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Influence of prolong curing, freeze thaw cycles on strength and compaction condition on water retention behaviour of bamboo biochar amended soils

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Biochar has emerged as a promising soil amendment material, offering the potential to enhance mechanical and water retention properties. Geo-environmental structures constructed with biochar-amended soils (BAS) might experience a change in strength and water retention capacity due to extreme climactic changes, resulting in structural failures. The existing literature lacks a comprehensive study on the strength of BAS under prolonged curing, freeze-thaw cycles, and water retention behaviour for varying compaction conditions. The current study focused on addressing this research gap. Bamboo biochar (BB) was mixed with lean clay (CL) and silty sand (SM) in five different percentages (0%, 1%, 2%, 3.5% and 5% w/w) to prepare BAS specimens for unconfined compressive strength (UCS) and water retention tests. Results showed that UCS of CL soil increased up to 2% BB content but decreased thereafter, whereas it consistently decreased for SM soil with increasing BB content. Irrespective of the BB content, both soils consistently showed an increase in UCS with the curing period, which can be attributed to the enhanced bonding between the soil and BB, as well as the formation of stable aggregates. In contrast, the strength of both biochar-amended soils (BAS) decreased with the increase in freeze-thaw cycles, due to the expansion and contraction of ice within the specimen. The porous and hydrophilic nature of biochar (BB) increased the water retention capacity of both soils, with a more significant improvement observed in CL soil compared to SM soil, under both compacted and slurry conditions. Specimen compaction significantly decreased the gravimetric water content at the permanent wilting point in both soils. These variations were also evident in the microstructural analysis.

Keywords UCS, Curing period, Freeze-thaw, Water retention capacity, Compaction condition

Waste generation is increasing at a rapid rate, creating massive accumulations in both villages and cities[1]. This waste is often burned in the open air, releasing environmentally harmful gases such as carbon dioxide and methane[2]. The waste generated by the agricultural sector is commonly found in many regions worldwide[1]. One such waste is bamboo waste. Bamboo plays a vital role as a structural and load-bearing element in various applications, including fencing, construction, roofing, and craftsmanship, particularly in developing countries such as India, China, and Malaysia. Despite its extensive use, only 30–40% of the global bamboo supply is effectively utilized, leading to the disposal of the remaining portion as waste through burning or burial[3]. A sustainable solution is recycling waste materials, such as bamboo waste, into biochar would be essential, advantageous, cost-effective, and beneficial for the environment[4]. Biochar is a stable, carbon-rich product obtained from the pyrolysis of biomass and other organic materials[5]. Numerous studies have explored the potential applications of biochar in carbon sequestration, heavy metal contamination remediation, and agricultural practices[6]. These applications leverage its beneficial properties, including high cation exchange capacity (CEC), water retention capability, specific surface area (SSA), favorable pH, high carbon content, and low density[7]. Recently, biochar has emerged as a promising soil amendment material, offering the potential to enhance the physical, mechanical, and hydraulic properties of soil[8]. Biochar typically lowers soil bulk density and enhances soil structural quality through

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improved soil aggregation[9]. Its positive impacts encompass increased porosity, enhanced aggregate stability, improved moisture retention capacity, more efficient water flow dynamics, and optimized gas exchange[10].

Past research has highlighted that a significant portion of waste is disposed of in landfills, forming large, towering heaps[1]. These high-rise landfills pose environmental and health challenges due to improper waste management practices[11]. Landfills located in metropolitan areas significantly degrade the value of surrounding real estate properties. Reclaiming these open landfills by implementing geo-environmental engineering structures, such as cover systems, can help restore the land and improve the value of nearby real state properties. Biochar has the potential to be utilized as an amendment material in landfill cover layers, bioengineered slopes, green roofs, and embankments[12]. The use of biochar in landfill covers has the potential to reduce methane emissions by up to 80% while simultaneously enhancing leachate quality through the reduction of heavy metals and other pollutants[13]. The use of biochar as soil amendment enhances water-retention capacity and influences soil tensile strength[14]. The moisture retention capabilities of biochar potentially establish a moisture content equilibrium for a long duration[15]. The prolonged moisture equilibrium of biochar-amended soil (BAS) affects strength, which is tricky and vital for geo-environmental engineering projects. This equilibrium can impact soil strength by optimizing compaction efficiency and reducing potential moisture-related degradation, thereby enhancing the overall strength. In addition, surface characteristics of biochar can evolve during the curing period, leading to chemical interactions with soil components[16]. These interactions might promote binding mechanisms between biochar, soil particles, and organic matter, enhancing soil cohesion and strength[17]. The strength of BAS varied notably with the type of biochar and soil in past lieratures[18,19]. In clayey soils, UCS values showed an initial increase with biochar addition, reaching an optimum before decreasing with further increments[18–20].

The properties of biochar and its enhanced water retention can introduce uncertainties for landfill cover layers by affecting the geotechnical properties of the structure over the long term[21,22]. Past studies showed the scarcity of literature on the strength characteristics of BAS under prolonged curing periods. Understanding the effect of moisture equilibrium (prolonged curing) on the compressive strength of BAS is vital for geo-environmental engineering, particularly in maintaining landfill cover integrity. In addition, seasonal temperature fluctuations, resulting in freeze-thaw cycles, have a significant impact on geotechnical infrastructure. Recent rapid environmental changes, notably global warming and cooling, have brought about considerable shifts in frozen soils, impacting both permafrost and seasonally frozen ground. Literature showed that approximately 23% of worldwide land is attributed to seasonally frozen ground[23,24]. The conversions from water to ice in the freeze-thaw process can notably modify soil structure and physical-mechanical properties and subsequently exacerbate instability[25]. The process of freezing and thawing brings about significant alterations in soil structure, influencing its physical and mechanical characteristics. The freeze-thaw cycle also leads to soil strength deterioration due to the formation of macro and micro-cracks alongside frost heaving[26]. In addition, seasonal temperature fluctuations in cold regions, leading to freeze-thaw cycles, substantially impact geotechnical infrastructure[27]. Over recent decades, extensive research has been conducted on the alterations in physical and mechanical properties triggered by freeze-thaw actions[28,29]. However, an in-depth examination of the literature affirms the scarcity of studies on the freeze-thaw properties of BAS. Biochar applications, especially in engineering contexts, have received minimal attention, and there is a lack of research exploring the effects of freeze-thaw cycles on strength behaviour. It becomes crucial to investigate the behaviour of BAS under freeze-thaw cycles and identify improvement techniques to mitigate associated problems, supporting engineering applications.

The construction of landfill covers relies on establishing stable layers that can support the growth of vegetation[30,31]. In contrast to agricultural soil, the materials used in landfill cover constructions are compressed to higher compactness to attain structural stability while supporting vegetation[32]. The vegetation contained by such structures contributes extra firmness by directly reinforcing roots and through hydrological processes like evapotranspiration[33,34]. The roots of vegetation function as tensile strengthening and enhance stability in the cover layer. Vegetation-induced evapotranspiration also generates soil suction, consequently supporting strength and firmness[35]. Water absorption by vegetation roots predominantly relies on the moisture conditions of materials[36]. A little fluctuation in soil water level directly impacts root water uptake and, consequently, the progress of plants. Hence, understanding the soil-water retention characteristics (SWRC) of the material becomes essential for nourishing sufficient growth and progress of plants. The current literature on the SWRC of soil amended with biochar focuses on the agricultural context with low compaction density[37,38]. The compaction of the material within geo-environmental engineering constructions, such as landfill covers, diverges from that of agricultural soil. These structures experience higher to moderate levels of compaction and are engineered for prolonged durability[33,39]. The compaction of material causes substantial changes in the pore size distribution[40]. The alterations in porosity associated with the degree of compaction (DOC) could impact the SWRC. A study by Wong et al.[33] showed the impact of both the initial moisture content and DOC on the SWRC of biochar-amended clay. The results showed that low DOC has increased SWRC with higher biochar addition. In contrast, no significant change was observed in SWRC with higher biochar content at higher DOC[33]. Therefore, examining the SWRC of biochar-amended soil under higher compaction levels is vital.

In conclusion, the existing literature suggests that the strength and water retention characteristics vary with biochar types[5], and the application of bamboo biomass-based biochar for landfill cover layer remains underexplored, highlighting a significant gap in research. The strength behaviour under prolonged curing periods and increasing freeze-thaw cycles is missing for BAS specimens. There is also a notable lack of studies exploring the correlation between compaction efforts and the soil-water retention characteristics of BAS. Hence, this study focused on the existing research gap and significant contribution to the potential utilization of BAS in geo-environmental engineering applications.

Materials and methodology
Soil and biochar
The current study has used two distinct types of soils and one type of biochar. Soils were collected from two distinct locations within the Patna district in Bihar, India. The classification of soils was determined after performing grain size, liquid limit, and plastic limit tests, which identified the soils as lean clay (CL) and silty sand (SM). CL soil contained 73% silt, while SM soil had 52% sand and 39% silt. The liquid limit and plastic limit for CL soil was 38.15% and 19.5%, respectively, whereas SM soil had a liquid limit of 24.9% and a plastic limit of 15.3%. The specific gravity values for CL and SM soils were 2.78 and 2.75, respectively. Bamboo biomass was used as feedstock and pyrolyzed at 650 and 700 °C to produce bamboo biochar (BB). The BB was procured from VR International Organic Farming Solution, Bhopal, India. It was stored in an airtight container without any alterations, remaining in its original state without being crushed before use. The detailed procurement procedure for soils and biochar are presented in the past article[19].

