhance the strength and FT resistance of the Eastern Himalayan soil. A representative image of the fibers used in this study is shown in Figure 3. The physical and mechanical properties of the PP fibers used in this study are summarized in Table 2. PP 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 subjected to repeated FT cycling. In the present study, fibers with a nominal length of 12 mm were selected to promote effective crack bridging and tensile load transfer within the soil matrix under FT-induced stresses. The PP fibers used in this study had a specific gravity of approximately 0.92 and a nominal length of 12 mm; their physical and mechanical properties are summarized in Table 2.

Methodology

Preparation of UCS Specimens

Specimens for UCS testing were prepared in accordance with IS 2720 (Part 10) [39]. Cylindrical UCS specimens were prepared with a diameter of 38 mm and a height of 76 mm, maintaining a height-to-diameter ratio of 2:1. All specimens were prepared at the OMC of 13.2% and compacted to the target MDD of 1.83 g/cm³, as determined from the standard Proctor compaction test. For fiber-reinforced specimens, the required fiber mass was determined gravimetrically based on the dry mass of soil. Before mixing, the PP fibers were manually separated to loosen fiber bundles and minimize entanglement. The fibers were then added gradually in small portions to the dry soil while continuously mixing, rather than being introduced as a single mass, to promote uniform distribution and reduce localized balling or clustering. After dry mixing, water corresponding to the OMC was added gradually, and mixing was continued until a visually homogeneous soil-fiber mixture was obtained. The prepared mixture was compacted in layers inside cylindrical split molds to achieve the target dry density. The same specimen geometry, target OMC and MDD, mixing procedure, and layered-

compaction method were maintained for all replicate specimens to minimize preparation-related variability. After compaction, the specimens were carefully extruded, sealed to minimize moisture loss, and laboratory-conditioned under laboratory storage conditions. To determine the PP fiber content producing the highest measured zero-day UCS, separate UCS specimens were prepared with fiber contents of 0.50%, 0.55%, 0.60%, 0.65%, 0.70%, 0.75%, 0.80%, 0.85%, 0.90%, 0.95%, and 1.00% by dry weight of soil. These specimens were tested immediately after preparation (zero-day condition), without an intervening laboratory conditioning period. Three replicate specimens were tested at each fiber content. The highest mean zero-day UCS of 125.67 kPa was obtained at 0.75% PP fiber content; therefore, 0.75% PP fiber was selected as the fiber content producing the highest measured zero-day mean UCS within the investigated dosage range for the subsequent laboratory conditioning and freeze-thaw investigations. The UCS value of 125.67 kPa obtained for 0.75% PP fiber in the optimization series was adopted as the common zero-day/zero-cycle baseline. Separate specimens containing 0.75% PP fiber were subsequently prepared for the laboratory conditioning and FT exposure programs. For the laboratory conditioning series, specimens were tested after 1, 3, 5, 7, 10, 15, 20, and 28 days of laboratory conditioning. For the FT series, separate specimens were subjected to 1, 3, 5, 7, 10, 15, 20, and 28 FT cycles. Thus, the zero-day laboratory-conditioning condition and zero-cycle FT condition correspond to the same initial reference state, represented by the zero-day mean UCS of 125.67 kPa for the 0.75% PP fiber condition. The specimen prepared is shown in Figure 4(a) and Figure 4(b). For the untreated-soil time-dependent UCS assessment, separate triplicate specimens were prepared for each designated laboratory-conditioning duration. Following compaction and extrusion, the specimens were sealed to minimize moisture exchange with the surrounding environment and maintained under laboratory storage conditions until the assigned testing age. The laboratory storage temperature and relative humidity were not systematically monitored or recorded during the conditioning program; therefore, these environmental conditions cannot be reported retrospectively. Separate specimens were tested at each conditioning age; therefore, no specimen was repeatedly tested during the conditioning program. Because the untreated soil contained no cementitious or chemical stabilizer, the storage period is referred to as laboratory conditioning rather than curing. Specimen mass change, water content at the time of UCS testing, degree of saturation, matric suction, and drying shrinkage were not systematically monitored during the conditioning period. Consequently, the individual contributions of moisture redistribution, suction development, and soil-fabric rearrangement to the observed time-dependent UCS variation could not be independently quantified.

Preparation of Permeability Specimens

Permeability specimens were prepared in accordance with IS 2720 (Part 17) [40] by compacting the soil directly in cylindrical permeability moulds having an internal diameter of 8.0 cm and a specimen height of 6.5 cm as shown in Figure 5 (a). The specimens were prepared at the same optimum moisture content (OMC) and target maximum dry density (MDD) used for UCS testing, namely 13.2% and 1.83 g/cm³, respectively. After compaction the specimens were

wrapped with thin plastic film to control moisture variation during FT process as shown in Figure 5 (b). For reinforced specimens, PP fibers were incorporated at contents of 0.1%, 0.2%, 0.3%, 0.4%, 0.5%, 0.6%, 0.7%, and 0.8% by dry weight of soil. The same incremental fiber-separation and dry-mixing procedure described for the UCS specimens was used to minimize fiber balling and localized clustering, after which water corresponding to the OMC was gradually added and the mixture was thoroughly blended. The mixtures were compacted in layers within the permeability mould to achieve the target dry density. Separate specimens were prepared for the pre-FT and post-FT permeability assessments, with three replicate specimens for each fiber content and exposure condition. Before permeability measurement, the mould containing the compacted specimen was immersed in water for 24 h to promote specimen saturation. Because the final degree of saturation was not independently measured, the 24 h immersion period is reported as the adopted saturation/preconditioning procedure rather than as verification of complete saturation. The fiber-dosage ranges were selected as planned experimental ranges based on previous studies of PP fiber-reinforced soils and the specific objectives of the two test programs, rather than through a separate preliminary optimization program. Previous studies have investigated PP fiber contents over relatively broad ranges, including 0.25-2.0%, 0.5-1.5%, and 0-1.0% by dry weight of soil [5, 15, 25]. For the UCS program, the range of 0.50-1.00% was therefore investigated at finer 0.05% increments to resolve the fiber content associated with the maximum measured UCS more closely. In contrast, the permeability program used 0.1-0.8% PP at 0.1% increments to characterize the broader hydraulic response to increasing fiber content rather than to identify a UCS-based optimum. Fiber dosage was controlled gravimetrically using a balance with a readability of 0.01 g, and the required fiber mass was calculated relative to the dry mass of soil for each mixture.

Unconfined Compressive Strength (UCS)

UCS tests were conducted in accordance with IS 2720 (Part 10) [39]. The tests were performed using a strain-controlled loading system at a constant axial strain rate of 1.25 mm/min. During testing, the axial load and corresponding deformation were continuously recorded until failure. The UCS was determined as the peak axial stress sustained by the specimen. Where no distinct peak was observed, the maximum recorded axial stress during loading was considered as the UCS. Although the soil was sand-dominated, the compacted specimens remained self-supporting after extrusion because of dense particle packing, the fines fraction, interparticle friction, and apparent cohesion associated with the partially saturated compacted state. Matric suction was not directly measured; therefore, its contribution is considered interpretative rather than quantitatively established. For FT-conditioned specimens, UCS testing was carried out immediately after completion of the designated number of FT cycles to minimize the effects of post-thaw moisture redistribution and structural recovery. The reported UCS values represent the mean of three replicate specimens, and the corresponding standard deviations were used to assess repeatability.

Permeability

The constant-head method was selected because the investigated SW-SM soil is dominated by coarse particles, comprising approximately 79.21% sand and 11.60% gravel, with only about 9.18% silt-plus-clay fines. The predominantly granular fabric permitted a measurable continuous discharge under the imposed hydraulic head. Moreover, the measured permeability values were of the order of 10^{-5} cm/s, which lies within the permeability range covered by IS 2720 (Part 17) [40]. Therefore, the constant-head arrangement was considered appropriate for obtaining reproducible comparative hydraulic-conductivity measurements for the untreated and PP fiber-reinforced SW-SM specimens. Cylindrical specimens with a diameter of 8.0 cm and a height (L) of 6.5 cm were tested, corresponding to a cross-sectional area of approximately 50.27 cm². Prior to permeability testing, the mould containing the compacted specimen was immersed in water for 24 h as the adopted saturation/preconditioning procedure. Because the final degree of saturation was not independently measured, complete saturation is not assumed. The specimen was then securely seated in the permeability apparatus to minimize sidewall or bypass flow. Water was allowed to flow vertically downward, from the top surface to the bottom surface of the specimen under a constant hydraulic head (h) of 82 cm. The corresponding applied hydraulic gradient, $i=h/L$, was approximately 12.62. Following establishment of seepage under the applied constant head, the discharge water was collected in a graduated measuring vessel. Each discharge observation was recorded over a fixed duration of 60 seconds. The coefficient of permeability was calculated from the constant-head relationship

$$k = \frac{QL}{Aht}$$

where Q is the volume of water collected during the observation interval, L is the specimen height, A is the specimen cross-sectional area, h is the applied hydraulic head, and t is the collection time. The permeant water was used at ambient laboratory room temperature; water temperature was not independently thermostatically controlled during testing. After steady seepage was established, three successive 60 second discharge observations were recorded for each specimen.

