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Investigation of heat transfer in biochar-based thermal backfill for energy storage facilities

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ABSTRACT

To improve the efficiency of thermal energy storage systems like underground crude oil pipelines in permafrost zones, crude oil storage tanks, and subsurface cold storage, the designated temperature around those facilities must be maintained utilizing thermal backfill. Biochar is a highly chemically stable and low thermally conductive material, which makes it suitable as a backfill for thermal energy systems. However, the utilization of biochar in thermal energy storage units is barely explored. The present work investigates the heat transfer in biochar-based thermal backfill (BBTB) for energy storage facilities. The prohibition potential of heat transfer of BBTB was investigated by fabricating a soil-biochar composite column by amending 5% biochar with highly plastic silty soil. For heat transfer investigation, a heater rod was inserted at the center of the soil column, and temperature sensors were installed at different radial distances. The spatio-temporal distribution of temperature was measured during heating and ambient cooling. The study reveals that BBTB exhibits lower temperatures than bare soil. The maximum temperature difference between bare soil and BBTB was noted to be 11°C, primarily due to the lower thermal conductivity and thermal diffusivity of biochar. The newly proposed BBTB has shown the potential to restrict heat transfer from the source.

Keywords: Biochar, Thermal backfill, Heat-transfer, Energy storage facilities, Soil temperature distribution

1 INTRODUCTION

Underground thermal energy storage structures such as buried crude oil pipelines, subsurface cold storage, and geo-energy storage units are desired to have maximum thermal insulation for long-term heat storage to improve performance (Danielewicz et al., 2016; Başer et al., 2018; Otomi et al., 2020). These thermal energy storage structures are generally installed in surrounding locally available soils as backfills to enhance their performance. The primary purpose of thermal backfill is either to dissipate or prohibit heat migration from the source. The thermal characteristics of locally available soils are often inadequate for thermal backfill applications. Hence, it is required to amend the soils for desired thermal migration properties. Soil thermal characteristics such as thermal conductivity (K) and volumetric heat capacity (C) are among the important soil physical properties and dominate the conduction and distribution of heat in the soil. The values of soil thermal characteristics depend on the soil density, porosity, water content, gradation and type of soil, and its mineralogical composition (Abu-Hamdeh and Reeder, 2000; Sah and Sreedeep, 2014; Tong et al., 2020; Li et al., 2021). Therefore, these backfills could be engineered further by modifying the abovementioned attributes to develop a material that possesses suitable thermal characteristics with reduced heat migration.

It is expected that the proposed soil amendment material needs to be environmentally friendly. One such eco-friendly material is biochar, which is produced from the thermochemical decomposition of biomass in a confined compartment under low oxygen availability (Lehmann and Joseph, 2015; Patwa et al., 2022a). Biochar is a carbon-rich porous organic material that is lighter in density, has a low thermal conductivity value, and is highly chemically stable in soil (Patwa et al., 2021; Patwa et al., 2022a). Previous studies suggest that the addition of biochar-amended soil (BAS) has lower thermal characteristics compared to bare soil, which is influenced by the changes in total porosity, mineralogical composition of the soil, and bulk density of soil (Liu et al., 2018; Patwa et al., 2021). Primarily, biochar is a by-product of the bio-oil or biofuel production process through the thermochemical conversion of

waste biomass (Lehmann and Joseph, 2015). Thus, the application of biochar in large-scale engineering projects not only has the potential to develop an efficient thermal backfill for heat mitigation but also leads to waste management required for a circular economy strategy.

Recently, BAS has been proposed as thermal backfill material to mitigate the heat transfer from underground thermal energy storage structures owing to its low thermal characteristics and exceptional carbon stability (Patwa et al. 2021, 2022b, c). Heat transfer in the soil mainly depends upon the initial degree of saturation, thermal characteristics of the soil, porosity, and pore geometry of the soil matrix (Moradi et al., 2015, 2016). However, there is limited study on the investigation of heat transfer in biochar-amended soil (Zhang et al., 2015). Therefore, a bench-scale study on thermal insulation efficiency through biochar-based thermal backfill (BBTB) in terms of heat transfer is required to facilitate field-scale applications. This study investigates the spatio-temporal distribution of heat transfer in BBTB. For this purpose, a soil column was fabricated utilizing the locally available highly plastic silty soil and biochar prepared from the hardwood of mesquite. The heat transfer in the prepared soil column was investigated using a heater rod and temperature sensors installed in the radial direction in the soil column. Further, the micrographical analysis was carried out via Field-Emission Scanning Electron Microscopy (FESEM) to explain the mechanism of heat transfer in BBTB.

