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Effect of bamboo biochar on the hydraulic conductivity of two different compacted soils

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ABSTRACT

Biochar is a carbon residue produced from the thermochemical decomposition of biomass. The inherent properties of biochar vary with the kinds of feedstock, heating rate and pyrolysis conditions. Consequently, the geotechnical properties of biochar-amended soil (BAS) were also found to differ with the types of biochar as per the past studies. However, the effect of bamboo biochar (BB) on the hydraulic conductivity of BAS was observed missing in the published literature. Hence the current research focuses on the influence of the amendment of BB on the hydraulic conductivity of low plastic clay (CL) and silty sand (SM) in compacted conditions. Samples were prepared using BB in 0%, 1%, 2%, 3.5%, and 5% proportions to the dry weight of the soils for experiments. The findings of this research showed that the biochar addition decreased the maximum dry density (MDD) and increased the optimum moisture content (OMC) of both soils. Moreover, falling head permeability test results showed that the hydraulic conductivity of CL soil mixed with BB decreased by 90% and 97% for 1% and 2% biochar content, respectively, and increased afterwards. In contrast to CL soil, a continuous increase in hydraulic conductivity was observed with an increase in biochar content for SM soil. The mean pore diameter (MPD) and surface morphology analysis confirmed that the biochar addition filled pore spaces in CL soil and created more voids in the SM soil, which led to a decrease and increase in hydraulic conductivity, respectively.

Keywords: bamboo biochar, maximum dry density, hydraulic conductivity, mean pore diameter, surface morphology

1 INTRODUCTION

Biochar is a carbon-rich, stable product produced from the pyrolysis or gasification of biomass in a closed chamber at high temperatures with little to no oxygen present (Lehmann & Joseph, 2012; Li et al., 2020). Agricultural residue, animal manure, municipal solid waste, forestry, and wood processing waste are the principal raw materials (feedstock) used for biochar production (Wani et al., 2022). Several studies on various types of feedstock-produced biochar have been performed in the past to investigate the geotechnical properties (compaction characteristics and hydraulic conductivity) of biochar-amended soils (BAS). Most studies have concluded that biochar properties vary with feedstock types, pyrolysis temperature, rate of heating, and atmospheric condition of the pyrolysis chamber, which resulted in the alteration of geotechnical properties of BAS (Yargicoglu et al., 2015; Kameyama et al., 2016; Garg et al., 2019; Bordoloi et al., 2020; Ganesan et al., 2020; Bora et al., 2021; Huang et al., 2021).

Hydraulic conductivity is one of the most critical and vital engineering properties for the stability of landfill cover projects. Hydraulic conductivity depends on many factors, such as soil types, amending material and compaction factors. In general, the review of past literature shows that the biochar amendment has decreased the maximum dry density of BAS (Kumar et al., 2019; Hussain et al., 2021). The decrease in dry density in BAS was due to the lighter biochar particle replacing the heavy soil particle from the mixture. However, the hydraulic conductivity of BAS was observed to vary with soil types in the previous studies. The investigation by Ouyang et al. (2013) on biochar (dairy manure) mixed with silty clay and sandy loam soil exhibited a slightly increased hydraulic conductivity compared to untreated soils. Another study by Barnes et al. (2014) on BAS presented that the hydraulic conductivity increased in clayey soil and decreased in sandy as well as organic soil with biochar (mesquite wood) amendment. Also, the gas permeability of sandy clay soil mixed with biochar (water hyacinth) was observed to be decreased (Garg et al., 2019). The investigation of biochar (mesquite hardwood) mixed with silty sand and pure sand soil revealed that the addition of biochar increased the hydraulic conductivity in silty sand, whereas it decreased with pure sandy soil (Hussain et al., 2021). Therefore, the previous investigations on the hydraulic conductivity of BAS showed that it not only varies with soil types but also with feedstock's based biochar. In previous studies, several types of biomass-based biochar were used as an amendment material to examine the hydraulic conductivity of BAS. Still, the research on biochar produced from bamboo biomass as a soil amendment is missing in the past literature.