Freeze-Thaw Cycling Procedure

For the UCS specimens, FT cycling was carried out under closed-system conditions using a programmable deep freezer. The specimens were prepared at the OMC of 13.2% and compacted to the target MDD of 1.83 g/cm³. For the untreated soil, using the measured specific gravity of 2.68, the nominal initial void ratio calculated from the target dry density was approximately 0.464, corresponding to a nominal porosity of approximately 31.7%. Using the target water content of 13.2%, the corresponding nominal initial degree of saturation was approximately 76.2%. Thus, the untreated UCS specimens were initially in a partially saturated condition. These values were calculated from the target compaction conditions and should be regarded as nominal values rather than specimen-specific measurements. After preparation, the specimens were wrapped and sealed with thin plastic film throughout FT exposure to minimize moisture

exchange with the surrounding environment. The sealed plastic wrapping was visually inspected during handling and remained intact throughout the designated FT exposure. No external water was added during cycling, and no intentional drainage was permitted during thawing. One FT cycle consisted of freezing at -15 °C for 12 h followed by thawing at a laboratory temperature of 20 ± 3 °C for 12 h, giving a total cycle duration of 24 h. The reported freezing and thawing temperatures refer to the imposed chamber and laboratory exposure conditions, respectively. Specimen-core temperature was not instrumentally monitored, and an independent temperature-time record was not obtained during the original experimental program. Therefore, although each specimen was subjected to the prescribed 12-h freezing and 12-h thawing periods, attainment of the target temperature throughout the specimen core and complete internal thawing before initiation of the subsequent cycle could not be independently verified. No directional freezing boundary was intentionally imposed; the wrapped specimens were exposed to the freezer environment without insulation designed to restrict freezing to a single direction. Frost heave, axial deformation, volumetric strain, and visible crack development were not instrumentally or quantitatively monitored during FT cycling. Specimen mass and water content were also not systematically recorded before and after cycling. The untreated specimens were subjected to 0, 3, 5, 7, 14, 28, 56, and 90 FT cycles, whereas the 0.75% PP fiber-reinforced specimens were subjected to 0, 1, 3, 5, 7, 10, 15, 20, and 28 FT cycles, with three independently prepared replicate specimens tested at each condition.

For the permeability specimens, the same freezing and thawing temperatures and durations were adopted. The specimens were prepared at the OMC of 13.2% and compacted to the target MDD of 1.83 g/cm³, after which they were sealed with thin plastic film to minimize moisture exchange during FT exposure. The post-FT permeability specimens were subjected to four FT cycles, with each cycle consisting of freezing at -15 °C for 12 h followed by thawing at 20 ± 3 °C for 12 h. Three independently prepared replicate specimens were used for each fiber content and exposure condition. After completion of the prescribed FT cycles, the specimens were subjected to the 24-h immersion preconditioning procedure described above before measurement of permeability using the constant-head method. Experimental matrix for PP fiber optimization, laboratory conditioning, and freeze-thaw durability testing are presented in Table 3.

SEM and SEM-EDS Analysis

Scanning electron microscopy (SEM) was used for qualitative microstructural assessment of untreated and PP fiber-reinforced soil before and after FT exposure. Representative fragments were taken from the central portions of failed UCS specimens. For each SEM condition, one specimen was examined and seven fields of view were inspected. Figures 12 and 13 present representative recurring features observed across these fields. Selected conditions, rather than every fiber dosage or FT level, were examined. SEM imaging was performed using a JEOL JSM-6390 in secondary-electron mode at 20 kV and a 10 mm working distance. Micrographs were acquired at 100× to 5500× depending on the feature of interest; therefore, identical magnification was not maintained across all images. Comparisons are accordingly qualitative

and are not used to quantify pore size, crack density, or pore area. Energy-dispersive X-ray spectroscopy (EDS) was used to characterize elemental composition and provide supplementary evidence for microstructural interpretation. SEM-EDS was not treated as direct proof of specific mechanical reinforcement mechanisms or mineralogical reaction products.

Statistical Analysis

All UCS and permeability results are reported as the mean $\pm$ sample standard deviation (SD) based on three independently prepared replicate specimens ($n=3$) for each experimental condition. The reported SD represents the sample standard deviation calculated from the three independent replicate measurements using an $n - 1$ denominator, rather than the standard error or population standard deviation. No tested specimens or replicate results were excluded from the reported UCS or permeability datasets; all three independently prepared replicate measurements obtained for each reported experimental condition were included in the calculation of the mean and sample standard deviation. For the zero-day UCS fiber-dosage series, differences among the investigated PP fiber contents (0.50-1.00%) were evaluated using one-way analysis of variance (ANOVA) at a significance level of $\alpha=0.05$. Where the ANOVA indicated a significant overall effect of fiber content, Tukey's honestly significant difference (HSD) post-hoc test was used for pairwise comparison of the dosage means. Statistical significance was accepted at $p < 0.05$. Particular attention was given to comparison of the 0.75% fiber dosage with the neighboring 0.70%, 0.80%, and 0.85% dosages to determine whether the observed maximum mean UCS was statistically distinguishable within the investigated dosage range.

Results and Discussion

Comparative Effects of Laboratory Conditioning and Freeze-Thaw Exposure on the Unconfined Compressive Strength of Untreated Soil

The variation in UCS of untreated soil with laboratory conditioning duration and FT exposure is presented in Table 4 and Figure 6. The FT results presented in this section correspond to the extended exposure program conducted specifically on the untreated soil. Specimens were subjected to 0, 3, 5, 7, 14, 28, 56, and 90 FT cycles, with three independently prepared replicate specimens tested at each condition. This extended program was adopted to establish the long-term baseline deterioration behavior of the natural soil and was distinct from the 0-28-cycle FT durability program used for the PP fiber-reinforced specimens. Mean UCS values and corresponding standard deviations were determined from triplicate specimens. The results demonstrate two contrasting responses of the untreated soil: time-dependent increase in UCS during laboratory conditioning and continuous strength degradation under repeated FT exposure. The UCS of the untreated soil increased from 45.0 ± 1.3 kPa at the initial condition to 49.87 ± 0.85 kPa, 55.23 ± 0.90 kPa, and 57.36 ± 0.60 kPa after 3, 5, and 7 days of laboratory conditioning, respectively. Continued laboratory conditioning further increased the UCS to 64.52 ± 0.22 kPa at 14 days and 69.70 ± 0.68 kPa at 28 days. Thereafter, the rate of strength gains

gradually diminished, reaching 71.40 ± 0.76 kPa and 73.10 ± 0.44 kPa after 56 and 90 days, respectively. Overall, the UCS increased by approximately 62.4% relative to the initial condition. The nonlinear trend indicates that the majority of strength development occurred during the first 28 days of laboratory conditioning, after which the soil approached a relatively stable structural state. Similar laboratory conditioning-induced strength evolution has been reported for compacted and stabilized soils, where progressive fabric stabilization and improved stress transfer efficiency govern long-term strength development [4, 9]. The observed time-dependent increase in UCS should not be interpreted as conventional curing because the untreated soil contained no cementitious or chemical stabilizer. The increase may be associated with progressive moisture redistribution, development of matric suction, changes in interparticle contact, and rearrangement or stabilization of the compacted soil fabric during sealed laboratory storage. However, specimen mass change, water content, degree of saturation, matric suction, and drying shrinkage were not systematically measured at each conditioning age. Therefore, the relative contribution of these mechanisms cannot be determined conclusively from the present experimental program. Comparable observations have been reported by [13, 19, 20], who highlighted the significant influence of laboratory conditioning duration on the mechanical behavior of geomaterials.

In contrast, repeated FT exposure resulted in a continuous reduction in UCS. Relative to the initial strength of 45.0 kPa, the UCS decreased to 41.2 ± 1.10 kPa after 3 FT cycles, representing an 8.4% reduction. Further decreases were observed with increasing FT exposure, with UCS values declining to 38.8 ± 0.88 kPa, 36.5 ± 0.47 kPa, and 32.4 ± 0.67 kPa after 5, 7, and 14 cycles, respectively. After prolonged FT exposure, the UCS further decreased to 28.1 ± 0.52 kPa at 28 cycles, 23.9 ± 1.30 kPa at 56 cycles, and 21.5 ± 1.06 kPa at 90 cycles. The overall reduction of approximately 52.2% demonstrates the severe deterioration induced by cyclic freezing and thawing. This strength loss is attributed to cumulative microstructural damage generated by repeated water-ice phase transformations within the pore network. During freezing, the volumetric expansion of pore water generates internal stresses that disrupt interparticle contacts and initiate microcracking, while subsequent thawing promotes structural softening and moisture redistribution [3, 11]. Repeated FT cycles progressively increase pore connectivity and weaken the integrity of the soil skeleton, resulting in a continuous decline in compressive resistance [23, 26]. The greater rate of strength reduction observed during the initial FT cycles suggests rapid degradation of the most vulnerable structural features, whereas the lower degradation rate at higher cycle numbers indicates that substantial damage had already accumulated within the soil matrix. Because specimen water content and degree of saturation were not monitored during FT cycling, these FT results represent the response of specimens prepared at the nominal initial moisture and compaction conditions described in the methodology. Consequently, any changes in moisture content or degree of saturation during repeated FT exposure, and their contribution to the measured strength degradation, could not be independently quantified.