Soil biochar composition
Initially, the soils (CL and SM) and BB samples were dried to remove moisture. The biochar contents were decided based on the available literature[15,41,42]. The BB was merged with soils at ratios of 0%, 1%, 2%, 3.5%, and 5% to form BAS, as shown in Fig. 1. The BB and soils were hand-mixed thoroughly for 10–15 min on an aluminium tray and then stored in a desiccator.

UCS specimen preparation procedure
The weight of soils, BB and water for the unconfined compressive strength (UCS) samples were calculated using the Maximum Dry Density (MDD) and Optimum Moisture Content (OMC) data[19]. The samples were mixed thoroughly and placed in a desiccator inside a plastic bag to attain moisture equilibrium. After 48 h, the mixtures were retrieved from the container and again thoroughly mixed. A standard mould measuring 38 mm in diameter and 76 mm in height was chosen to form the UCS specimen. The moist sample was statically compressed within a cylindrical mould using a physically operated UCS sampler from both ends. The UCS specimen was left to reach steadiness for five minutes before being extracted. Likewise, all UCS specimens were prepared using the same technique.

The UCS test was carried out to examine the specimens following the procedure specified in ASTM D2166[43]. The prepared specimen was placed on a 50 kN capacity loading frame obtained from Aimil, India. Subsequently, a gradual loading was applied, carrying axial deformation at a rate of 1.25 mm/min. The loading continued until the specimen failed, and the data logger automatically recorded both the load and displacement data. Three tests were conducted on identical specimens to ensure result consistency, and the average value obtained was reported.

Curing and freeze-thaw procedure of UCS specimens
The UCS specimens, consisting of untreated and BAS with varying levels of BB, were placed in desiccators and cured at a constant temperature of 25–27 °C while maintaining OMC for 1, 7, 15, 30, 60, and 120 days (Table 1). The extended curing period was selected to investigate any alterations in the strength properties of bamboo biochar-amended soil. The cured specimens were then subjected to unconfined compression tests.

UCS specimens were also subjected to freeze-thaw cycles to assess the impact of freezing and thawing on the UCS of soils amended with BB. The 30th-day cured UCS specimens were subjected to freeze-thaw conditions in this test. These specimens underwent 1, 3, 5, and 8 freezing and thawing cycles. The number of cycles was selected based on the variations and stabilization of strength reported in previous studies[44–47]. The freezing-

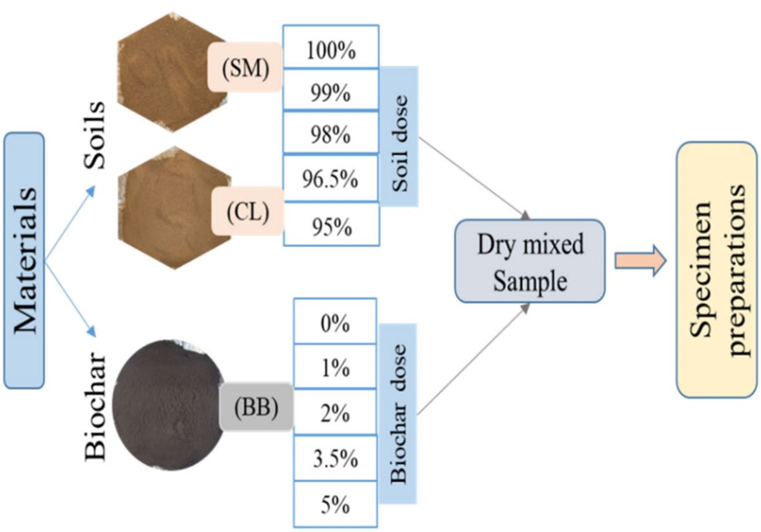

Fig. 1. Materials and soil-biochar composition for specimen preparation.

Tests	Specimen condition	Test conditions	Microstructural investigation
UCS	OMC & MDD	Curing (1, 7, 15, 30, 60 and 120 days)	FESEM MIP
		Freeze-thaw (1, 3, 5, 8 cycles)	
WP4C	Unconfined (slurry) & Confined (0.9MDD)	Wetting to drying	FESEM MIP

Table 1. Program for conducting UCS, WP4C and microstructural tests. WP4C, equipment for water retention test; FESEM, field emission scanning electron microscopy; MIP, mercury intrusion porosimetry.

	CL	SM
BB (%)	0.9MDD (g/cc)	0.9MDD (g/cc)
0	1.62	1.81
1	1.60	1.78
2	1.59	1.75
3.5	1.56	1.67
5	1.53	1.59

Table 2. Compaction (confined) density of biochar-amended CL and SM soil for WP4C test.

thawing process was carried out within a closed system. The specimens exposed to freeze-thaw conditions were placed inside a digital freezing cabinet set at − 10 °C for 12 h, followed by a thawing phase at + 30 °C for an additional 12 h. Each iteration of this freezing and thawing cycle was referred to as one cycle, and this procedure was repeated up to a total of 8 cycles. Finally, the specimens were tested with a load cell to determine UCS.

The temperature ranges for freeze-thaw were selected based on data presented in the Intergovernmental Panel on Climate Change (IPCC) report, which accounts for the global cooling and heating trends of the Earth's surface over time[48]. The report highlights that many cities in India undergo severe summer heat, with temperatures surpassing 40 degrees Celsius, while high-altitude areas endure extremely cold winters, with temperatures dipping to minus 20 degrees Celsius or lower.

Specimen preparation for water retention test

Soil-water retention tests were conducted on both soils (CL and SM) under confined (compacted at 0.9MDD) and unconfined (slurry prepared at LL) conditions with varying concentrations of BB (0%, 1%, 2%, 3.5%, and 5%). The 0.9MDD was chosen for confined samples to simulate the compaction level expected in geo-environmental engineering structures, ensuring relevance to real-world applications. Table 1 shows the detailed program for the water retention test. A 1 cm depth and 4 cm diameter round mould was selected for specimen preparation. The mould's volume was calculated, and the required material weights for specific conditions were determined using MDD values. The measured samples were accurately compressed to their 0.9MDD level, as presented in Table 2.

The prepared specimens were placed in an environmentally controlled desiccator, with water placed underneath to facilitate wetting through vapour adsorption till it reached the lower suction. Afterwards, the specimen was individually placed in the WP4C dew-point chilled mirror potentiometer device (Decagon Devices Inc., USA) for suction measurement. The suction reading was recorded, and the specimen was removed from the device to measure its weight. The specimen was then placed in controlled temperature conditions for drying. Following a short interval (approximately 10–20 min), it was returned to the WP4C instrument to measure suction. The process continued until the suction value steadied. Once consecutive suction values showed a minimal difference, the test concluded, and the water content of samples was measured through oven drying.

FESEM, MIP and chemical examinations of specimens

FESEM (Field Emission Scanning Electron Microscopy) and mercury intrusion porosimetry (MIP) analyses were conducted on both the non-amended and BAS samples to assess morphological changes and alterations in pore size. Specimens were extracted from the tested specimen and then meticulously diced into small cubes measuring 1 × 0.5 × 0.5 cubic centimetres (length × width × height). Each specimen underwent rapid immersion in liquid nitrogen (at − 196 °C) for freezing to minimize rebound effects and prevent any associated microstructural changes upon unloading.

Following the method outlined in Oualmakran et al.[49], the frozen samples underwent sublimation in the lyophilizer for 96 h. Additionally, Jadda and Bag[50] asserted that freeze-drying is the optimal approach for examining soil microstructure while causing minimal disturbance. The lyophilized samples were utilized for surface morphology and pore size analysis. The FESEM images were captured using the Sigma-300 microscope from Zeiss, Germany, at different magnifications. The pore size distributions in the sample were observed through the Mercury Intrusion Pore Size Analyzer (PM-20) of Quantachrome. Elemental studies were also performed using the energy-dispersive X-ray spectroscopy (EDS) method using the Sigma-300, Zeiss. In addition, X-ray diffraction and a pH meter were used to measure the variation in pH and mineralogy of non-amended and BB-amended soils for further insights into the effects of biochar on soil behaviour over time[51]. EPA 9801 was

Property	BB	CL	SM	Standards
CEC (meq/100 g)	23.63	12.65	7.56	[52]
pH value	8.90	7.75	7.85	[51]
SSA (m^2/g)	209.16	52.72	21.21	[53]

Table 3. Physicochemical properties of biochar and soils. CEC, cation exchange capacity; SSA, specific surface area,

	CL	SM	BB	CL + 2%BB	SM + 2%BB
Element	Weight(%)	Weight(%)	Weight(%)	Weight(%)	Weight(%)
C	–	–	83.02	2.67	2.28
O	48.52	45.23	11.08	44.41	47.25
Si	25.45	31.27	0.69	27.29	30.62
Al	11.39	10.52	0.35	10.34	10.24
K	2.76	3.69	2.82	3.67	2.61
Fe	6.11	2.76	0.23	6.05	2.26
Na	0.45	0.03	0.02	0.52	0.06
Ca	0.55	0.29	1.61	1.14	0.63
Mg	1.23	0.16	0.16	1.24	0.97

Table 4. EDS results of soils, bamboo biochar and biochar-amended soils.

followed to determine soil and biochar cation exchange capacity (CEC)[52]. The total surface area (SSA) of soil and biochar was determined using the ethylene glycol monomethyl ether (EGME) adsorption and desorption method[53].

Results and discussion

Physicochemical properties of soils, BB and BAS

Table 3 shows the CEC, pH, and SSA results of BB, CL and SM soil. The analysis reveals that the CEC, pH, and SSA of BB were higher than those of both CL and SM soils. The higher CEC of BB signifies that its addition to soils would increase the CEC of the BAS, thereby improving the ability to retain nutrients in the mix. The higher SSA of BB would provide more surface area in BAS for water absorption, thereby enhancing the water retention of BAS. This characteristic can be advantageous for vegetation growth by ensuring improved moisture availability in the soil.