2 MATERIALS AND METHODS

2.1 Soil and biochar

The soil used in this study was collected from the campus of the Indian Institute of Technology Guwahati, Assam, North-east India. The gathered soil is easily accessible in the Guwahati region and is frequently utilized as filling material. The dead roots and small stones were manually removed from the collected soil and were further sieved through a 4.75 mm sieve. The soil was tested for specific gravity (Gs), particle size gradation, and Atterberg limit according to ASTM standards (ASTM D854-2014; ASTM D422-63-2007; ASTM D4318-10). The compaction characteristics (i.e., optimum moisture content, OMC and maximum dry density, MDD) of bare soil and BAS were determined by following the guidelines recommended in ASTM standard (ASTM D698-12). The soil was classified as inorganic silt of high plasticity (MH) based on the USCS (ASTM D 2487-11). The basic characterization of soil is presented in Table 1.

Table 1. *Basic physical properties of the studied soil*

Properties	Value
Location coordinates	26.19 ˚N; 91.69 ˚E
Ambient temperature (℃)	29±3 ℃
Specific gravity, Gs	2.71±0.04
Particle size gradation (%)	
Coarse sand (4.75mm–2 mm)	0.8
Medium sand (2mm–0.425 mm)	12.1
Fine sand (0.425mm–0.075 mm)	9.1
Silt (0.075mm-0.002mm)	39.74
Clay (< 0.002 mm)	38.26
Atterberg limits (%)	
Liquid limit	54.45±1.56
Plastic limit	35.27±1.16
Shrinkage limit	30.14±1.11
Plasticity index	19.18
USDA soil classification	Clay loam
USCS soil classification	MH
Taxonomy	Ultisols
Specific surface area (m^2/g)	41.15±1.28

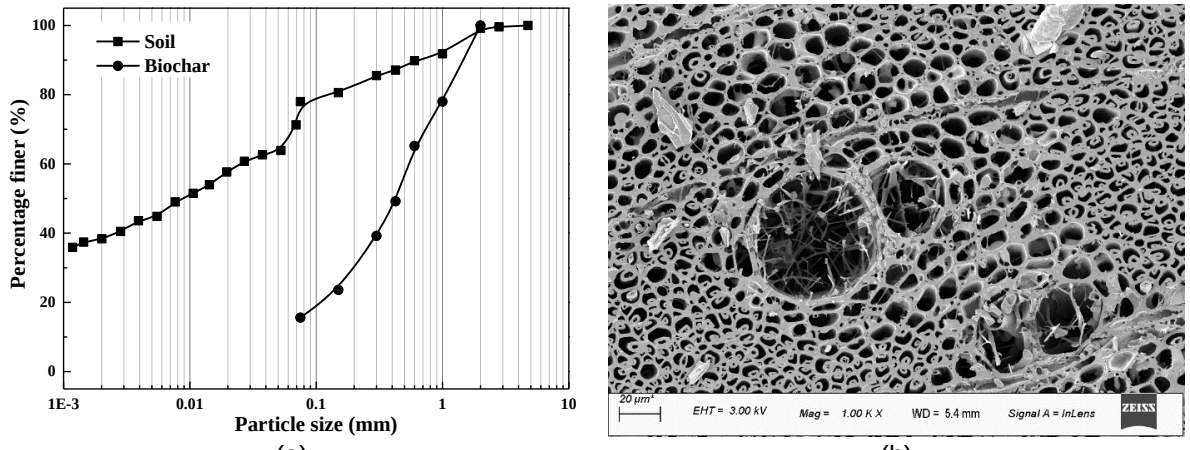
A commercial biochar prepared from the hardwood of mesquite (*Prosopis juliflora*) as feedstock at a pyrolysis temperature of 500°C and 45-minute residence time (Greenfield Eco Solutions Private Limited, Rajasthan, India) was used in this study. The granular biochar was grounded to a smaller size using the grinder. Thereafter, it was sieved through a 2 mm sieve and stored in an airtight container for subsequent testing. The basic characterization of biochar is presented in Table 2. The particle size distribution of soil and biochar is presented in Figure 1(a). The surface morphology of biochar captured using field

emission scanning electron microscopy (FESEM) is displayed in Figure 1(b). The inclusion of lignin, cellulose, and hemicellulose polymer in wood biomass results in a honeycomb structure of intra-pores in biochar. During pyrolysis, cellulose and hemicellulose break down first, followed by lignin. The porous nature of biochar is due to this thermal breakdown. The procedure adopted for the characterization of soil and biochar has been explained in detail by Patwa et al. (2021).