A direct comparison of the two trends highlights the fundamentally opposite influence of laboratory conditioning and FT exposure on untreated soil behavior. While laboratory conditioning was associated with a gradual increase in UCS, FT exposure continuously weakened the soil through progressive deterioration of the soil skeleton. After 90 days of laboratory conditioning, the UCS reached 73.10 kPa, whereas after 90 FT cycles it decreased to 21.5 kPa. Consequently, the laboratory-conditioned soil exhibited a strength approximately 3.4 times greater than that of the FT-damaged soil. Figure 6 clearly illustrates the divergence between the two responses, emphasizing that FT-induced deterioration can progressively outweigh the beneficial effects of laboratory conditioning when no stabilization measure is incorporated. These findings establish a critical baseline for assessing the effectiveness of polypropylene fiber reinforcement in mitigating FT-induced damage and maintaining soil strength under cold-region environmental conditions.

Determination of Fiber Content for Maximum UCS

The effect of PP fiber content on the zero-day UCS of the studied soil is presented in Table 5 and Figure 7. The specimens used for fiber-content optimization were tested immediately after preparation, without an intervening laboratory conditioning period, and three replicate specimens were tested at each fiber dosage. The results show a nonlinear dependence of UCS on PP fiber content, with strength increasing up to 0.75% fiber content and decreasing at higher dosages. The maximum mean UCS of 125.67 kPa was obtained at 0.75% PP fiber content; therefore, this dosage was selected for the subsequent laboratory conditioning and FT durability investigations. The measured UCS of 125.67 kPa at 0.75% PP fiber content was subsequently used as the common zero-day/zero-cycle reference for evaluating time-dependent UCS development during laboratory conditioning and FT-induced strength degradation. At a fiber content of 0.50%, the UCS was 79.66 kPa, increasing steadily to 95.34 kPa and 105.76 kPa at 0.55% and 0.60%, respectively. Further increases in fiber content resulted in UCS values of 112.33 kPa and 118.33 kPa at 0.65% and 0.70%, with a maximum UCS of 125.67 kPa at 0.75% fiber content. The increase in UCS at low to intermediate fiber contents can be attributed to improved fiber-soil interaction, tensile resistance, crack bridging, stress redistribution, and mechanical interlocking. These mechanisms are consistent with studies showing that PP fibers increase UCS and ductility in untreated and stabilized soils [2, 5, 9, 21]. Similar improvements in tensile resistance, deformation resistance, and post-peak performance have been reported in stabilized geomaterials and pavement-related materials [4, 17, 19, 24]. The 0.75% fiber content producing the highest measured zero-day UCS in this study falls within the broad dosage range reported in the literature, although the dosage associated with maximum strength varies with soil type, fiber geometry, binder content, and compaction condition [10, 11, 22]. Beyond 0.75%, UCS decreased to 121.40, 118.00, 108.30, 82.86, and 65.24 kPa at 0.80%, 0.85%, 0.90%, 0.95%, and 1.00% fiber content, respectively. This reduction is attributed to fiber clustering, nonuniform distribution, increased voids, reduced soil-soil contact, and lower compaction efficiency, as also observed by [10, 18, 23, 24]. Similar physical reinforcement roles have also been identified in studies on swell-shrink

control, cyclic loading resistance, and tensile cracking behavior of PP fiber-reinforced soils [15, 16, 41].

A one-way ANOVA conducted across the eleven investigated fiber dosages indicated a statistically significant effect of PP fiber content on zero-day UCS, $F(10, 22) = 1533.83$, $p < 0.001$. Tukey's HSD post-hoc analysis further showed that the mean UCS at 0.75% PP fiber was significantly higher than those at the neighboring 0.70%, 0.80%, and 0.85% dosages ($p < 0.001$ for each comparison). The corresponding differences in mean UCS were 7.34, 4.27, and 7.67 kPa, respectively. Thus, within the investigated zero-day UCS series, the measured peak at 0.75% PP fiber was statistically distinguishable from the adjacent tested dosages. Nevertheless, because the analysis was based on three replicate specimens per dosage and on a single soil-fiber system, 0.75% is interpreted as the statistically supported maximum within the investigated experimental range rather than as a universal optimum fiber content.

Accordingly, 0.75% PP fiber was identified as the fiber content producing the highest measured zero-day mean UCS within the investigated dosage range, and this maximum was statistically distinguishable from the neighboring tested dosages based on Tukey's HSD analysis. This highlights the importance of selecting an appropriate fiber dosage for cold-region soils, because insufficient fiber content may not form an effective reinforcement network, whereas excessive fiber content may increase voids, reduce soil continuity, and increase susceptibility to FT damage. The observed reduction in UCS beyond 0.75% fiber content agrees with studies in which excessive fiber addition caused clustering or poor dispersion [22-24]. Similar reductions in strength at higher fiber contents have also been reported for residual soils and geopolymer-or CSA-treated systems [10, 11, 18].

Comparative UCS Response of 0.75% PP Fiber-Reinforced Soil under Laboratory Conditioning and Freeze-Thaw Exposure

The comparative UCS response of soil reinforced with 0.75% PP fiber, the dosage producing the highest measured zero-day UCS within the investigated range, under laboratory conditioning and FT exposure is presented in Table 6 and Figure 8. The zero-day reference value of 125.67 kPa corresponds to the mean UCS measured at 0.75% PP fiber during the fiber-content optimization series and was adopted as the common baseline for the subsequent laboratory conditioning and FT assessments. Separate specimens containing 0.75% PP fiber were subsequently prepared and subjected to the specified laboratory conditioning durations and FT exposure levels. To enable a direct comparison, replicate specimens prepared at the same fiber content were subjected to laboratory conditioning periods of 0, 1, 3, 5, 7, 10, 15, 20, and 28 days, while another set of identically prepared specimens was exposed to 0, 1, 3, 5, 7, 10, 15, 20, and 28 FT cycles. This parallel testing program allows the strength gain associated with laboratory conditioning and the strength degradation caused by FT cycling to be evaluated under comparable material and exposure conditions. The UCS of the 0.75% PP fiber-reinforced soil increased from 125.67 kPa at 0 days to 155.10 kPa after 28 days of laboratory conditioning, corresponding to a strength gain

of approximately 23.42%. The UCS increased gradually from 130.24 kPa after 1 day to 133.68, 139.83, 143.49, 147.20, 152.00, and 153.85 kPa after 3, 5, 7, 10, 15, and 20 days of laboratory conditioning, respectively. This improvement indicates progressive stabilization of the compacted soil-fiber matrix, enhanced interparticle contact, and improved stress transfer through fiber-soil interaction. Similar time-dependent UCS development during laboratory conditioning has been reported for compacted and stabilized geomaterials, where progressive matrix densification, fabric stabilization, and improved bonding efficiency contribute to strength gain with laboratory conditioning duration [4, 9, 13, 22].

In contrast, the FT conditioned specimens showed a continuous reduction in UCS with increasing number of cycles. The UCS decreased from 125.67 kPa before FT exposure to 119.12 kPa after one cycle, corresponding to a strength loss of 5.21%. With further cycling, the UCS decreased to 112.00, 103.46, 96.50, and 88.70 kPa after 3, 5, 7, and 10 cycles, respectively. Beyond 10 cycles, the rate of strength reduction became comparatively lower, with UCS values of 85.83, 83.20, and 81.40 kPa after 15, 20, and 28 cycles, respectively. After 28 FT cycles, the total strength loss was 35.23%, while the strength retention ratio remained 64.77% relative to the initial UCS. The nonlinear degradation trend, characterized by rapid early-stage strength loss followed by gradual stabilization, is consistent with previous studies on FT affected fiber-reinforced and stabilized soils [1, 2, 21, 25]. The comparison between laboratory conditioning and FT exposure clearly demonstrates the opposite effects of these two conditions on the mechanical behavior of the 0.75% PP fiber-reinforced soil. At the end of the 28-day/cycle period, the laboratory-conditioned specimen reached a UCS of 155.10 kPa, whereas the FT-exposed specimen decreased to 81.40 kPa. Thus, the 28-day laboratory-conditioned UCS was approximately 1.91 times higher than the UCS after 28 FT cycles. The FT-exposed specimen retained only about 52.48% of the UCS of the corresponding 28-day laboratory-conditioned specimen, indicating that cyclic freezing and thawing substantially counteracted the strength gain associated with laboratory conditioning. The rapid strength loss during the early FT cycles can be attributed to water-ice phase transformation, ice-induced volumetric expansion, pore enlargement, disruption of interparticle contacts, and initiation of microcracks. During later cycles, damage mainly propagates through pre-existing weak zones, resulting in a lower rate of strength degradation and a more stable residual structure. Similar mechanisms have been reported for FT-exposed soils, where repeated freezing and thawing alters soil fabric, increases pore connectivity, weakens interparticle contacts, and reduces compressive resistance [1, 3, 6, 26]. Despite the reduction in UCS under FT exposure, the reinforced soil retained a considerable proportion of its initial strength after 28 cycles. This residual strength retention suggests that PP fibers contributed to tensile resistance, crack bridging, stress redistribution, and preservation of matrix continuity under cyclic freezing and thawing. These reinforcement mechanisms have been widely associated with improved post-FT performance of fiber-reinforced soils and fiber-stabilized geomaterials [2, 5, 10, 25]. Overall, the combined laboratory conditioning-FT comparison provides a more realistic assessment of the long-term mechanical behavior of PP fiber-reinforced Himalayan subgrade soil than laboratory-conditioned-strength evaluation alone.