Unlike other cash crops, grass and timber species, bamboos are fast-growing indigenous material with faster maturation and higher productivity. Bamboos require initial plantation costs with no additional expenditure during the growth period (Nath et al., 2015; Kumar et al., 2022). Also, bamboo is being widely used in developing countries like India, Malaysia and China; as a support and bearing member in fencing, roofing, construction and crafts (Nath et al., 2009). Bamboo is extensively present in large quantities worldwide. India, being the second-largest producer of bamboo in the world, it has spread over11.4 million-hectare of the entire forest cover of the country. However, the current effective utilization of bamboo is around 30-40%, and the remaining bamboo is either incinerated or buried directly (Nath et al., 2009). Nath et al. (2009) and Kumar et al. (2022) reported that around 4.5 million tons of bamboo are used in industries for various purposes, generating a tremendous aggregation of bamboo scrap or waste materials at the end of the work. The continuous increase in the large quantity of bamboo waste causes a scarcity of dumping space, leading to a severe environmental and waste management problem. To address these challenges, recycling of bamboo waste into biochar is essential and necessary for the environment as it helps in carbon sequestration in the ground for long period (Lehmann & Joseph, 2012). The production of biochar would be beneficial as well as economical in dealing with such waste as it would reduce the land scarcity by curtailing the waste mountain in cities. Moreover, bamboo biochar could be a potential amendment material for the landfill cover layer. So, the effect of bamboo biochar (BB) on the compaction and hydraulic properties of BAS needs to be investigated to understand its efficacy.

Therefore, the effect of BB on the compaction and hydraulic properties of two distinct soils has been investigated. This investigation will assist in selecting an effective and optimal proportion of biochar for soil amendment. Moreover, the current study would further help to study BB as an amendment material for other types of soils.

2 MATERIALS AND METHODOLOGY

2.1 Soil and biochar

In the current study, two types of soil and bamboo biochar were utilized. The soil samples were collected from two places in Patna, Bihar, India. The soil samples were grounded to disintegrate the agglomerated soil into coarse and fine particles. Afterwards, the soil samples were passed through a 2.36 mm sieve and stored in two separate airtight containers. The bamboo biochar was procured from VR International Organic Farming Solution, Bhopal, India. The procured biochar was pyrolyzed at 650 – 700 °C temperature using bamboo biomass in the industry. The biochar procured from the supplier was also stored in a separate airtight container.

2.2 Tests procedure, standards and instruments

Soils and biochar were categorized according to the procedure outlined in ASTM standards. Particle size distribution, Atterberg limits, soils and biochar classification, specific gravity, and pH of the soils and biochar were determined as per the procedure mentioned in ASTM standards (ASTM D422, 2007; ASTM D4318, 2010; ASTM D2487, 2017; ASTM D854, 2014; ASTM D4972, 2007). The total specific surface area (SSA) of soils and biochar was determined by the ethylene glycol monomethyl ether (EGME) adsorption and desorption method (Cerato & Lutenegger, 2002).

Furthermore, the proximate analysis was carried out to determine the moisture content, fixed carbon, volatile carbon and ash content of bamboo biochar. The combustion of bamboo biochar was carried out, and weight by weight relation was used to calculate every value (ASTM D1762, 2011). The ultimate analysis was also carried out to determine the elemental composition of carbon, hydrogen, sulphur and nitrogen in bamboo biochar (ASTM D5373, 2014). For this, the CHNS analyzer, Elementar, Vario MICRO CUBE, India, was used.

2.2.1 Preparation of biochar-amended soil sample

The soils samples were added with biochar in five different ratios (i.e. 0, 1, 2, 3.5 and 5% w/w) in dry state and these samples were packed in a plastic bag and kept in desiccator for seven days to achieve homogeneity. The biochar percentages mixed in soil were decided based on past literature (Bordoloi et al., 2020; Wong et al., 2022; Hussain & Ravi, 2022). The samples were taken out from desiccator after seven days and mixed thoroughly to prepare the biochar-amended specimens.