The EDS results of both soils, BB and BAS, were determined and presented in Table 4. The results indicated a higher carbon and calcium content in BB and a prevalence of silica in soils. EDS analysis was also conducted on UCS specimens of 2% BB amended CL and SM soil and cured for 30 days. The results indicate a significant increase in calcium content. Calcium plays a crucial role in soil aggregation and the formation of stable soil structures. The results suggest that the mixing BB in soils increased the availability of calcium ions in the matrix, facilitating reactions with silicates.

Figure 2a, b shows the pH results of CL and SM soil amended with varying proportions of BB for different curing periods. The results revealed that incorporating BB into both soils led to a noticeable increase in the pH of mixtures. This phenomenon occurred because of the higher pH of BB compared to both CL and SM soils.

In contrast, a decrease in pH was observed over the curing period, possibly due to the formation of acidic substances from the oxidation and decomposition of organic matter within the soil. As reported in the past, biochar isn't completely inert in soil and can undergo oxidation as a result of chemical and microbial activity, and carboxylic functional groups may be produced through the gradual oxidation of biochar in soils[54]. The escalation of acidic functional groups counteracted alkalinity and reduced the pH during the curing period.

Effect of curing period on UCS of BAS

Figure 3a, b exhibits the variation in UCS over time for soils mixed with different BB content. The results indicate that the strength characteristics of both soils behave differently with the addition of BB. UCS of CL soil was observed to increase with a lower level of biochar amendment, but it decreased upon further addition of BB. The percentage increase in UCS was observed to be 2.69% and 10.51% with the addition of 1% and 2% BB in CL soil, respectively.

However, the subsequent inclusion of 3.5% and 5% BB in CL soil resulted in a strength reduction of 12.92% and 24.29%, respectively, compared to non-amended CL soil for day one. The results indicate that the CL soil amended with BB reached its peak strength at a 2% biochar content. The rise in strength occurred because adding 2% BB in CL soil filled the pores and facilitated improved connectivity between the CL soil and BB particles. On the contrary, the addition of BB (from 1 to 5%) in SM soil resulted in a consistent decrease in strength. The percentage decrease in UCS strength for 1% and 5% BB amended SM soil was 21.47% and 51.02%, respectively, with respect to non-amended SM soil for day one. The reduction in UCS was attributed to the introduction of BB

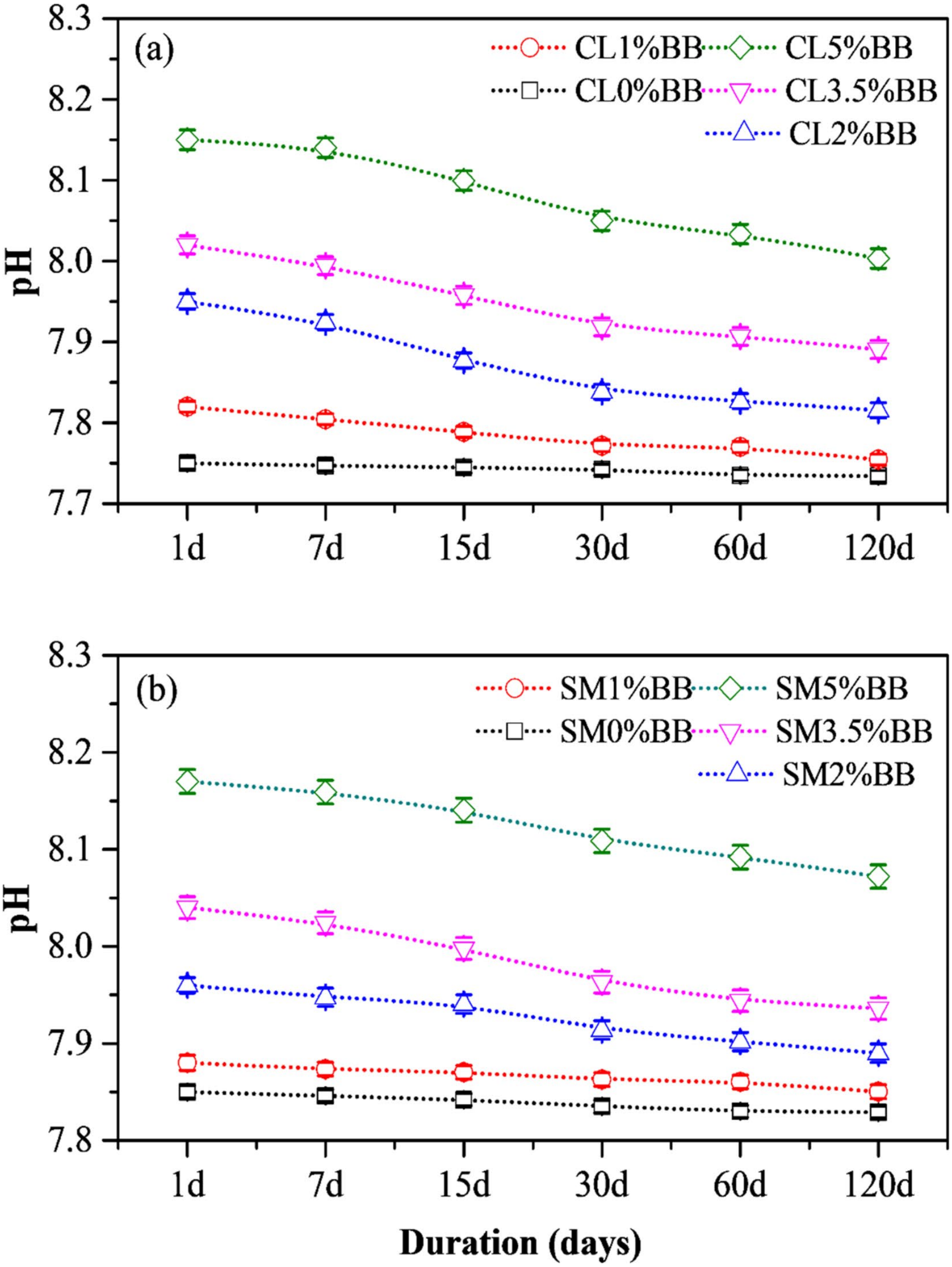

Fig. 2. Variation of pH over curing period and with addition of BB in (a) CL soil and (b) SM soil.

into the SM soil, which induced an increase in pores and subsequently disrupted the optimized interconnectivity between the soil matrix and BB particles. The details of the microstructural analysis and in-depth exploration of the mechanisms governing correlation with UCS results on day one have been presented in a previous study[19].

The strength development over the curing period is crucial for evaluating the properties of biochar-treated soils, as the composition of these materials may change over time due to various reactions. The time-based UCS results showed a consistent trend of increasing UCS with the curing period, irrespective of soil and BB content. The results indicated that the strength of both soils (CL and SM) increased at the intervals of the 7th day, 15th day, 30th day, 60th day, and 120th day compared to the strength observed on the first day.

In the case of BB-amended CL soil, the percentage increases in strength at the 7th day, 15th day, 30th day, 60th day, and 120th day were observed to be 1.50%, 4.96%, 7.27%, 7.63%, and 9.13% for 0% BB content, and 2.34%, 5.53%, 7.19%, 8.65%, and 10.87% for 2% BB content, respectively, relative to the strength observed on

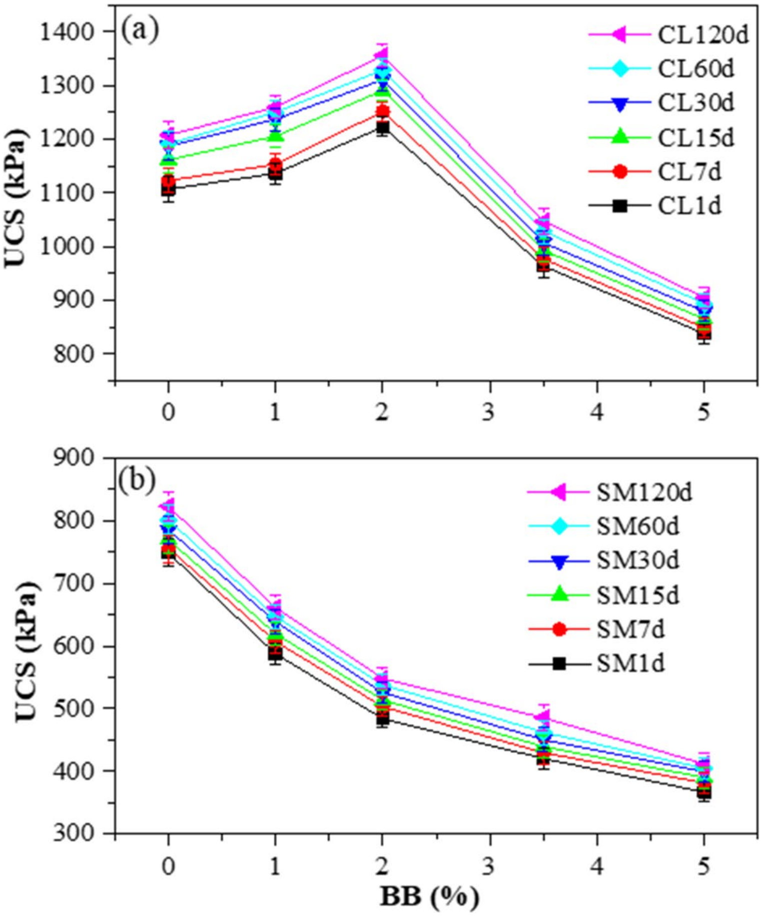

Fig. 3. Strength variation of BB-amended soil with varying curing period and biochar percentage for (a) CL soil and (b) SM soil.

the first day. The results also indicate that the increase in strength was more significant in BB-amended CL soil than in non-amended soil with the curing period. However, for the BB-amended SM soil, the percentage increases in strength at the 7th day, 15th day, 30th day, 60th day, and 120th day were observed to be 0.95%, 2.87%, 4.95%, 7.06%, and 9.96% for 0% BB content, and 3.99%, 6.22%, 6.67%, 11.26%, and 13.327% for 2% BB content, respectively, relative to the strength observed on the first day. The results also suggest that the strength increase was relatively greater in soils amended with BB than in non-amended soil throughout the curing period. The increase in UCS of non-amended CL and SM soil was due to moisture redistribution within the specimens, which reduced localized weaknesses. This process caused macrostructural changes in the soil matrix by facilitating particle rearrangement and increasing bonding over time, thereby enhancing the overall strength. The ageing of biochar improved BAS stability and impacts compressive strength over time, consistent with previous studies and validating the observed trends and mechanisms[55–59].