UCS Degradation of PP Fiber-Reinforced Soil under Freeze-Thaw Cycles

The variation in UCS and the corresponding degradation percentage of the 0.75% PP fiber-reinforced soil after repeated FT cycles are summarized in Table 7 and graphically presented in Figure 9. The results indicate a progressive increase in UCS degradation with increasing number of FT cycles. The degradation increased from 5.21% after one cycle to 10.88%, 17.67%, and 23.21% after 3, 5, and 7 cycles, respectively. A more pronounced deterioration occurred during the early stages of FT exposure, indicating rapid disruption of vulnerable particle contacts and soil-fiber interfaces. Beyond 10 cycles, the rate of degradation gradually decreased, reaching 29.42%, 31.70%, 33.79%, and 35.23% after 10, 15, 20, and 28 cycles, respectively. The nonlinear trend suggests that the majority of microstructural damage occurred during the initial FT cycles, while subsequent cycles mainly propagated pre-existing defects within the soil matrix. This behavior is consistent with SEM observations showing void enlargement, particle separation, and progressive disruption of the reinforced soil fabric after repeated FT exposure. Similar degradation patterns characterized by rapid initial damage followed by gradual stabilization have been reported for fiber-reinforced and stabilized soils subjected to FT cycling. Quantitatively, the present 0.75% PP fiber-reinforced soil retained 64.77% of its initial UCS after 28 FT cycles, corresponding to a strength reduction of 35.23%. [21] reported approximately 20-25% UCS reduction after 10 FT cycles in fiber-reinforced and unreinforced clay specimens, while 3% PP fiber increased UCS by approximately 60-160% relative to the corresponding unreinforced clay. [25] reported that PP fiber reinforcement reduced FT-induced strength loss from 43% in unreinforced fine-grained soil to 32% in reinforced soil after up to nine FT cycles. In the present SW-SM soil, the zero-day UCS increased from 45.00 kPa in the untreated condition to 125.67 kPa at 0.75% PP fiber, corresponding to an increase of approximately 179.3%. Although these results are broadly consistent with the strength-enhancing and FT-damage-mitigating effects reported previously, direct numerical comparison is limited by differences in soil type, fiber dosage, specimen condition, and FT protocol.

Figure 10 presents representative stress-strain responses of the untreated and 0.75% PP fiber-reinforced SW-SM soil before and after 28 FT cycles. The stress-strain responses show a marked increase in deformation capacity following PP fiber reinforcement. The mean axial strain corresponding to the maximum recorded stress increased from approximately 3.07% for untreated soil to 7.28% for 0.75% PP fiber-reinforced soil. After 28 FT cycles, the reinforced specimens retained a mean strain at maximum stress of approximately 7.28%, despite the reduction in mean UCS from 125.67 to 81.40 kPa. This indicates that PP fiber reinforcement increased the deformation capacity of the compacted SW-SM soil and helped retain this response after FT exposure. The available records did not contain a complete descending post-peak branch; therefore, post-peak softening and a quantitative post-peak ductility index were not determined. From an engineering perspective, the measured UCS values demonstrate the relative improvement produced by PP fiber reinforcement, but they should not be interpreted as direct evidence that the material satisfies a specific pavement-subgrade acceptance criterion. The

untreated soil had an initial mean UCS of 45.00 kPa, whereas 0.75% PP fiber increased the zero-day mean UCS to 125.67 kPa; after 28 FT cycles, the reinforced soil retained a mean UCS of 81.40 kPa. However, pavement-subgrade suitability is generally evaluated using parameters such as CBR, resilient modulus, compaction characteristics, and project-specific design requirements rather than UCS alone. Because CBR and resilient modulus were not measured in the present study, the investigated soil cannot be assigned to a specific pavement-subgrade strength category, and compliance with field subgrade criteria cannot be established from the present UCS results. Accordingly, the results demonstrate laboratory-scale mechanical improvement and FT strength retention, but additional stabilization requirements, if any, should be determined from project-specific CBR, resilient-modulus, compaction, drainage, and field-performance assessments.

Permeability Response of PP Fiber-Reinforced Soil Before and After Freeze-Thaw Exposure

The comparison of mean permeability before and after four FT cycles shows that FT exposure increased the coefficient of permeability for all mixtures; however, the magnitude of increase varied markedly with PP fiber content as presented in Table 8, while the variation with polypropylene fiber content is shown in Figure 11. In the untreated soil, the mean permeability increased from 4.30×10^{-5} to 5.47×10^{-5} , corresponding to a 27.21% increase. This pronounced increase indicates that the natural soil fabric was highly susceptible to FT-induced structural disturbance. The increase in permeability can be attributed to ice-lens formation, volumetric expansion during freezing, and particle rearrangement during thawing, which collectively promote pore enlargement and the development of connected seepage pathways. Similar mechanisms have been reported in previous FT studies, where freezing and thawing increased pore radius, porosity, total pore area, and the proportion of medium and large pores, thereby modifying hydraulic conductivity through changes in pore-size distribution and pore connectivity [30-32, 35]. In contrast, PP fiber inclusion reduced the FT-induced increase in permeability, particularly at higher fiber contents. The most stable hydraulic response was observed at 0.6% fiber content, where the mean permeability increased only slightly from 2.90×10^{-5} to 2.97×10^{-5} , representing a marginal increase of 2.41%. This behavior suggests that an appropriate fiber dosage enhances hydraulic stability by restraining crack propagation, limiting the interconnection of preferential flow channels, and preserving a comparatively stable soil-fiber matrix during FT exposure. This interpretation agrees with previous observations that PP fibers can reduce crack development and restrict crack connectivity, while crack formation can substantially alter both the mechanical and hydraulic properties of soils, including hydraulic conductivity [33-35]. However, the higher permeability response observed at 0.7% and 0.8% fiber contents suggests that excessive fiber inclusion may reduce the beneficial densification effect, possibly due to fiber clustering, weak soil-fiber interfaces, or localized void formation, which can increase hydraulic pathway connectivity. Overall, the permeability results demonstrate that PP fiber reinforcement not only modifies the initial seepage behavior of the soil but also

improves its resistance to FT-induced hydraulic degradation. Among the investigated mixtures, 0.6% PP fiber provided the most effective hydraulic stabilization after four FT cycles.

The mechanical and hydraulic results demonstrate that the preferred PP fiber dosage depends on the governing performance criterion. The highest measured zero-day mean UCS was obtained at 0.75% PP fiber (125.67 kPa), whereas the minimum pre-FT permeability was obtained at 0.50% PP fiber (2.63×10^{-5} cm/s). In contrast, the smallest measured FT-induced permeability increase occurred at 0.60% PP fiber, for which the mean coefficient of permeability increased only from 2.90×10^{-5} to 2.97×10^{-5} cm/s after four FT cycles. At 0.60% PP fiber, the corresponding zero-day mean UCS was 105.76 kPa, which is approximately 84.2% of the maximum measured zero-day UCS obtained at 0.75% PP fiber. Therefore, within the investigated laboratory conditions, 0.60% PP fiber may be considered a practical mechanical-hydraulic compromise because it retained a substantial proportion of the maximum measured UCS while exhibiting the smallest FT-induced increase in permeability. However, this dosage should not be interpreted as a mathematically determined or universal multi-performance optimum. The UCS and permeability programs employed different fiber-dosage intervals, and permeability was not measured specifically at 0.75% PP fiber. Accordingly, the present results support performance-specific dosage selection rather than identification of a single global optimum.

SEM Analysis of PP Fiber-Reinforced Soil before and after Freeze-Thaw Cycles

SEM micrographs of the PP fiber-reinforced soil before FT exposure are presented in Figure 12(a) and Figure 12(b). The images show that the polypropylene (PP) fibers are embedded within the soil matrix and interact with surrounding particles through physical contact. In Figure 12(a), soil particles are visibly adhered to the surface of the PP fiber, forming a particle-coated PP fiber. This observation suggests effective particle confinement and improved stress transfer between the fiber and surrounding soil matrix. Figure 12(b) shows a fiber interlocking zone where intersecting fibers and adjacent soil particles create localized mechanical interlocking. Such interactions contribute to tensile resistance, restraint of particle displacement, and improved structural integrity of the reinforced soil. Similar reinforcement mechanisms involving fiber-soil interaction, particle confinement, and mechanical interlocking have been reported in PP fiber-reinforced soils and stabilized geomaterials [4, 22, 25, 38]. Because no chemical stabilizer was incorporated in the present study, the observed strength improvement is attributed primarily to physical reinforcement mechanisms rather than chemical bonding.

After FT exposure, the SEM images shown in Figure 12(c) and Figure 12(d) reveal a comparatively loosened and disturbed soil fabric. In Figure 12(c), qualitatively, the selected micrographs show features interpreted as void enlargement and particle separation, consistent with disruption of the compacted soil fabric after FT exposure. The observed open or enlarged void-like features are qualitatively consistent with FT-induced disturbance; however, pore dimensions and pore-area changes were not quantified. The qualitative observations in Figure 12 are consistent with the UCS trends, showing soil-fiber interaction before FT exposure and a more

open and disrupted fabric after FT exposure. Because quantitative image analysis was not performed, the SEM images are used only for qualitative interpretation and not to quantify FT-induced changes in pore size, crack density, or void area. These observations are consistent with previous SEM studies reporting that FT cycling enlarges pores, weakens particle contacts, reduces interfacial strength, and promotes microcrack development [3, 36]. Nevertheless, the presence of PP fibers appears to maintain partial continuity within the soil matrix, supporting residual strength retention even after repeated FT cycles. Therefore, Figure 11 provides qualitative microstructural evidence supporting the UCS results, where PP fibers enhance strength before FT exposure, while repeated FT cycling progressively degrades the soil structure through void enlargement, particle separation, and weakening of fiber-soil interaction.