2.2.2 Compaction and hydraulic conductivity test procedure

The premixed biochar-soil samples were picked up from the desiccator and used for compaction and hydraulic conductivity tests. Firstly, standard Proctor tests were carried out on untreated and biochar-amended samples. Afterwards, the bulk unit weight and moisture content relations were developed to determine the maximum dry density (MDD) and optimum moisture content (OMC) for each biochar–soil mixture (ASTM D698, 2012).

The hydraulic conductivity tests of all BAS samples were carried out in the compacted state. For this test, a mould of 8.95 cm in diameter and 14.95 cm in height was used, and BAS specimens were prepared at the OMC and MDD obtained for each biochar–soil mixture. The sample were compacted in three layer for the uniformity. Thereafter, the compacted BAS specimen mould was connected to the falling head permeability test setup (i.e. standpipes filled with deionized water as permeate liquid for saturation. Once complete saturation of the specimen reached, the water started dripping from bottom nozzle. This process was continued and waited for flow to reach steady state. Once the flow reached steady state, the drop in standpipe water level were noted at regular intervals for few days. This test was terminated when the fluctuation was below 5% for five consecutive readings. The hydraulic conductivity of every biochar–soil mixture was calculated per Darcy's law (ASTM D5856, 2015). Darcy's equation used for falling head hydraulic conductivity determination is as follows:

$$k = (aL/A\Delta t)*\ln(h_1/h_2) \qquad (1)$$

where k is hydraulic conductivity; a, h_1 and h_2 are the area, initial and final water level of the standpipe; L and A are the height and area of specimen mould; Δt is the time elapsed during the drop in water level from h_1 to h_2.

2.2.3 Microstructural and surface morphology examination of specimens

The microstructural and morphological analysis of the biochar–soil mixture specimens were carried out after each hydraulic conductivity test. The specimen was carefully extracted from the mould, and a sample of about 0.5 to 1 gram (sizes of 0.5 cm in width and 1 cm in height) was instantly cut with a sharp paper cutter. Then, these smaller-sized specimens were immediately kept for freeze-drying in the lyophilizer (M. K. Scientific Instruments -134) until the sublimation of pore water (Jadda & Bag, 2020). Further, the lyophilized samples were used to study the pore size and surface morphology. The pore diameters of the specimens between 100 μm and 0.01 μm were measured using the mercury intrusion porosimetry (MIP) technique. The mercury intrusion pore size analyzer PM-20 from Quantachrome was used for the MIP test. In addition, Field Emission Scanning Electron Microscopy (FESEM) tests were performed to examine the surface morphology of BAS specimens using Sigma-300, Zeiss, Germany. The same lyophilized BAS specimen was used for the surface morphology test. Before putting the sample in the FESEM machine, all samples were coated with gold to improve the conductivity of the sample surface and enhances images quality. The images were captured at magnifications of 5000X for unambiguous interpretation.

3 RESULTS AND DISCUSSION

3.1 Materials characterization

3.1.1 Physical characterization of soils and biochar

The soil and biochar particle size distribution (PSD) curves are reported elsewhere (Yadav & Bag, 2023). The grain size range of soils and biochar are presented in Table 1. The PSD of soils and biochar were performed in accordance with the procedure mentioned in the ASTM D422 (2007). The sieve analysis of CL showed that the soil consists of fine soil particles having 73% silt content. However, the PSD of SM showed the dominance of coarse soil particles containing sand (52%), followed by silt (39%). The sieve analysis of bamboo biochar also showed the dominance of coarse biochar particles.