Microstructural and mineralogical analysis of 30th days UCS specimen

The UCS specimen tested after 30th days of curing was selected for microstructural analysis. The FESEM image of non-amended and 2% BB amended CL and SM samples are shown in Figs. 4a, c and 4b, d, respectively. The results showed that the microstructural changes occurred in BAS with curing periods. The observation reveals that the addition of BB and the curing process effectively fill the pores and establish bonds between soil biochar particles, as shown in Fig. 4b, d. The reduction in pores and enhancement of interparticle bonding contributed to increased compressive strength in BB-amended soils.

Pore size distribution was also analysed for the 30-day cured UCS specimens of non-amended and 2% BB-amended CL and SM soils, as shown in Fig. 5a, b. The MIP results showed that adding 2% BB to CL soil caused a shift in the mean pore diameter towards smaller values, indicating a reduction in pore size compared to non-amended CL soil. This reduction further improved the bonding between the soil and BB particles, resulting in an increase in the compressive strength of the specimen. In contrast, the incorporation of 2% BB into SM soil increased the mean pore diameter compared to the non-amended SM soil. This change indicated larger pore sizes and reduced bonding between the soil and biochar particles. As a result, there was a corresponding decrease in the compressive strength of BAS compared to the non-amended SM soil. Tt confirms that the pore sizes observed in the MIP analysis were consistent with the surface morphology revealed by the FESEM analysis. These findings show that CL soil intermingled more effectively with 2% BB than SM soil.

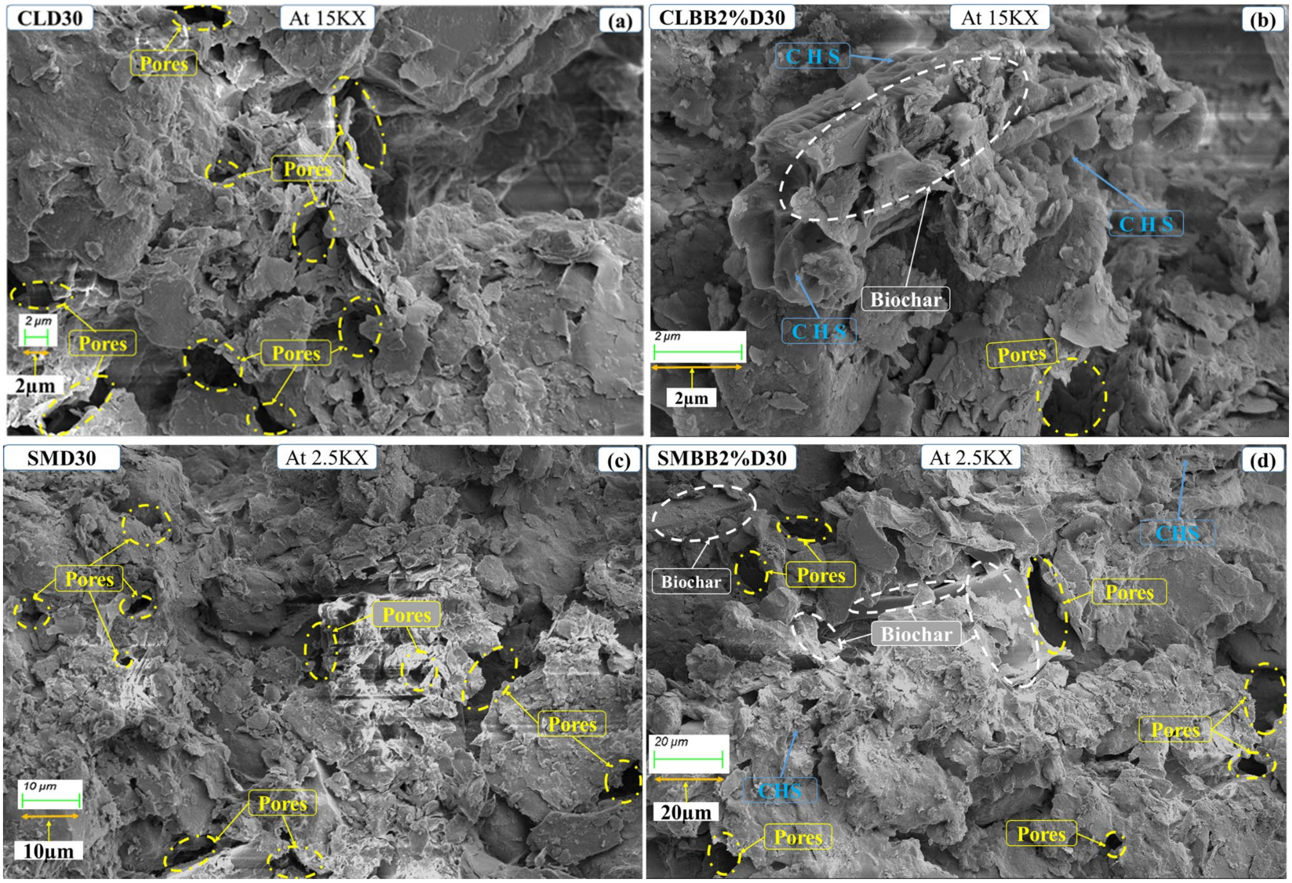

Fig. 4. The alteration in pores size and development of bonding between soil-BB in the UCS specimen cured for 30th day for (a, c) non amended CL, SM soil; and (b, d) CL, SM soil mixed with 2% (w/w) biochar content.

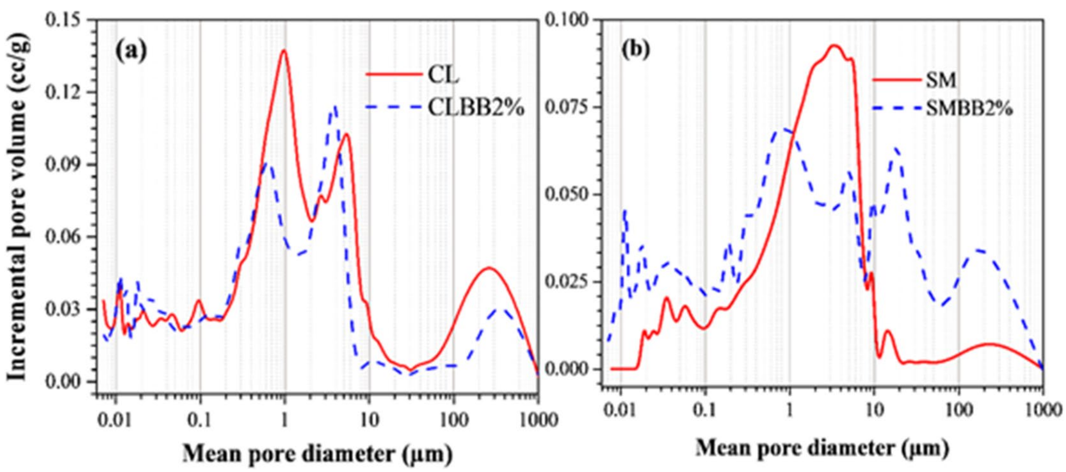

Fig. 5. The variation of mean pore diameter of (a) CL and (b) SM soil of the UCS specimen cured for 30th day for non-amended and 2% (w/w) biochar amended case.

In addition, the EDS (Table 4) results of 2% biochar (BB) CL and SM reported a significant increase in calcium content. It has occurred because mixing BB in soils increased the availability of calcium ions in the matrix, facilitating reactions with silicates. The silicon ions released from silicate minerals in the matrix reacted with calcium ions to form calcium silicate compounds, which may share some similarities with Calcium silicate hydrate (C-S-H) in terms of structure and properties, and it was observed in FESEM image analysis and presented in Fig. 4b, d. The higher calcium content in BAS contributed to the aggregation and formation of stable soil structures. The observed strength development during the curing stage indicates that a pozzolanic reaction occurred due to the interaction between the calcium in BB and the soil particles in the mixtures.The enhanced bonding and reduced pore size in CL soil resulted in a notable increase in compressive strength.

Figure 6 presents the XRD results for non-amended and 2% BB-amended CL and SM UCS specimens cured for 30 days. The mineralogical analysis of CL and SM soils showed no significant changes after the 30-day curing period (Fig. 6a and b). However, after this curing period, the 2% BB-amended CL and SM UCS specimens exhibited new peaks of carbonate minerals, as shown in Fig. 6c and d. The mineralogical analysis confirms that the CHS compounds observed in the FESEM images were due to the formation of carbonate minerals in the BAS, which contributed to the increase in UCS strength over the curing period in both soils.