SEM Analysis of Natural Soil and Microstructural Interpretation

SEM was employed to examine the microstructure of the untreated SW-SM soil and to provide microstructural evidence supporting its mechanical behavior under laboratory conditioning and FT conditions. At 300× magnification (Figure 13(a)), the soil exhibits large particle aggregates separated by large inter-aggregate pores, resulting in a highly open and heterogeneous fabric. The presence of extensive pore spaces and limited particle contacts indicates a weak skeletal framework with poor packing density. Such a macro-porous structure facilitates moisture movement and increases susceptibility to FT-induced deterioration. Similar loose and porous soil fabrics have been identified as important factors governing strength loss and durability reduction in FT-affected soils [4, 10, 25, 36]. At 500× magnification (Figure 13(b)), the soil fabric appears heterogeneous, with sparse particle contacts and visible void spaces distributed throughout the matrix. The absence of obvious cementation products or bonding phases suggests that the soil behavior is governed primarily by particle contact and frictional interaction rather than chemical bonding. At 1500× magnification (Figure 13(c)), loosely packed particles and large interparticle voids become more evident, indicating limited contact efficiency and reduced load-transfer capability within the soil skeleton. At 5500× magnification (Figure 13(d)), microvoids and localized crack-like features are visible. These defects may act as stress concentration zones and preferential pathways for crack propagation, contributing to progressive strength degradation during repeated FT exposure.

Overall, the SEM observations indicate a loose, porous, and heterogeneous soil fabric characterized by large particle aggregates, extensive inter-aggregate pores, weak particle contacts, and localized microvoids. These features are consistent with the relatively low UCS of the untreated soil and its susceptibility to FT-induced deterioration, in agreement with previous microstructural studies on FT-affected soils.

SEM-EDS Results and Microstructural-Chemical Interpretation

To further elucidate the mechanisms governing UCS variation with PP fiber inclusion and FT cycling, SEM observations were complemented by energy dispersive X-ray spectroscopy (EDS)

analysis. The representative EDS spectrum of the untreated soil is presented in Figure 14. The EDS results indicate that the soil matrix is dominated by oxygen (52.92 wt%), silicon (20.10 wt%), and aluminum (10.98 wt%). Iron (7.06 wt%) is present as a secondary constituent, while potassium, magnesium, sodium, and calcium occur in minor proportions. This elemental composition is consistent with a silicate- and aluminosilicate-rich soil matrix; however, EDS alone does not identify specific mineral phases. The relatively low calcium content in the examined spectrum did not indicate a calcium-rich composition suggestive of cementitious products. Accordingly, the UCS improvement associated with PP fiber inclusion is interpreted as being consistent with a predominantly physical reinforcement mechanism. This interpretation agrees with studies showing that PP fibers improve soil behavior mainly by mechanical interlocking, crack bridging, tensile resistance, and stress transfer when no binder or chemical stabilizer is present [15, 16, 25, 41]. It also contrasts with binder-treated systems, where hydration, pozzolanic reactions, or geopolymerization products contribute substantially to strength [3, 19, 23, 38].

Conclusions

This study evaluated the mechanical, hydraulic, freeze-thaw, and microstructural responses of PP fiber-reinforced Eastern Himalayan SW-SM soil under controlled laboratory conditions. The principal conclusions are:

- The untreated soil exhibited increasing UCS during laboratory conditioning, whereas repeated FT exposure progressively reduced its strength. Because no cementitious stabilizer was used and moisture-related variables were not independently monitored, the conditioning-induced strength increase should not be interpreted as conventional curing.
- PP fiber content significantly affected the zero-day UCS. Among the investigated dosages, 0.75% PP fiber produced the highest measured zero-day mean UCS, while higher fiber contents resulted in reduced strength. This value represents the maximum within the tested dosage range rather than a universal optimum.
- Repeated FT cycling progressively reduced the UCS of the 0.75% PP fiber-reinforced soil, with greater degradation during the early cycles followed by a lower rate of strength loss. Nevertheless, the reinforced specimens retained substantial residual strength after 28 FT cycles, indicating that PP fibers continued to provide mechanical reinforcement under the investigated laboratory FT conditions.
- The fiber dosage associated with the preferred hydraulic response differed from that producing the highest UCS. The minimum pre-FT permeability occurred at 0.50% PP fiber, whereas the smallest measured FT-induced permeability increase occurred at 0.60% PP fiber. At 0.60% PP fiber, the zero-day UCS was approximately 84.2% of the maximum measured UCS obtained at 0.75% PP fiber, indicating that 0.60% may provide a practical laboratory-scale compromise between mechanical and hydraulic performance within the investigated range. However, because the UCS and permeability programs

employed different dosage intervals and permeability was not measured at 0.75% PP fiber, no unique global multi-performance optimum is claimed.

- SEM observations were consistent with physical soil–fiber interaction, while FT exposure was associated with qualitative features of void enlargement, particle separation, and disruption of the soil fabric. SEM-EDS indicated relatively low calcium content and did not indicate a calcium-rich composition suggestive of cementitious products. Taken together, these observations are consistent with a predominantly physical reinforcement interpretation, although SEM-EDS does not independently establish the reinforcement mechanism.

These findings are restricted to the investigated SW-SM soil, PP fiber type, specimen preparation conditions, and laboratory exposure program. The results demonstrate laboratory-scale improvement in strength, hydraulic response, and FT resistance, but they do not establish direct field-design suitability. Additional evaluation, including CBR, resilient modulus, shear strength, traffic-loading response, and field-scale validation, is required before application to subgrade, embankment, or slope design.

Limitations of the Study

Although the present study provides region-specific experimental evidence on the strength, permeability, and FT durability of PP fiber-reinforced Eastern Himalayan SW-SM soil, the findings should be interpreted within the following limitations:

- First, the investigation was limited to one naturally occurring soil collected from the Sela Pass region. Therefore, the fiber dosages associated with the measured mechanical and hydraulic responses, as well as the measured strength and permeability trends, may not be directly transferable to soils with different gradation, fines content, plasticity, mineralogy, moisture condition, or compaction characteristics.
- Second, FT durability was evaluated under controlled laboratory and closed-system conditions. Field conditions in high-altitude Himalayan corridors may involve longer exposure periods, variable freezing and thawing rates, partial saturation, moisture migration, snowmelt infiltration, drainage changes, and seasonal temperature fluctuations, which could alter the rate and magnitude of deterioration. In addition, specimens were prepared at the specified target OMC and MDD, and the untreated soil had a calculated nominal initial degree of saturation of approximately 76.2%; however, specimen-specific mass, water content, and degree of saturation were not measured immediately before and after FT cycling. Therefore, FT-induced changes in moisture condition and degree of saturation could not be quantified.
- Third, the mechanical evaluation was based primarily on UCS testing, while the hydraulic evaluation considered permeability before FT exposure and after a limited number of FT cycles. Other performance indicators relevant to pavement and

embankment design, such as CBR, resilient modulus, tensile strength, shear strength, deformation under traffic loading, and long-term permeability evolution, were not included.

- Fourth, only one PP fiber type and one fiber length were examined in the main durability assessment. The effects of fiber length, aspect ratio, surface texture, tensile strength, orientation, dispersion quality, and alternative fiber materials were not independently evaluated.
- Fifth, SEM and SEM-EDS analyses were used mainly for qualitative interpretation of soil fabric, soil-fiber interaction, and elemental composition. Quantitative microstructural techniques, such as image-based crack-density analysis, pore-size distribution measurement, XRD, FTIR, micro-CT, or mercury intrusion porosimetry, would provide deeper insight into pore connectivity, mineralogical changes, and FT-induced damage mechanisms.
- Sixth, the time-dependent UCS increase observed in the untreated soil was evaluated without systematic measurements of specimen mass change, water content, degree of saturation, matric suction, or drying shrinkage at each conditioning age. Therefore, the relative contributions of moisture redistribution, suction development, and fabric rearrangement to the measured strength increase could not be quantified conclusively.
- Seventh, specimen-core temperature was not instrumentally monitored during FT cycling, and an independent temperature-time record was not obtained. Consequently, complete thermal equilibration during the prescribed freezing and thawing periods could not be independently verified. Frost heave, axial deformation, volumetric strain, and visible crack development were not quantitatively monitored during cycling. Therefore, FT-induced thermal and dimensional responses could not be independently quantified.
- Finally, the study was performed on laboratory-compacted specimens. Field-scale validation is required before direct implementation in subgrade, slope, or embankment design because in-situ performance may be affected by construction quality, compaction variability, drainage boundary conditions, traffic loading, scale effects, aging, and environmental exposure. The long-term environmental implications of PP fiber use, including fiber persistence and possible microplastic release, also require further assessment before field application.

Data Availability Statement

Some or all data generated or used during this study are available from the corresponding author upon reasonable request. The available data include the individual replicate-level UCS and permeability measurements underlying the reported means and standard deviations, freeze-thaw cycle data, strength-retention calculations, SEM micrographs, and SEM-EDS interpretation data.

Conflict of Interest Statement

The authors declare that they have no known financial, professional, or personal conflicts of interest that could have influenced the work reported in this paper.

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Author contributions

Chukhu Tagar: Conceptualization, methodology, investigation, experimental work, data collection, formal analysis, visualization, and writing original draft preparation.

Ajanta Kalita: Conceptualization, supervision, methodology, validation, writing review and editing, and project guidance.

Arindam Dey: Supervision, validation, technical guidance, writing review and editing, and critical revision of the manuscript. All authors read and approved the final manuscript.