Table 1. *Particle size distribution of soils and biochar.*

Material	Grain size range (mm)			Standard
	4.75 - 0.075	0.075 - 0.002	<0.002	
CL	10.17	72.25	16.77	ASTM D422
SM	52.97	39.25	7.78	ASTM D422
Bamboo biochar (BB)	59.83	40.15	NA	ASTM D422

Note: BB – bamboo biochar, CL – low plastic clay (soil1), SM – silty sand(soil2), NA – no data available

The analysis of Atterberg limits, classification, specific gravity, pH and specific surface area (SSA) of both the soils and biochar are presented in Table 2. As per the Unified Soil Classification System (USCS), Soil1 was categorized as lean clay (CL), whereas soil2 was classified as silty sand (SM) (Yadav & Bag, 2023). Similar soils have been largely used as landfill cover materials in countries like India, the USA and China (Shaikh et al., 2019; Ng et al., 2019). The Atterberg's limits and specific gravity of CL soil were found higher than SM soil. Moreover, the specific gravity of BB results showed a lower value than both soils. The lower specific gravity of BB was due to lightweight and porous nature of BB. The pH of bamboo biochar (8.9) was observed to be more alkaline than the soils (7.75-7.85). The higher pH in biochar is due to the higher carbon content and surface functional groups (hydroxide, alkali and carbonate) of bamboo biochar (Liao & Thomas, 2019). The higher pH value of BB signifies that it can be potentially utilized to treat acidic soil. Moreover, specific surface area (SSA) of BB (209.16 m^2/g) was observed to be more than both soils (52.72 m^2/g for CL and 21.21 m^2/g for SM) in the EGME analysis.

Table 2. *Basic physical properties, classification, pH and specific surface area of soils and biochar*

Properties	Soil1	Soil2	BB	Standards
Liquid limit (%)	38.15	24.90	NA	ASTM D4318
Plastic limit (%)	19.50	15.30	NA	ASTM D4318
Plasticity index (%)	18.64	9.60	NA	ASTM D4318
Classification	CL	SM	NA	ASTM D2487
Specific gravity	2.78	2.75	1.61	ASTM D854
pH value	7.75	7.85	8.90	ASTM D4972
SSA (m^2/g)	52.72	21.21	209.16	(Cerato & Lutenegger, 2002)

Note: BB – bamboo biochar, CL – low plastic clay, SM – silty sand, SSA – specific surface area, NA – no data available

3.1.2 Proximate and elemental characterization of bamboo biochar

The proximate and ultimate analysis of bamboo biochar is shown in Table 3. From the proximate analysis, it was observed that BB contains a large amount of volatile matter (42.41%), a moderate amount of fixed carbon content (37.50%) and a small amount of ash content (14.32%).

Table 3. *Proximate and ultimate analysis of bamboo biochar*

Proximate analysis	Value(%)	Ultimate analysis	Value(%)
Moisture content	5.77	**C**	67.65
Fixed carbon	37.50	**H**	1.94
Volatile matter	42.41	**N**	4.81
Ash content	14.32	**S**	0.014

Note: C – carbon, H – hydrogen, N – nitrogen, S – sulphur

The elemental analysis of BB showed a low percentage of sulphur, which signifies that less quantity of sulphur will release from soil to air and ground water in the form of sulphur dioxide, hydrogen sulphide etc. This indicates the favourable environmental behaviour of bamboo biochar.

3.2 Compaction characteristics of biochar-amended soil

The compaction results of both BAS are shown in Figure 1. The analysis of compaction results of BAS shows that maximum dry density (MDD) decreased while optimum moisture content (OMC) increased with the biochar addition in both soils. However, it was observed that the reduction in MDD was more prominent in CL than in SM soil. The addition of biochar was observed to replace the heavy soil particles with lighter ones and creates more void space, leading to decreased BAS weight in the system. Moreover, biochar addition has enhanced water and air in the matrix due to the high specific surface area, which facilitated a slippery surface at the interface of soil biochar composite leading a decrease in MDD.