Table 2. *Characteristics of selected biochar*

Properties	Values
Proximate Analysis (%)	
Moisture content	10.11±1.02
Volatile matter	12.81±1.01
Ash content	2.12±0.11
Fixed carbon[a]	74.96
Ultimate Analysis (%)	
Carbon (C)	74.01
Hydrogen (H)	3.05
Nitrogen (N)	0.18
Oxygen (O)	20.64
Atomic ratios	
H/C	0.49
O/C	0.21
C/N	479.69
pH	7.79 ± 0.03
EC (mS/cm)	0.560±0.02
Zeta potential (mV)	-27.2±1.2
Water holding capacity (%)	212.07±5.0
Specific gravity	1.498±0.05
Specific surface area (m^2/g)	100.729
Average pore diameter (nm)	2.723
Total pore volume (cm^3/g)	0.068

[a] By difference; Values are denoted as mean value ± standard deviation



(a) (b)

Figure 1. *(a) Particle size gradation of soil and biochar; (b) Surface morphology of biochar*

2.2 Experimental setup

The soil heating system used in this study, as shown in Figure 2, contains the heater rod, temperature sensor, and temperature controller. A nichrome wire wrapped around a ceramic core having a length of 190 mm and diameter of 15 mm with 1000 W power was used as the heater rod. A temperature thermistor was used to measure the temperature (ACETEQ, Model No. DTM-X7). The diameter and measurement range of this thermistor probe is 2.5 mm and -50°C to 300 °C, respectively. The accuracy of this sensor is ±1°C for the temperature range of -10°C to +110°C. A digital thermostat temperature controller switch was also used to control the temperature of the heater rod. The measurement and

control range of this temperature controller is -50°C to 110°C. The control precision and measuring accuracy of this controller is ±0.1 °C and ±0.2 °C. The controlling temperature in the temperature controller was set to 100±1 °C.



Figure 2. *Soil heating system (a) Electric heating rod; (b) Temperature measurement thermistor; (c) Temperature controller*

Figure 3 shows the schematics diagram and photograph of the experimental setup used for the measurement of heat transfer in bare and BAS. A cylindrical acrylic mold with an internal diameter of 300 mm and a height of 250 mm with a base plate was fabricated for preparing the soil column. Howards (1996) recommended that the thermal backfill should be compacted at a minimum of 95% maximum dry density and ± 2% of optimum moisture content. Thus, the bare soil and BAS samples were prepared at OMC and 0.95MDD according to the compaction characteristics of soil and BAS. Liu et al. (2018) documented that the BAS with an amendment rate from 0.5% to 2.5% did not notably influence the thermal characteristics of the soil. Therefore, the biochar amendment rate in the current study was chosen as 5% by the total dry weight of the composite.