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(a)

(b)

Fig. 1 (a) and (b) Sampling location near Sela Pass in the Eastern Himalaya, showing the high-altitude terrain and slope conditions representative of frost-susceptible subgrade soils

Table 1. Soil properties

Properties	Values
Specific Gravity	2.68
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

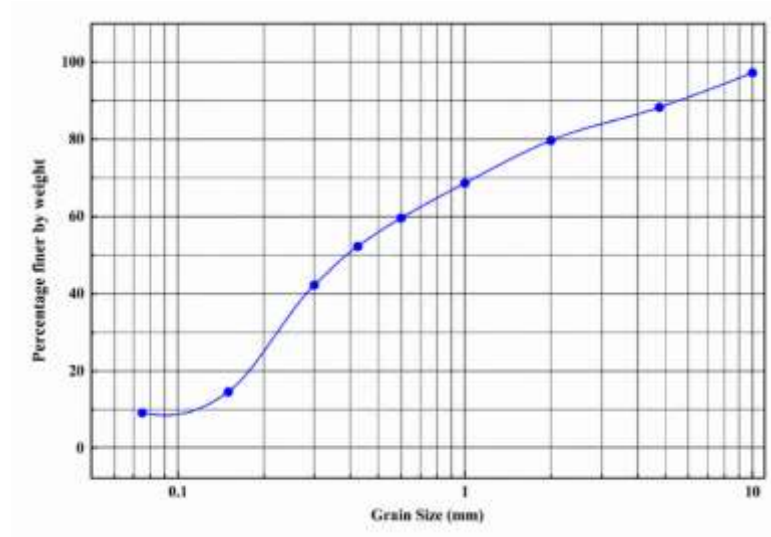


Fig. 2 Grain size distribution curve of the studied soil, indicating a well-graded sandy matrix with a minor silt fraction (SW-SM classification), relevant to moisture migration and FT susceptibility

Table 2. Polypropylene Fiber Properties

Properties	Value
Fiber length (mm)	12
Specific Gravity	0.92
Fiber diameter (μm)	30
Aspect ratio (L/D)	400
Tensile strength (MPa)	600-700
Elastic modulus (GPa)	3.7
Water absorption	Negligible



Fig. 3 PP fibers used in the study (length=12 mm), illustrating the geometry and form of discrete reinforcement employed for improving soil strength and FT resistance



(a)

(b)

Fig. 4 UCS specimens prepared for testing: (a) compacted natural soil specimen and (b) compacted polypropylene fiber-reinforced soil specimen



(a)

(b)

Fig. 5 Permeability specimen preparation: (a) compacted soil specimen inside the permeability mold and (b) compacted specimen sealed with plastic film to control moisture loss during storage prior to testing or FT conditioning

Table 3. Experimental matrix for PP fiber optimization, laboratory conditioning, and freeze-thaw durability testing

Experimental series	Fiber content	Exposure / conditioning	Replicates	Purpose
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Untreated-soil FT baseline	0% PP	0, 3, 5, 7, 14, 28, 56, 90 FT cycles	3 per condition	Evaluate long-term FT degradation of untreated soil
Fiber-content optimization	0.50-1.00% PP	0 day	3 per dosage	Determine PP fiber content giving the highest zero-day UCS
Selected UCS baseline	0.75% PP	0 day / 0 FT cycle	3	Baseline UCS = 125.67 kPa
Laboratory conditioning series	0.75% PP	1, 3, 5, 7, 10, 15, 20, 28 days	3 per condition	Evaluate laboratory conditioning-induced UCS development
Reinforced FT durability series	0.75% PP	1, 3, 5, 7, 10, 15, 20, 28 FT cycles	3 per condition	Evaluate FT-induced UCS degradation
Permeability FT series	0-0.8% PP	Before FT and after 4 FT cycles	3 per condition	Evaluate hydraulic response before and after FT exposure

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Table 4. Comparative time-dependent UCS response of untreated soil under laboratory conditioning and FT exposure (mean $\pm$ SD; $n = 3$).

Period/Cycles	UCS after laboratory conditioning (kPa)	UCS after FT (kPa)
0	45.00 $\pm$ 1.30	45.00 $\pm$ 0.27
3	49.87 $\pm$ 0.85	41.20 $\pm$ 1.10
5	55.23 $\pm$ 0.90	38.80 $\pm$ 0.88
7	57.36 $\pm$ 0.60	36.50 $\pm$ 0.47
14	64.52 $\pm$ 0.22	32.40 $\pm$ 0.67
28	69.70 $\pm$ 0.68	28.10 $\pm$ 0.52
56	71.40 $\pm$ 0.76	23.90 $\pm$ 1.30
90	73.10 $\pm$ 0.44	21.50 $\pm$ 1.06

1052

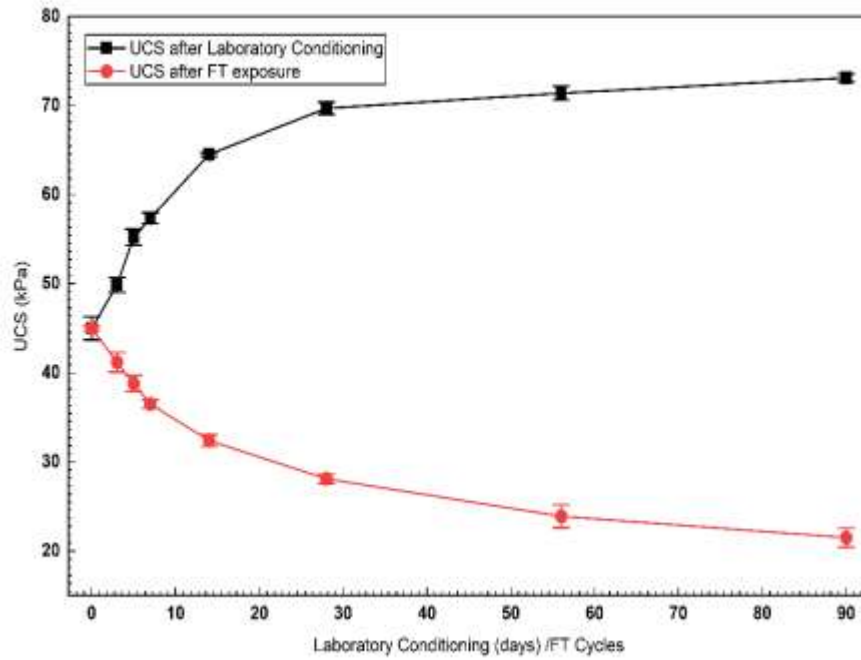


Fig. 6 Variation in UCS of untreated soil with laboratory conditioning duration and FT exposure; error bars represent ± 1 SD based on triplicate specimens.

Table 5. Zero-day mean UCS of soil at different PP fiber contents ($n = 3$).

Fiber Content (%)	UCS (kPa)
0.50	79.66 $\pm$ 1.00
0.55	95.34 $\pm$ 0.85
0.60	105.76 $\pm$ 1.40
0.65	112.33 $\pm$ 0.85
0.70	118.33 $\pm$ 0.66
0.75	125.67 $\pm$ 0.45
0.80	121.40 $\pm$ 1.10
0.85	118.00 $\pm$ 0.75
0.90	108.30 $\pm$ 0.63
0.95	82.86 $\pm$ 0.48
1.00	65.24 $\pm$ 0.94

Note: Values are mean $\pm$ sample SD ($n=3$). One-way ANOVA indicated a significant effect of fiber content on zero-day UCS [$F(10, 22)=1533.83, p<0.001$]. Tukey's HSD test indicated that the mean UCS at 0.75% PP fiber was significantly higher than the neighboring 0.70%, 0.80%, and 0.85% dosages ($p<0.001$).

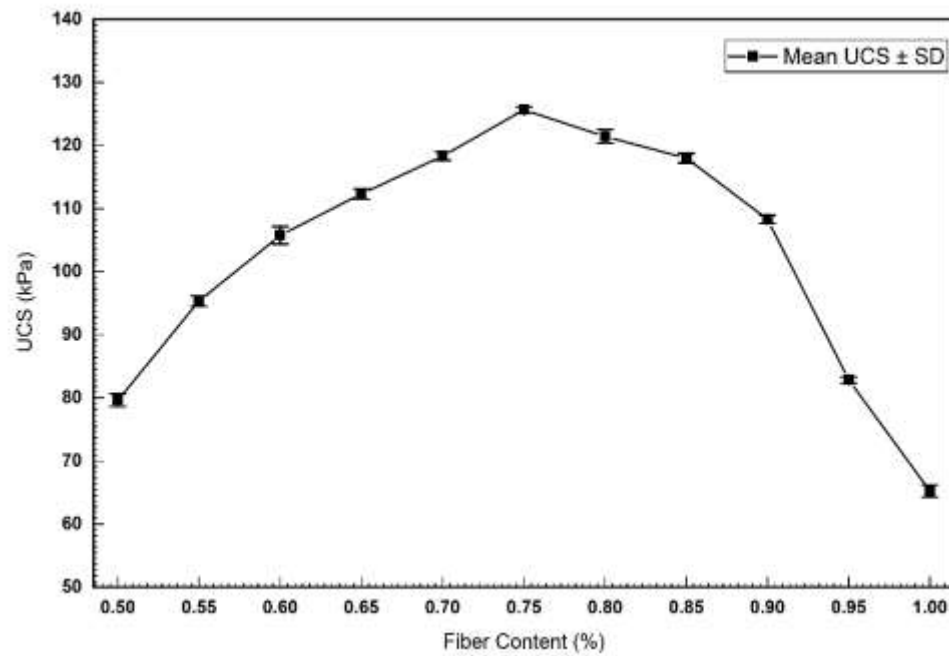


Fig. 7 Variation of zero-day mean UCS with PP fiber content; error bars indicate ± 1 standard deviation based on triplicate specimens ($n = 3$).