Effect of freeze-thaw on UCS of BAS

The 30-day cured UCS specimen of non-amended, and BAS has been utilized as a benchmark to evaluate the influence of freeze-thaw cycles. The specimens were subjected to 1, 3, 5, and 8 cycles within a specialized cabinet. The variation in the UCS value of BAS for different F-T cycles was analysed and shown in Figs. 7a and 8a. The result shows that for the same F-T cycle, 1% and 2% BB-amended CL soils exhibited higher UCS values than non-amended CL soil. Also, it was observed that the UCS of 3.5% and 5% BB-amended CL soils was lower compared to non-amended CL soil across all F-T cycles. These trends were similar to the curing results, wherein the addition of BB resulted in a notable increase in UCS of CL soil upto 2% BB content and decreased after that. Thus, the results showed that smaller (1% and 2%) BB-amended CL soil experiences a milder impact from F-T cycles than non-amended and soil amended with higher BB concentrations (3.5% and 5%). In contrast, biochar-amended SM soil showed a consistent decrease in UCS value with the addition of BB ranging from 1 to 5%, for all F-T cycles. In BB-amended SM soil, the UCS was higher at lower BB content and lower at higher BB content for the same F-T cycle. These patterns imitate those observed in the curing tests, where the addition of BB led to a significant reduction in UCS of SM soil. Moreover, in all scenarios, the UCS of biochar-amended soils diminishes after being subjected to F-T action.

Figures 7b and 8b illustrate the variation in UCS with different numbers of F-T cycles for BB-amended soils. The results show that F-T cycles have negatively affected the strength of BAS. The UCS value was observed to decrease with an increase in the number of freeze-thaw cycles for both soil types, compared to non-F-T tests. The utmost decrease in UCS value was observed during the initial F-T cycle, while it was found to be decreased at higher cycles for both soil types. In the case of BB amended CL soil, the percentage decrease in strength for 0%, 1%, 2%, 3.5%, and 5% BB content ranged from 31.80 to 43.47%, 31.16–43.69%, 29.32–40.22%, 30.29–42.51%, and 33.10–44.53% for the first–third F-T cycles, and from 53.94 to 59.59%, 53.80–59.32%, 51.03–57.16%, 52.58–

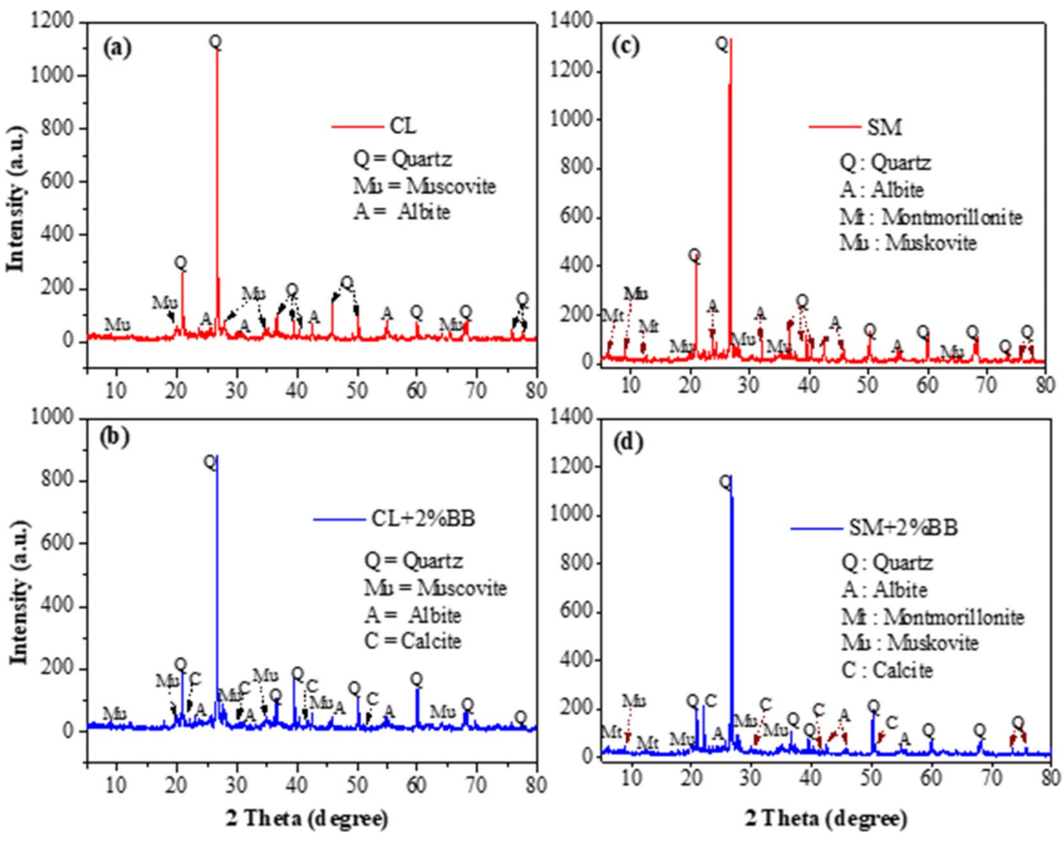

Fig. 6. Mineralogical analysis of UCS specimen cured for 30th day for (a, c) non amended and (b, d) 2% BB amended CL and SM soil.

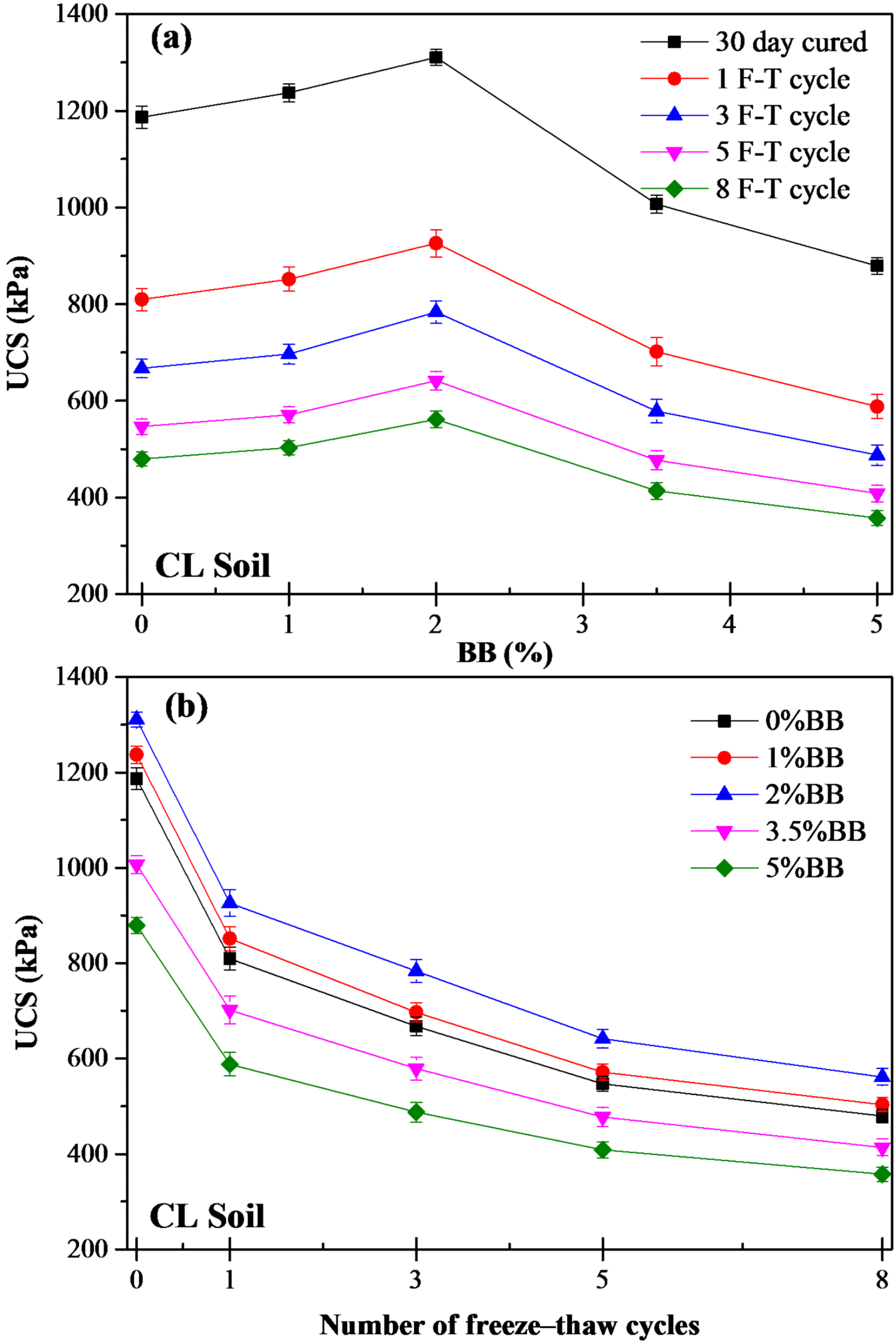

Fig. 7. Strength variation under freeze thaw condition of BB-amended CL UCS specimens cured for 30 days with varying (a) BB percentage and (b) the number of freeze-thaw cycles.

58.92%, and 53.54–59.34% for the fifth to eighth F-T cycles, respectively, compared to the strength after 30 days of curing.