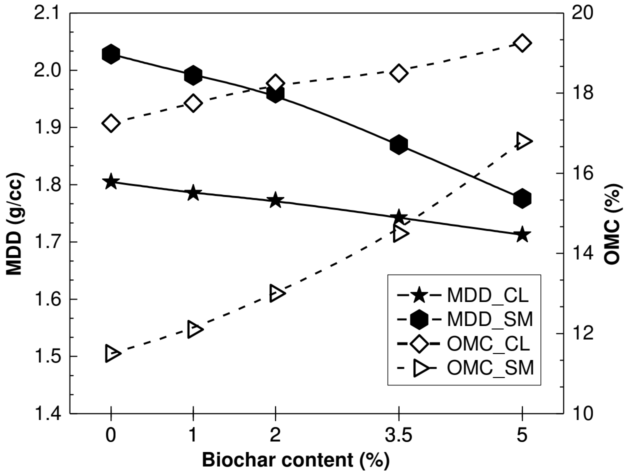

Figure 1. *The variation of maximum dry density (MDD) and* optimum moisture content (*OMC) of CL and SM soil with the increment of biochar content from 0% to 5% (w/w).*

3.3 Hydraulic Conductivity characteristics of BAS

The hydraulic conductivity results of biochar-treated and untreated soils (CL and SM) are presented in Figure 2. The hydraulic conductivity of biochar-amended CL soil showed a significant decrease of 90% and 97% for 1% and 2% of biochar content, respectively (Figure 2a). The further addition of biochar (3.5% and 5%) resulted in a slight increase in hydraulic conductivity.

In the subsequent tests on SM soil mixed with biochar, a continuous increase in hydraulic conductivity was observed with the increment in biochar content (Figure 2b).

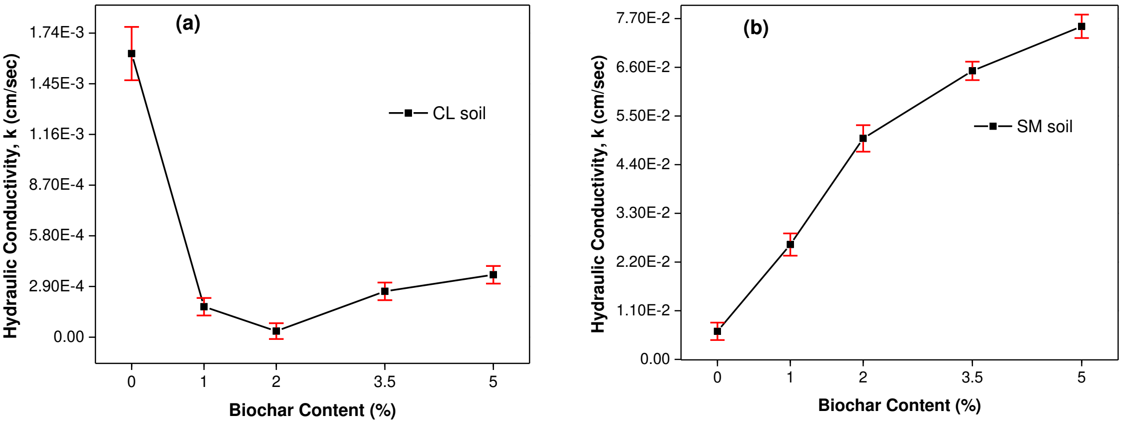

Figure 2. *The variation of hydraulic conductivity of* ***(a)*** *CL and* ***(b)*** *SM soil with the increment of biochar content from 0% to 5% (w/w).*

The hydraulic conductivity of SM soil, treated with biochar, was increased by 686% and 1085% for 2% and 5% biochar content, respectively, compared to untreated SM soil.

3.3.1 Pores size analysis of biochar amended soil

The pore size distribution analysis for both soils mixed with biochar are shown in Figure 3. The lyophilized BAS specimens were used to analyze the pore size distribution. The MIP result of the CL soil showed that with the 1% and 2% biochar increment, the mean pore diameter (MPD) of the BAS sample decreased (Figure 3a). The decrease in pore diameter altered the flow of water through the compacted BAS specimen, which led to a decrease in hydraulic conductivity. Further increments of biochar by 3.5% and 5% resulted in a slight increase in the MPD of biochar mixed CL soil. As a result, the increased hydraulic conductivity value for 3.5% and 5% biochar content was also observed (Figure 2a). Furthermore, the MIP test for biochar-amended SM soil revealed that the addition of biochar increased the pore diameter in the specimen (Figure 3b). The MPD of biochar-treated SM soil was observed to increase with biochar content. Likewise, the maximum pore diameter was observed for 5% biochar amended specimen among all the treated and untreated soil. Consequently, the hydraulic conductivity value of biochar-treated SM soil was noted to be increased with biochar increment (Figure 2b).