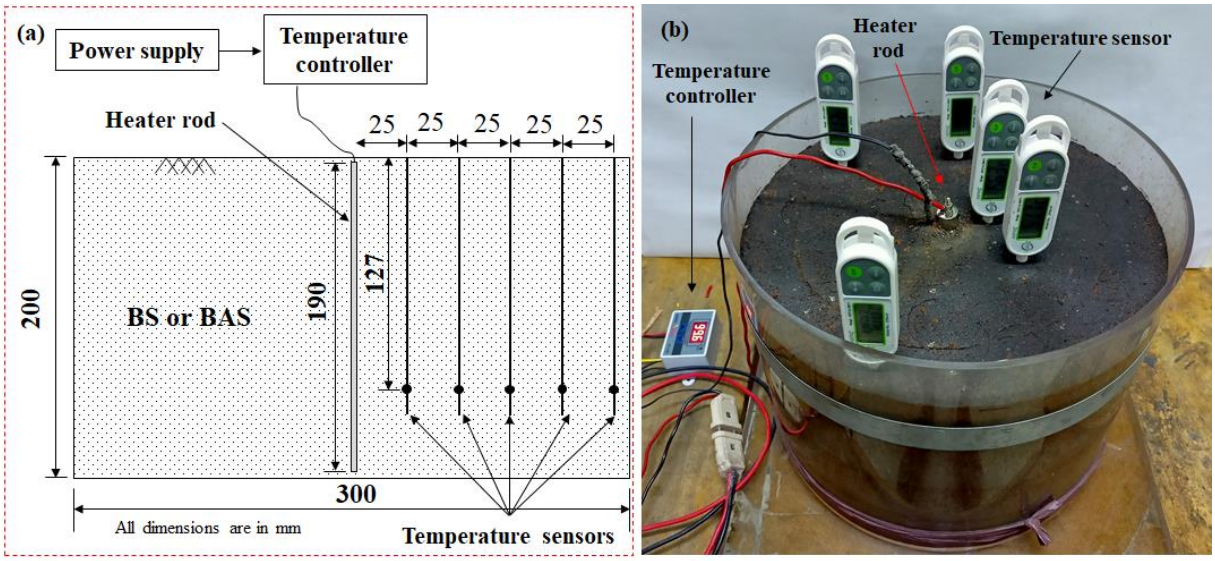


Figure 3. *Experimental setup (a) sectional view (b) Photographic view*

The following test procedures were followed for the preparation of the soil column and measurement of the temperature distribution in soil and BAS. A calculated amount of oven-dried soil and biochar were weighed considering the volume of mold and target density. Thereafter, the weighed soil mass and biochar were homogenously mixed with calculated amount distilled water which is equal to the target moisture content of the composite on a glass plate using the spatulas. The moist soil or soil-biochar mixture was kept in sealed plastic bags for 24 hours in a desiccator for uniform mixing. The soil-biochar mix was then compacted to a target dry density of 0.95 MDD. A dummy steel rod of a diameter slightly less than the heater rod was placed at the center during compaction. The heater rod was inserted in the center of the soil column after removing the dummy rod. The temperature probe was installed at a radial distance of 25, 50, 75, 100, and 125 mm from the heater rod, as shown in Figure 3 (a and b). Thereafter, the heater rod was connected to an electric power supply, and the temperature in the heater rod was

controlled using a temperature controller. Subsequently, the temperatures were measured at different radial distances from the heater rod until they attained a constant value, termed the heating cycle in the current study. Further, the heater rod was switched off, and the decreasing temperature was measured again at different radial distances, termed ambient cooling in the current study. The same procedure was repeated for the second cycle of heating and ambient cooling.

3 RESULTS AND DISCUSSION

3.1 Compaction characteristics of BAS

The compaction characteristics (variation of OMC and MDD) of bare soil and soil amended with 5% biochar content are presented in Figure 4. It is noted from Figure 4 that adding biochar to bare soil enhances OMC and decreases MDD. A decrease in the MDD value of soil was noted from 1.58 Mg/m^3 to 1.46 Mg/m^3 upon 5% biochar amendment. The decrease in density is mainly credited to the substitution of heavier soil particles with lighter biochar particles. Further, adding biochar increased the porosity and entrapped the air in the soil, decreasing the soil's compressibility at given compaction energy and reducing the dry density of soil (Reddy et al., 2015). On the contrary, the OMC of soil was found to be increased from 22.72% to 26.25% upon 5% biochar amendment. The higher OMC of BAS is credited to the larger surface area and higher porosity of biochar particles that enhanced the water absorption of BAS (Blanco-Canqui, 2017).