Similarly, for BB-amended SM soil, the percentage decrease in strength for 0%, 1%, 2%, 3.5% and 5% BB content were observed to be 29.47–46.03%, 28.33–45.65%, 28.52–43.76%, 30.93–46.87%, and 32.17–47.03% for 1st–3rd F-T cycle; and 57.23–63.68%, 55.94–61.08%, 54.01–58.86%, 53.48–59.22%, and 52.80–58.04% for 5th–8th F-T cycle, respectively, in comparison to the strength after 30 days of curing. The results validate that

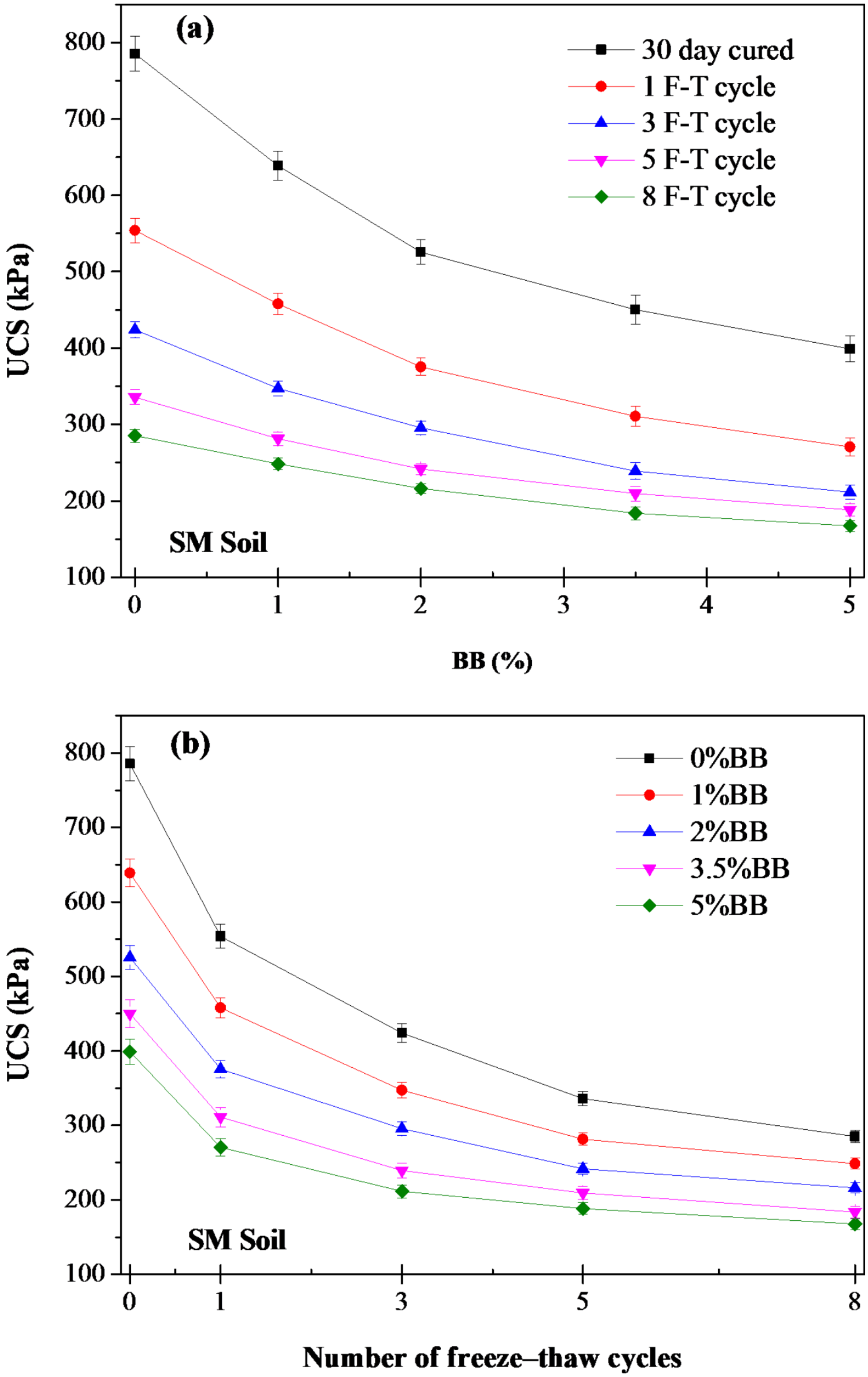

Fig. 8. Strength variation under freeze thaw condition of BB-amended SM UCS specimens cured for 30 days with varying (a) bamboo biochar content and (b) freeze-thaw cycles.

the UCS of biochar-amended soils declines significantly following one or third cycles of freeze-thaw action, with subsequent cycles showing a minor influence. The decrease in the UCS value of BAS was observed because it underwent microstructural changes due to ice expansion and contraction during F-T cycles. These cycles have exaggerated volume fluctuations in BAS, resulting in internal stresses that reduce the UCS. The pores and voids generated by biochar particles in BAS facilitated ice penetration and expansion during freezing, compromising the matrix structure and damaging strength. These results are consistent with findings from prior studies[29,44].

SWRC of BAS in slurry and compacted conditions

Soil water retention characteristics (SWRC) are vital for understanding the water dynamics of soil with suction level. The water retention characteristics are influenced by soil structure and porosity. Soil water retention significantly contributes to vegetation growth.

Figures 9b and 10b illustrate the results of soil-water retention tests conducted on CL and SM soil types under confined conditions (compacted at 0.9MDD) with varying concentrations of BB (0%, 1%, 2%, 3.5%, and 5%). Whereas, Figs. 9a and 10a depict the SWRC of BAS under unconfined conditions (slurry prepared at LL). The results over the suction range of 10–10^6 kPa indicate that the water retention capacity increased with BB content (0–5%) for both confined and unconfined conditions. The results show that the water retention capacity of all BAS specimens decreased as the total suction increased along the drying paths. The increase in water retention was found to be more prominent in the lower suction range (wet state) and less noticeable in the higher suction range (dry state) in both sample conditions. However, variations in the increment of water retention capacity were also observed between unconfined and confined conditions. The increase in water retention capacity of soils in confined conditions was found to be lower than that in unconfined conditions at a particular BB content.

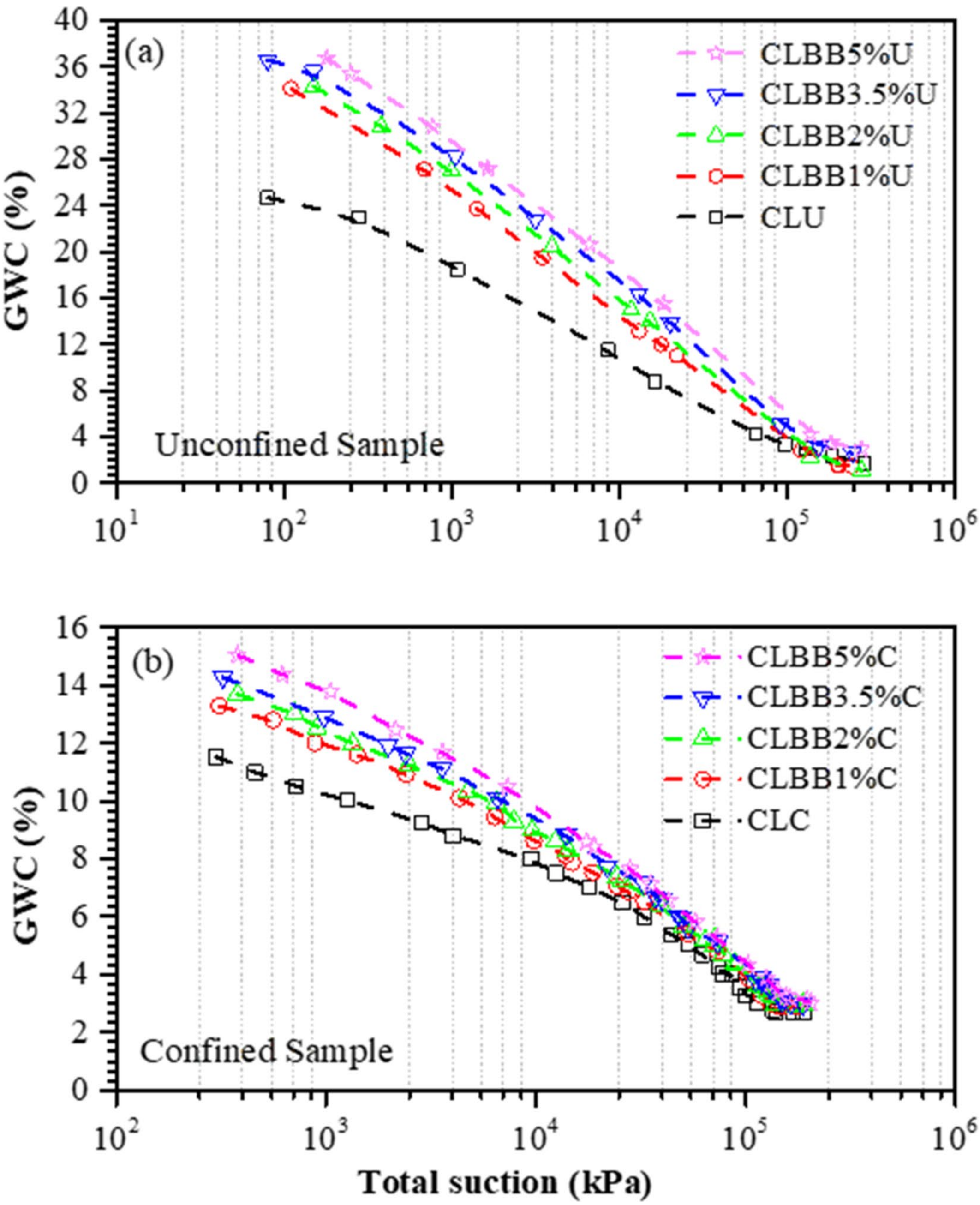

Fig. 9. Variation of Soil water characteristics curve of BB-amended CL soil over suction range under (a) Unconfined and (b) confined sample condition.