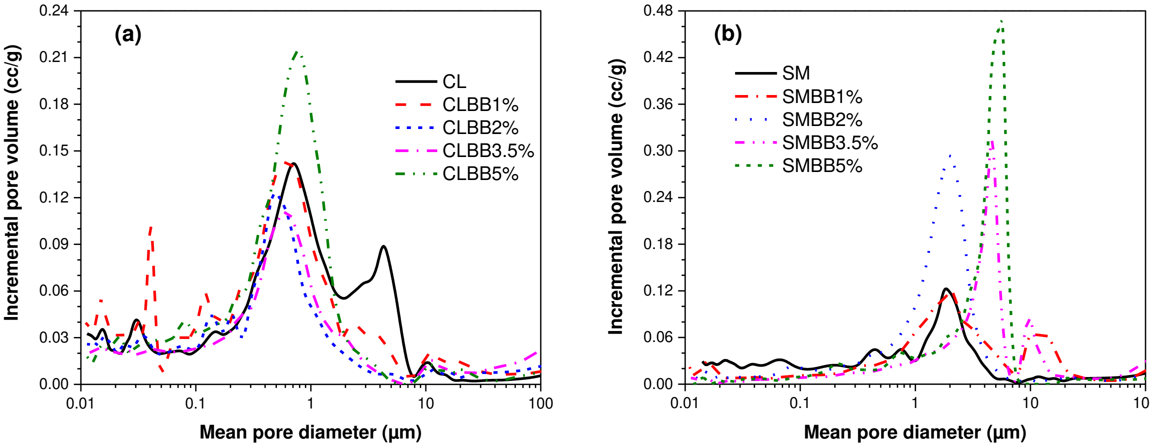

Figure 3. *The variation of mean pore diameter of* ***(a)*** *CL and* ***(b)*** *SM soil with the increment of biochar content from 0% to 5% (w/w).*

3.3.2 FESEM investigation of biochar-amended soil

The FESEM analysis of the soil amended with 2% biochar content is presented in Figure 4. It is evident from the surface morphology of CL soil mixed with biochar (Figure 4a) that the finer soil particles entered into biochar pores and filled the voids of the specimen. Moreover, the MIP analysis also showed reductions in mean pore diameter in CL soil with 2% biochar content compared to untreated soil. Thus