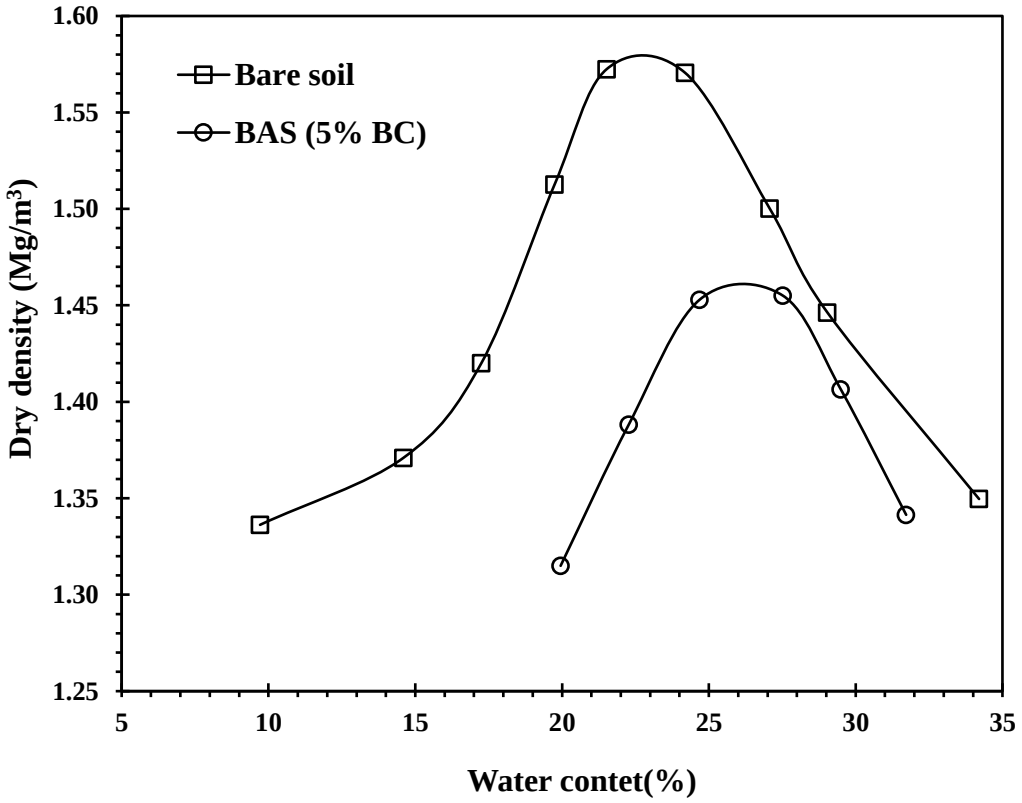


Figure 4. *Compaction characteristics of soil and BAS*

3.2 Thermal characteristics of biochar

The *K* and *C* value of the hardwood biochar (HWBC) employed in this study was noted to be 0.130 Wm^{-1}K^{-1} and 0.713 MJm^{-3} K^{-1} (refer to Table 3). The observed *K* value was notably lower than the value of quartz (7.7 Wm^{-1}K^{-1}), clay (1.5 Wm^{-1}K^{-1}), and water (0.595 Wm^{-1}K^{-1}, at 20 °C) (Lu et al., 2007). The average *C* value of soil solids (2.025 MJm^{-3} K^{-1}) and water (4.184 MJm^{-3} K^{-1}) is higher than the above-documented value of biochar from the current study. The presence of air in the intra-pores of the biochar skeleton accounts for the lower *K* and *C* values of biochar, which is also endorsed by the FESEM micrographs of biochar, as presented in Figure 1b. Therefore, the amendment of biochar in soil is expected to reduce the heat transfer in thermal backfill.

Table 3. *Thermal Characteristics of soil and biochar*

Soil/ Biochar	Thermal conductivity, (W/m K)	Volumetric heat capacity, ($MJ/m^3 K^1$)	Dry density, (Mg/m^3)
Soil	0.209±0.102	1.145±0.065	1.201±0.009
HWBC	0.130±0.002	0.713±0.016	0.420±0.007

3.3 Temperature migration in BAS

Figure 5 and Figure 6 show the temporal variation of soil column temperature at a radial distance of 25, 50, 75, and 100 mm from the heat source for bare soil and BAS in the first and second cycles of heating and ambient cooling. The red and blue colour data points denotes temperature value during heating and ambient cooling. For the sake of brevity, temporal variation at a radial distance of 125 mm is not presented, which also gave a similar trend. It was observed from Figure 5 that assessment of the soil temperature suggests that the steady-state conditions were achieved within 200 hours at all radial distances in the first cycle of heating. In contrast, the steady-state conditions were achieved within 30 hours in the second cycle of heating. Moreover, in both cycles of ambient cooling, the steady-state conditions were achieved within 30 hours. The thermal diffusivity of soil primarily governs the rate of heat conduction through the soil. The longer period for the first heating cycle is primarily due to the smaller thermal diffusivity of wet soil compared to dry soil, which is attributed to the lesser thermal diffusivity of water (0.147 $mm^2 s^{-1}$) as compared to air (23.5 $mm^2 s^{-1}$). Further, a peak in soil temperature was noted at around 10 hours for both bare and BAS at all radial distances in the first heating cycle, while no peak value was observed in the second heating cycle (refer to Figure 6).