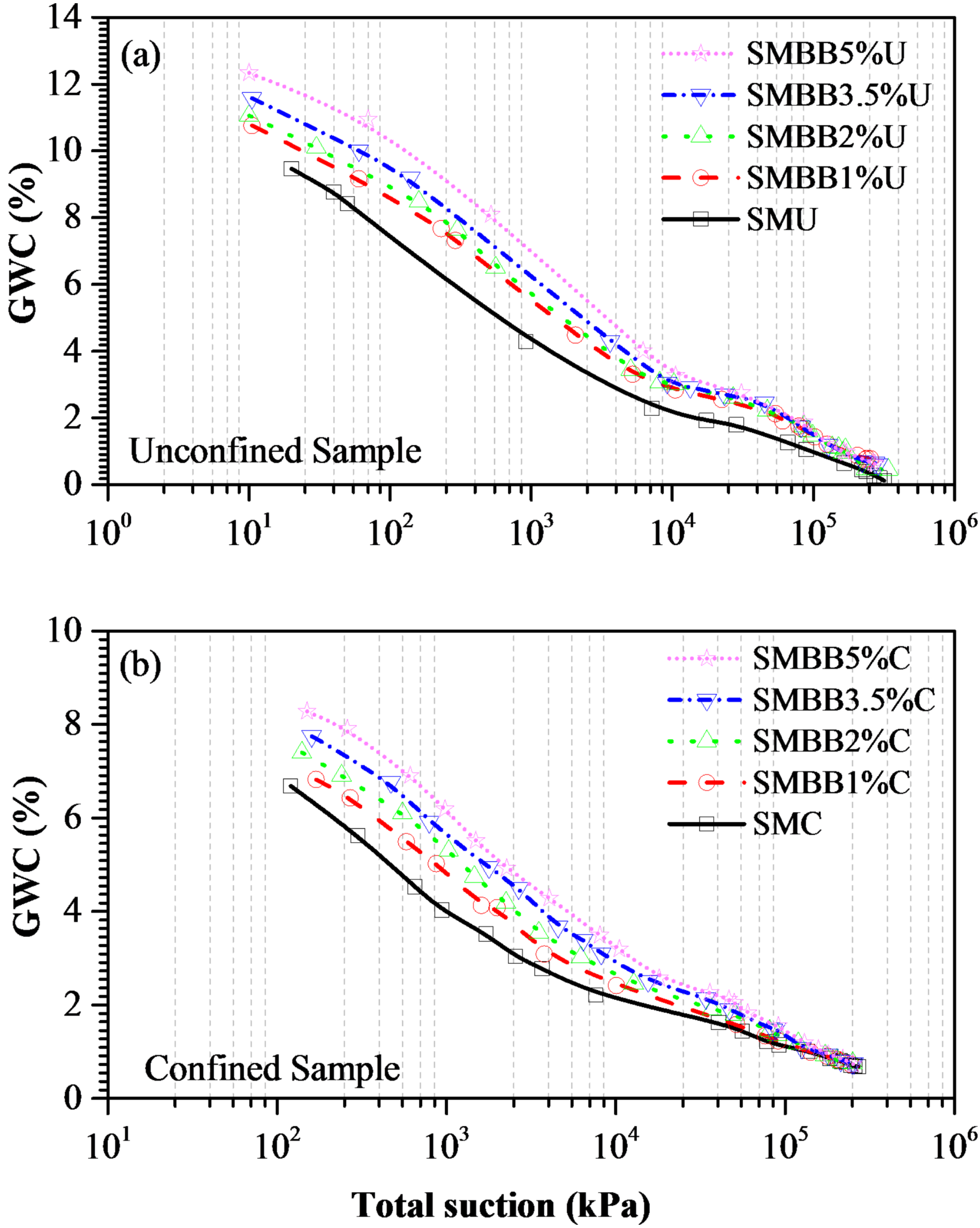

Fig. 10. Variation of Soil water characteristics curve of BB-amended SM soil over suction range under (a) Unconfined and (b) confined sample condition.

This reduced water retention in confined conditions was attributed to the decreased pore space resulting from the high compaction levels in BAS.

The SWRC of BB-amended CL and SM soils also exhibits with total suction in comparative analysis. The findings indicate that the SWRC of CL soil experienced a greater increase with BB addition compared to SM soil under both unconfined and confined conditions. The greater increase in SWRC suggests higher water retention characteristics of the materials. Therefore, it implies that BB-amended CL soils exhibit greater water retention potential compared to SM soil. The results signify that not only does BB contribute to water retention characteristics, but minerals present in the soil also play a role in this process. The mineralogical analysis of CL soil confirms the presence of muscovite minerals, which are recognized for their water-retentive properties.

In addition, it was observed that the specific surface area (SSA) of CL soils was higher compared to SM soil. The increased SSA facilitated greater surface availability for water absorption, thereby resulting in an increase in water retention of the material. The SSA, mineralogical composition of soils and BB have influenced the SWRC under both confined and unconfined conditions. Hence, a greater increase in water retention capacity was observed for BB-amended CL soil compared to biochar-amended SM soil in both confined and unconfined conditions. This occurred due to the presence of water-holding minerals present in CL soil. Biochar addition in CL-soil also supported the water retention characteristics. These results align with findings from prior studies, reinforcing the observed trends and underlying mechanisms[15,41].

Variation of GWC with suctions in unconfined and confined conditions

The variations in gravimetric water content (GWC) significantly influence the vegetation growth. The GWC at the 1500 kPa suction level represents the permanent wilting point (PWP), the minimum water content necessary for plants to extract water. It is essential to observe and understand the influence of biochar on the PWP (1500 kPa) of soil. The GWC at lower suctions (500 kPa) and higher suctions (180×10^3 kPa) also plays a role in determining the overall water availability and plant growth in soil ecosystems. The fluctuations in GWC of BAS at lower suctions (500 kPa), PWP (1500 kPa), and higher suction (180×10^3 kPa) were also observed, as illustrated in Fig. 11.

The results in Fig. 11a, b show that the increase in GWC were observed to be higher in unconfined condition compared to confined condition at all suction levels (500 kPa, 1500 kPa and 180×10^3 kPa) for BB amended CL and SM soil. The GWC at PWP decreases from 25.87 to 11.89% from unconfined to confined conditions for 2% BB-amended CL soil. Moreover, it decreases from 27.76 to 13.27% for 5% BB-amended CL soil. Similarly, the GWC at PWP for 2% and 5% BB-amended SM soil, decreases from 5.87 to 4.47% and 7.38% -5.1% in unconfined conditions to confined conditions, respectively.

It was noticeable that GWC decreased at PWP in confined conditions for both soils. The GWC at PWP increases with a higher quantity of BB. It was observed that the GWC at the PWP was still significantly higher in

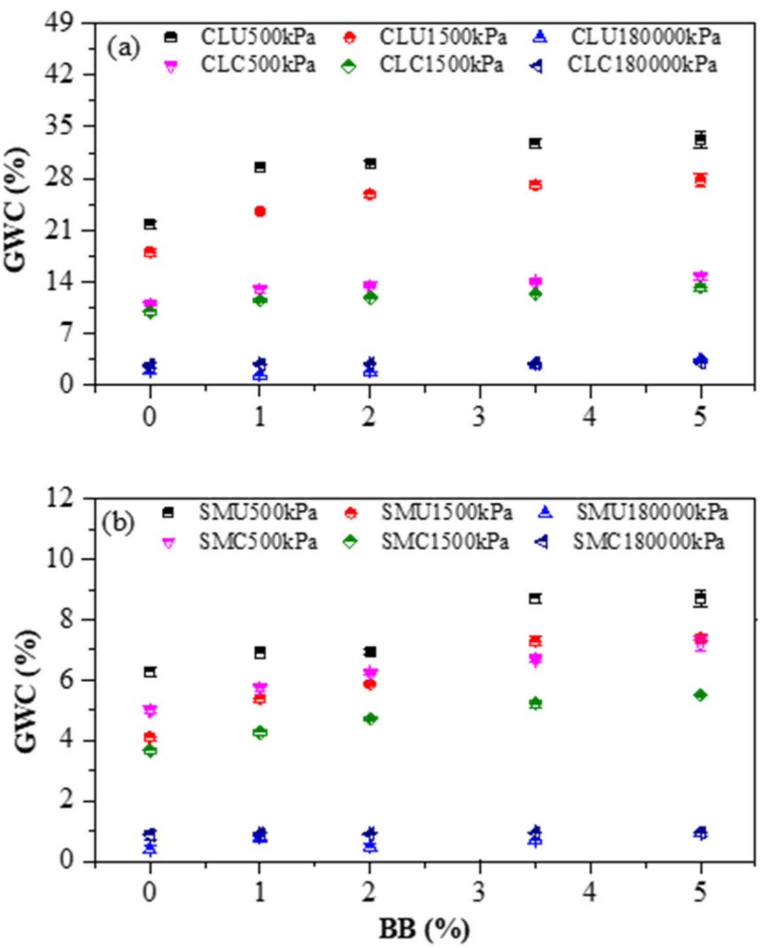

Fig. 11. Variation of GWC under unconfined and confined condition at different suctions levels of (a) CL soil and (b) SM soil, mixed with increasing BB content.