Table 6. Comparative UCS response of 0.75% PP fiber-reinforced soil under laboratory conditioning and FT exposure

Laboratory conditioning Duration (days)/FT	UCS due to laboratory conditioning (kPa)	UCS after FT (kPa)
0	125.67 $\pm$ 0.45	125.67 $\pm$ 0.45
1	130.24 $\pm$ 1.10	119.12 $\pm$ 1.28
3	133.68 $\pm$ 1.00	112.00 $\pm$ 0.97
5	139.83 $\pm$ 0.65	103.46 $\pm$ 1.17
7	143.49 $\pm$ 1.21	96.50 $\pm$ 1.10
10	147.20 $\pm$ 0.86	88.70 $\pm$ 1.36
15	152.00 $\pm$ 0.45	85.83 $\pm$ 0.87
20	153.85 $\pm$ 0.38	83.20 $\pm$ 0.82
28	155.10 $\pm$ 1.05	81.40 $\pm$ 0.64

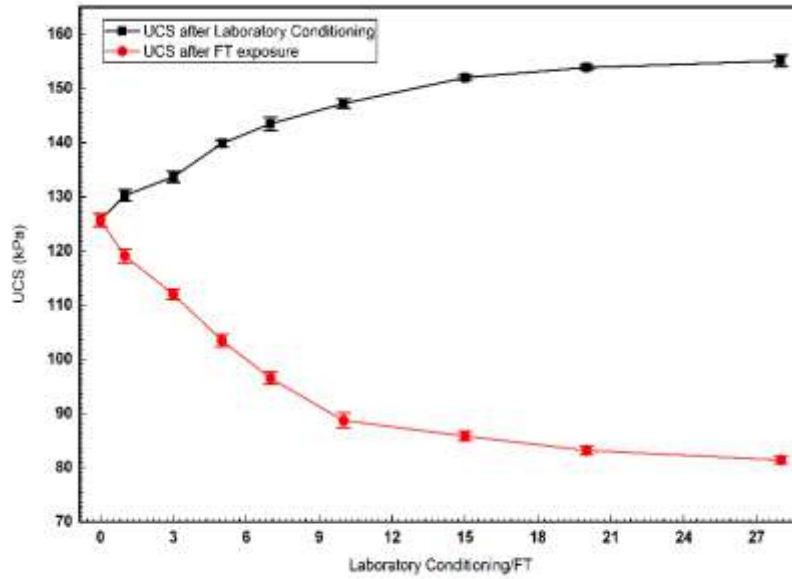


Fig. 8 Comparative variation of UCS of 0.75% PP fiber-reinforced soil under laboratory conditioning and FT exposure; error bars indicate ± 1 standard deviation based on triplicate specimens

Table 7. UCS degradation of 0.75% PP fiber-reinforced soil under FT cycling

FT cycles	UCS (kPa)	UCS degradation (%)
0	125.67 $\pm$ 0.45	0
1	119.12 $\pm$ 1.28	5.21
3	112.00 $\pm$ 0.97	10.88
5	103.46 $\pm$ 1.17	17.67
7	96.50 $\pm$ 1.10	23.21
10	88.70 $\pm$ 1.36	29.42
15	85.83 $\pm$ 0.87	31.7
20	83.20 $\pm$ 0.82	33.79
28	81.40 $\pm$ 0.64	35.23

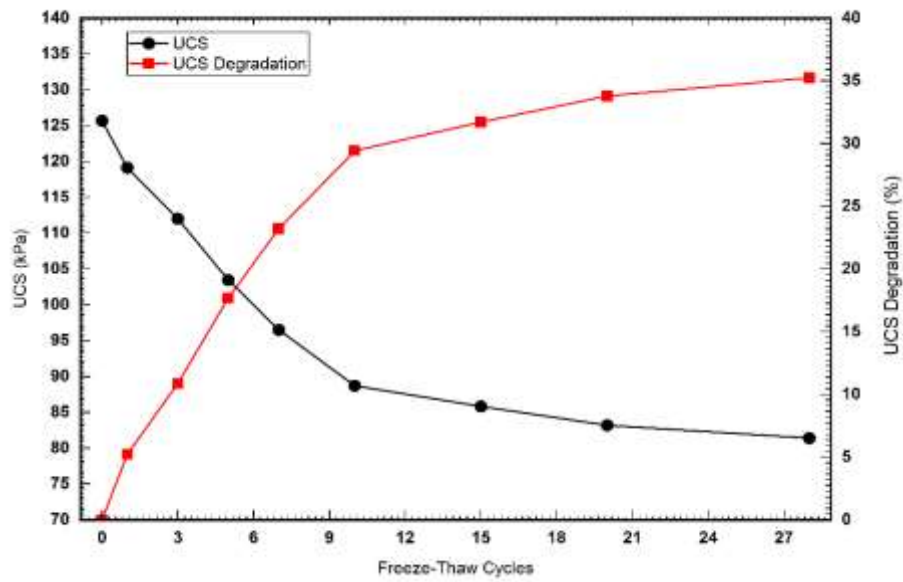


Fig. 9 Changes in UCS and corresponding degradation percentage of 0.75% PP fiber-reinforced soil subjected to repeated FT cycles

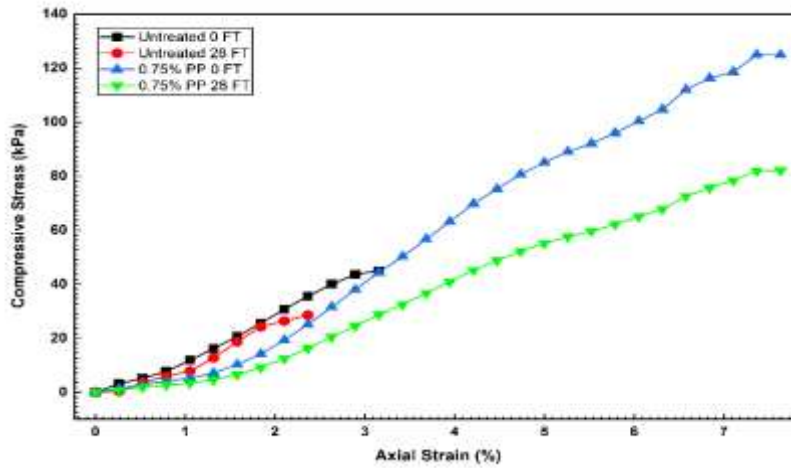


Fig. 10 Representative axial stress-strain curves of untreated and 0.75% PP fiber-reinforced SW-SM soil before and after 28 FT cycles.

Table 8. Mean coefficient of permeability (k) before and after 4 FT cycles

Fiber content (%)	Before FT, Mean $k \pm SD$	After 4 FT, Mean $k \pm SD$
0.0	4.30 ± 0.27	5.47 ± 0.23
0.1	3.77 ± 0.35	4.60 ± 0.10
0.2	3.57 ± 0.25	4.33 ± 0.15
0.3	3.17 ± 0.25	3.83 ± 0.06

0.4	2.90 ± 0.30	3.30 ± 0.20
0.5	2.63 ± 0.06	3.10 ± 0.20
0.6	2.90 ± 0.20	2.97 ± 0.12
0.7	3.23 ± 0.23	3.40 ± 0.20
0.8	3.50 ± 0.35	3.83 ± 0.12

Note: Values are presented as mean $\pm$ sample standard deviation (SD) based on three replicate measurements ($n = 3$). The coefficient of permeability, k , is reported in $\times 10^{-5}$ cm/s