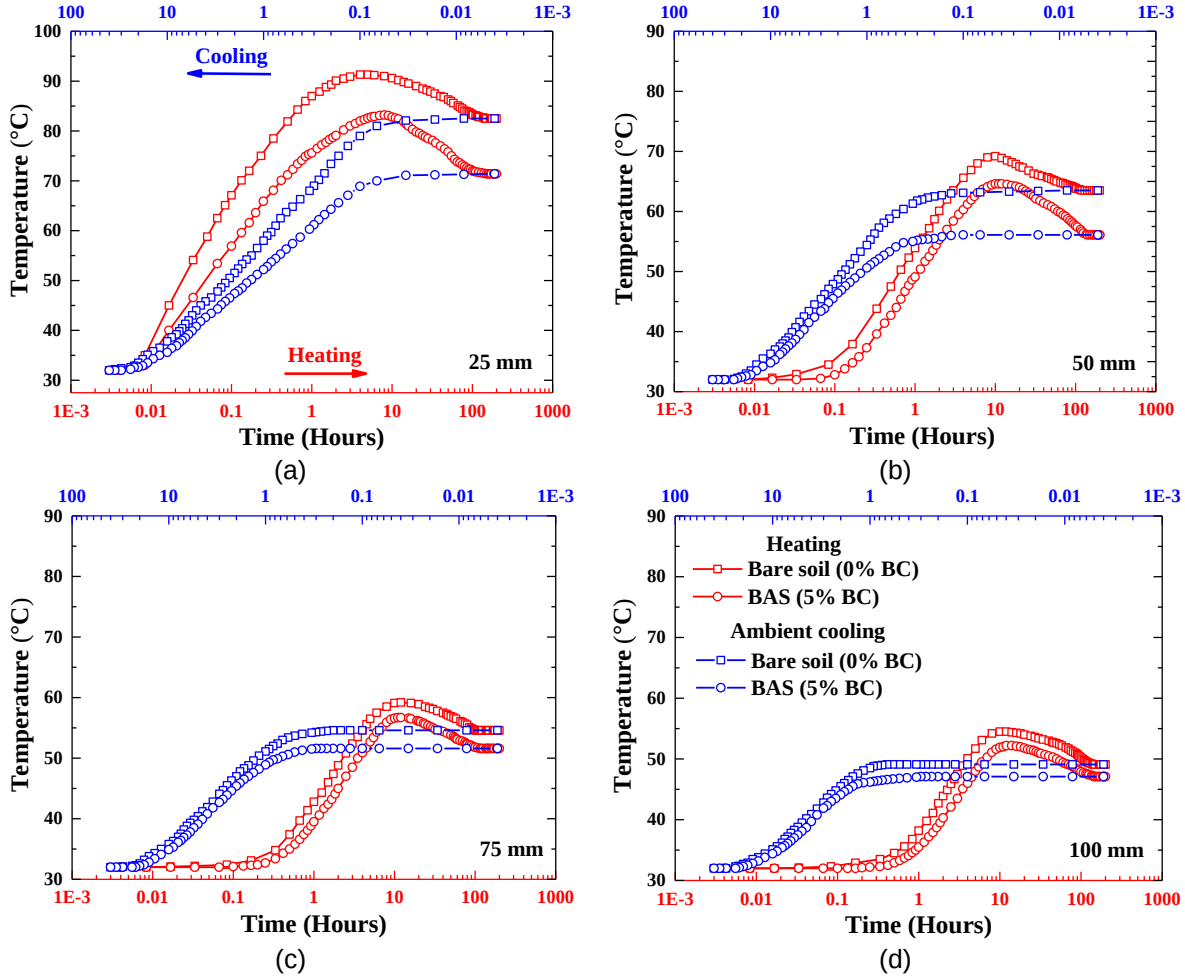


Figure 5. *Temporal distribution of soil temperature at (a) 25; (b) 50; (c) 75; and (d) 100 mm radial distances in the first cycle of heating and ambient cooling*