BB-amended CL soil compared to SM soil. Furthermore, in both test conditions, the GWC was observed to be highest at lower suctions (500 kPa), and lowest at higher suctions (180×10^3 kPa) at a fixed BB content for both soils. The GWC follows a similar decrease pattern at both lower (500 kPa) and higher suction (180×10^3 kPa) levels in confined conditions for both soils, as presented in Fig. 11a, b. The increase in GWC for BB-amended CL soil was greater than the SM soil. The occurrence is attributable to the greater SSA and the existence of minerals in the CL soil with water-retentive properties.

Microstructural analysis of compacted specimens

The microstructural analysis of WP4C specimens was conducted to determine the cause of the variation in GWC, offering insights into the underlying mechanisms that influence water retention in the soils. The FESEM images in Fig. 12 illustrate these findings, with Fig. 12a, c showing the compacted (confined) non-amended CL and SM soils, respectively, and Fig. 12b, d presenting the 3.5% BB amended CL and SM soils. The FESEM images of slurry (unconfined) specimens can be referred from our previous study[19].

The FESEM images indicate that variations in GWC were influenced by changes in pore sizes in both soil types. The analysis showed a decrease in larger pores and an increase in smaller pores in the confined specimens compared to the unconfined ones for both non-amended soils. The pore structure of the specimen significantly influences the SWRC. Thus, the reduction in pore size under confined conditions decreased the GWC of soil. This occurred because the addition of 3.5% BB increased pore size in both soils (Fig. 10b and d), thereby resulting in an increase in GWC.

To validate the FESEM results, MIP analysis was conducted on the same WP4C specimens, as depicted in Fig. 13a, b. Figure 13a shows that the mean pore diameter of CL soil increased with the addition of 3.5% BB. Similarly, a larger mean pore diameter was observed in 3.5% BB-amended compared to non-amended SM soil, as shown in Fig. 13b. The FESEM analysis also showed similar alterations in pore size between non-amended and BB-amended soils. The MIP results confirm that the addition of BB increased the pore size in both soils under confined conditions. The application of BB has potentially supported the enhancement of GWC in BAS under confined conditions, which could be beneficial for promoting vegetation growth.

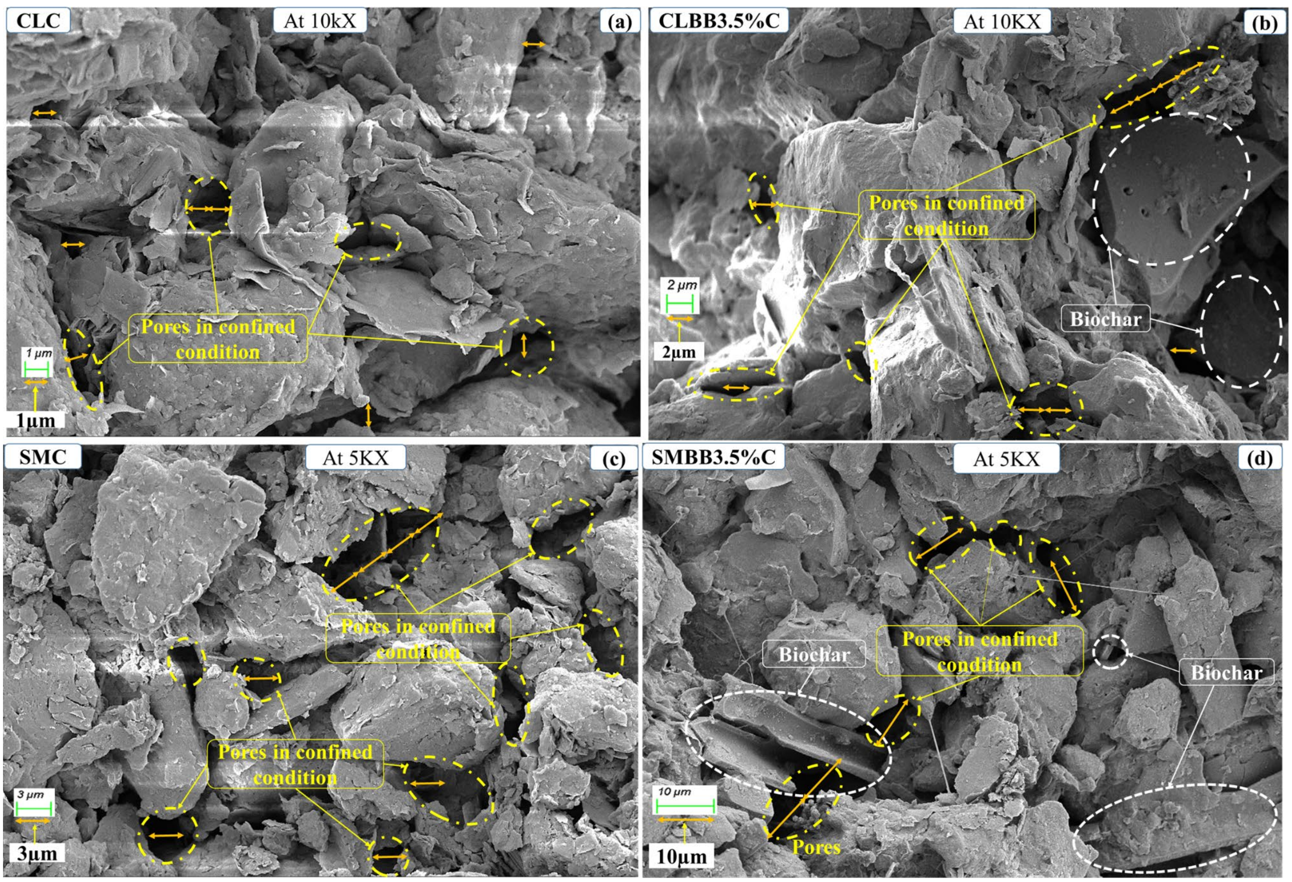

Fig. 12. The surface morphology of WP4C specimens in compacted conditions for (a, c) non-amended, and (b, d) 3.5% BB amended CL and SM soil.

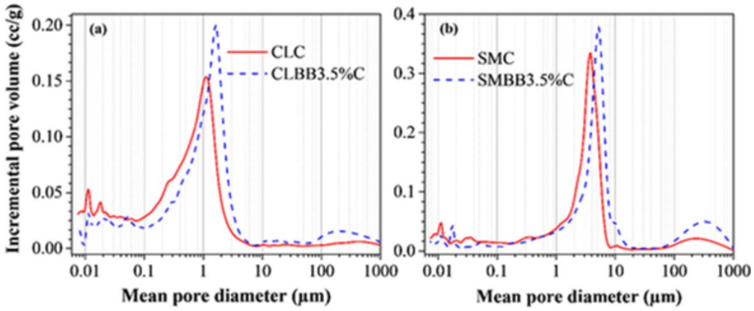

Fig. 13. The pore size variation of non-amended and 3.5% BB amended WP4C specimens in compacted conditions for (a) CL and (b) SM soils.

Summary and conclusions

This study explores the impact of BB on UCS of CL and SM soils under curing periods and freeze-thaw cycles, as well as water retention in compacted and slurry conditions. The following conclusions can be drawn from the results:

The addition of 1–2% BB increased the strength of CL soil by 2.69–10.51%, while further addition decreased strength. In contrast, BB consistently decreased the strength of SM soil. Both soils showed a steady increase in UCS with curing, with BB-amended CL and SM soils gaining 7.19% and 6.67% in strength, respectively, by the 30th day compared to day one at 2% BB. The increase in strength was attributed to reduced pore spaces and improved interparticle bonding with curing. The compressive strength of both CL and SM soils decreased with increasing freeze-thaw cycles, with 2% BB-amended soils showing strength reductions of 29.32–40.22% for CL and 28.52–43.76% for SM soils from the first to the third freeze-thaw cycle. The water retention of both soils increased with BB addition, with CL soil showing a greater increase in water retention compared to SM soil under both unconfined and confined conditions. In addition to BB, the muscovite mineral and higher SSA of CL soil also contributed to the improved water retention. The GWC decreased at all suction points under confined conditions for both biochar-amended soils. Microscopic analysis revealed that the reduction in GWC was due to a decrease in pore spaces under confined conditions in both soils.

The observed increase in strength and water retention at 2% BB-amended CL soil demonstrates its potential as an effective material for landfill cover applications. This optimal proportion offers a balance between geotechnical performance and environmental benefits, making it a sustainable solution for addressing challenges like stability, moisture retention, and vegetation growth in landfill systems. However, the results presented in this study may vary with different soil types and biochar varieties. Environmental factors, such as variations in curing conditions and freeze-thaw cycles across different climates, could influence the performance of biochar-amended soils. The freeze-thaw cycles demonstrated a reduction in UCS values, indicating the sensitivity of BAS to environmental fluctuations requirement of mitigation strategies such as optimizing the biochar content and moisture control. The long-term stability of biochar-amended soil under wetting-drying cycles, dynamic loading, and varying environmental conditions is needed to evaluate before field applications. These factors introduce uncertainties, highlighting the need for further investigation to fully understand the stability and effectiveness of biochar-amended soils.

Data availability

The data is included within the manuscript. Additionally, materials and supplementary data can be provided upon a legitimate request to the corresponding author of this study.

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Author contributions
Shailesh Kumar Yadav. Contributed to the conceptualization and experimental execution, data extraction, prepared Tables and Figures, and wrote the original skeleton of the entire draft.Ramakrishna Bag. Contributed to the interpretation of the discussion of various sections and provided critical revision and editing of the article.

Competing interests
The authors declare no competing interests.

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