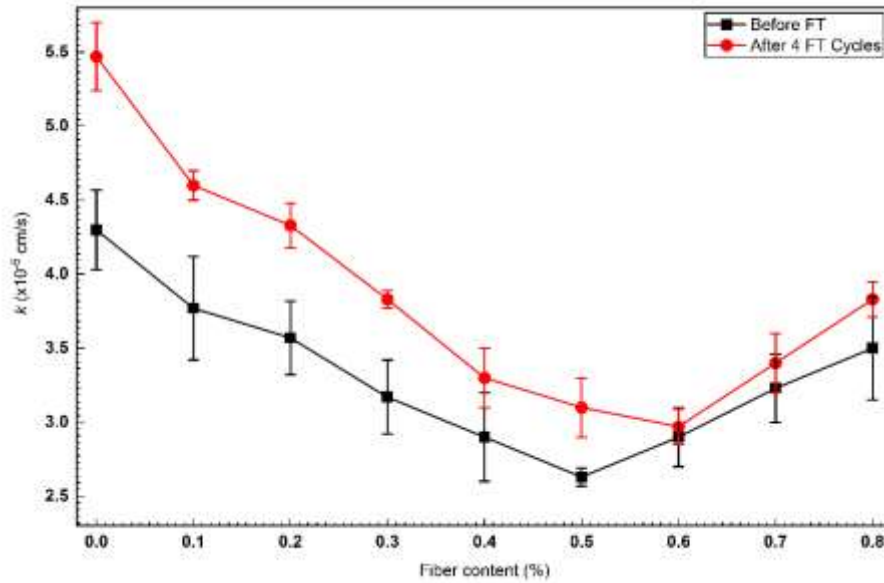
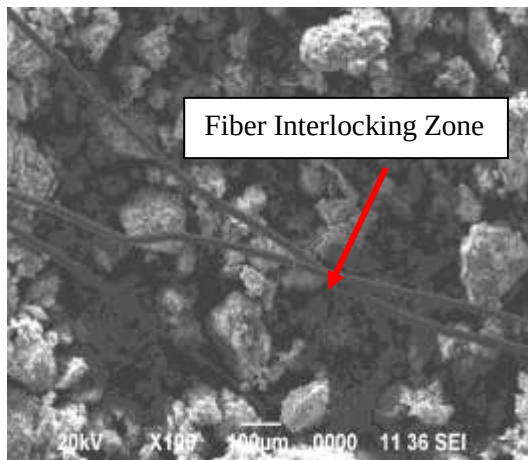
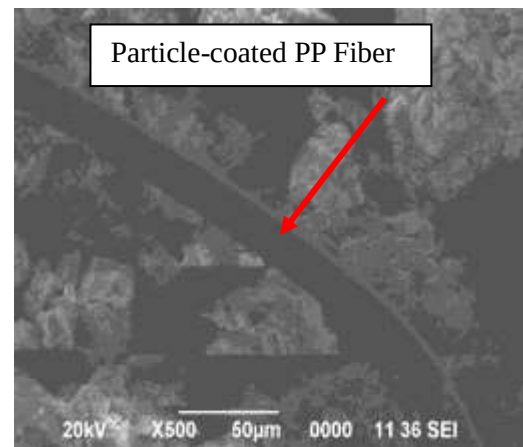


Fig. 11 Variation in the coefficient of permeability of polypropylene fiber-reinforced soil with fiber content before and after 4 FT cycles. Error bars indicate the sample standard deviation of triplicate measurements ($n = 3$)



(a)



(b)

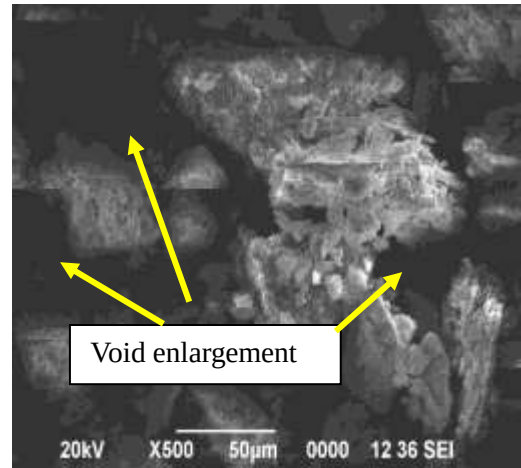
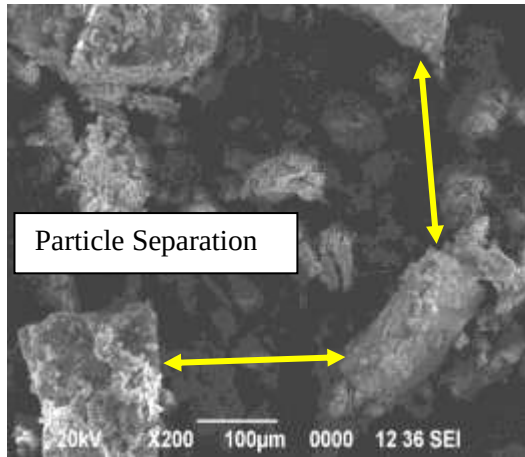
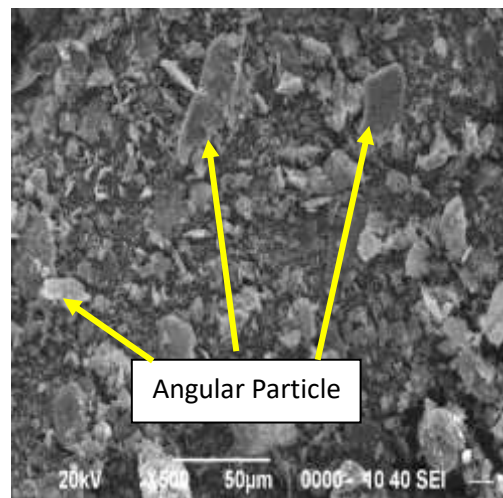
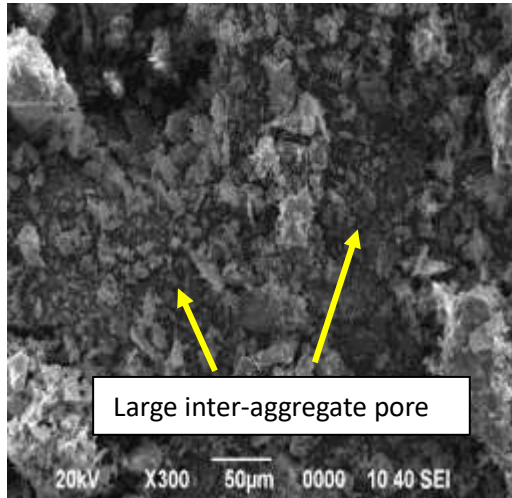
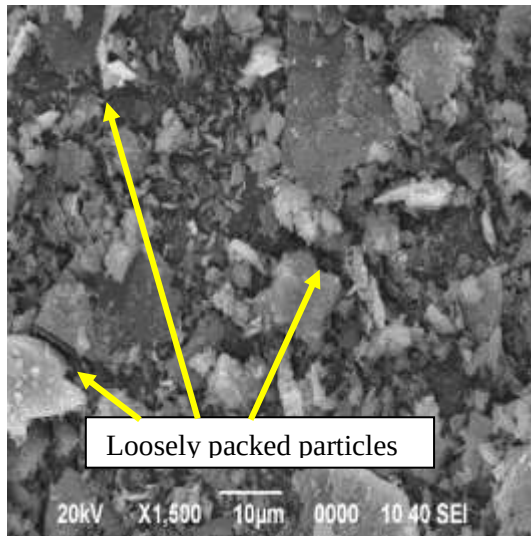
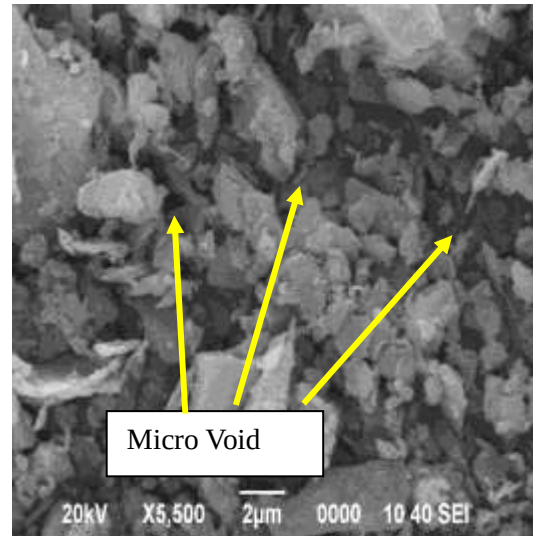


Fig. 12 SEM-SEI micrographs of PP fiber-reinforced soil before and after FT exposure (a) PP fiber-reinforced soil before FT exposure showing fiber bridging and soil-particle interaction. (b) closer view of the fiber-soil interface before FT exposure. (c) PP fiber-reinforced soil after FT exposure showing enlarged voids and particle separation, and (d) disrupted soil fabric after FT exposure showing microvoids and crack-like spaces





(c)



(d)

Fig. 13 SEM-SEI micrographs of untreated SW-SM soil: (a) low-magnification view showing large particle aggregates and large inter-aggregate pores; (b) heterogeneous soil fabric with sparse particle contacts and visible void spaces; (c) loosely packed particles with large interparticle voids; and (d) microvoids and localized crack-like features within the soil matrix

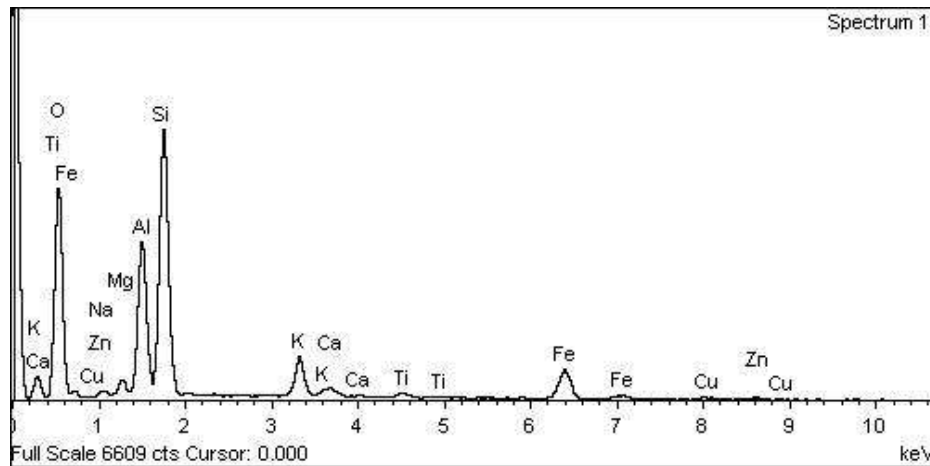


Fig. 14 Representative EDS spectrum showing dominant O, Si, and Al peaks with minor Fe, K, Mg, Na, and Ca, indicating a silicate-aluminosilicate soil matrix