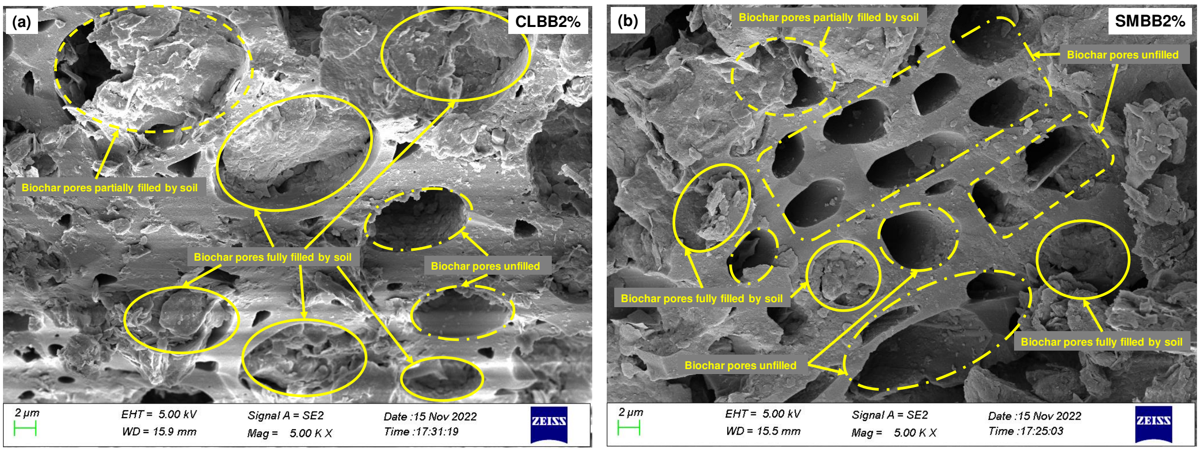

Figure 4. *The surface morphology of* ***(a)*** *2% biochar amended CL soil and* ***(b)*** *2% biochar amended SM soil.*

FESEM and MIP analysis validate that the compacted specimen of biochar-amended CL soil filled the pores spaces efficiently, which led to a decrease in hydraulic conductivity.

On the other hand, the FESEM image of SM soil at 2% biochar content showed a significant amount of unfilled pores in the specimen (Figure 4b). As shown in the grain size analysis, the SM soil consists of more sand particles (Table 1). Therefore, due to the dominance of large grain-size particles in the SM soil, more unfilled pores were observed in the soil-biochar specimen. Moreover, the MIP analysis of biochar-amended SM soil revealed an increase in mean pore diameter with biochar increment. Therefore, the MIP and FESEM analysis confirmed that the higher hydraulic conductivity in biochar-amended SM soil was due to an increase in the pore sizes of the specimen.

These observations marked that hydraulic conductivity is not only affected by biochar content but also by soil types. The hydraulic conductivity decreased for biochar amended CL soil and increased for biochar amended SM soil. The reduced hydraulic conductivity signifies that the landfill final cover layer constructed with this material (biochar amended CL soil) would decrease the seepage of water into lower landfill cover layers and thereby reduce the leachate generation rate and uneven decomposition of waste. However, the properties of biochar varies with age which may also alter the hydraulic conductivity of cover layer in future. Therefore, a time-dependent analysis is required to comprehend the hydraulic conductivity behaviour of BAS.

4 CONCLUSIONS

The current study demonstrated the effect of bamboo biochar amendment (0, 1, 2, 3.5 and 5% by weight) on the compaction and hydraulic conductivity characteristics of CL and SM soil. The index and basic physical properties of untreated soil and biochar were also analyzed. Based on the findings of the current investigation, the following conclusions can be drawn:

The compaction results of BAS showed that for both soils, the maximum dry density (MDD) decreased while the optimum moisture content (OMC) increased with the biochar addition. However, it was observed that the reduction in MDD was more in the CL than in the SM soil. In addition, the falling head permeability test results showed that the biochar amendment of 1% and 2% in the CL soil led to a decrease in hydraulic conductivity by 90% and 97%, respectively, compared to untreated CL soil. On the other hand, further increments of biochar (3.5% and 5%) showed an increase in hydraulic conductivity, although it was lower than the untreated CL soil. Moreover, the FESEM and MIP analysis confirmed that biochar addition filled more pore spaces in CL soil at lower biochar content (2%) compared to untreated CL soil, leading to a decrease in hydraulic conductivity.

In contrast to CL soil, a continuous increase in hydraulic conductivity was observed in SM soil with biochar increment. The hydraulic conductivity of SM soil was found to be increased by 686% and 1085% for the 2% and 5% addition of biochar, respectively, compared to untreated SM soil. Furthermore, the MIP and FESEM analysis showed that the biochar addition resulted in more pore spaces, leading to increased hydraulic conductivity of SM soil with biochar amendment.

The reduced hydraulic conductivity signifies that the biochar amended CL soil is a promising landfill final cover material. However, the hydraulic conductivity not only varies with soil types but also with the biochar and their age. Therefore, a time-dependent analysis on BAS is required to comprehend the hydraulic conductivity behaviour of BAS.

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