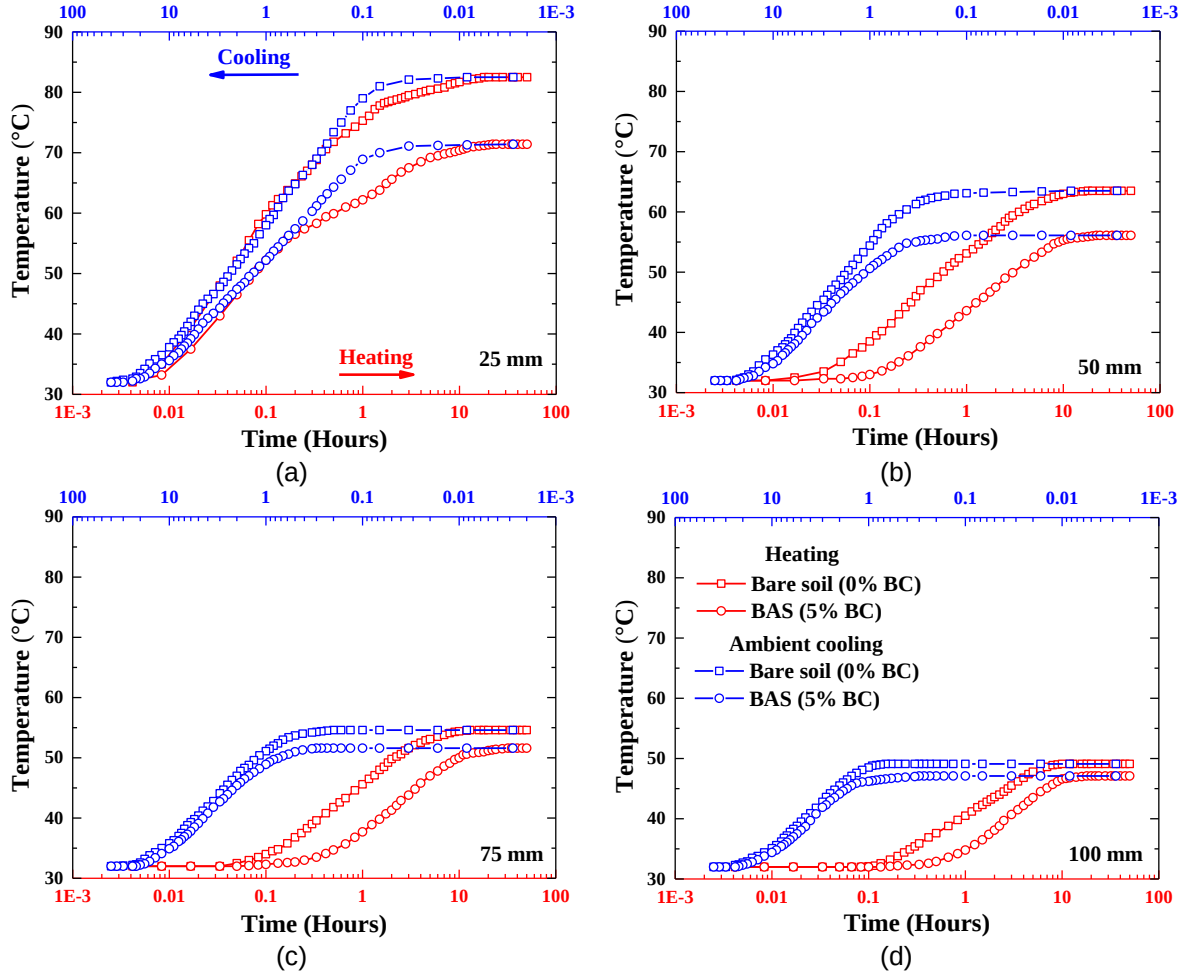


Figure 6. *Temporal distribution of soil temperature at (a) 25; (b) 50; (c) 75; and (d) 100 mm radial distances in the second cycle of heating and ambient cooling*

The peak value in the first heating cycle is attributed to the heat transfer due to the continuous generation of water vapor in wet soil. The water vapor has higher thermal diffusivity compared to water, which increases the heat transfer in the initial phase. Afterward, it decreases consistently and reaches a steady state around 200 hours. In addition, an increase in lag in measured temperature value was also noted with an increase in radial distance from the heat source. This might be attributed to the higher thermal resistance at a greater distance from the heat source. Moreover, an increase in lag in measured temperature value was also found in BAS compared to bare soil, primarily due to the lower thermal conductivity and thermal diffusivity of biochar. Additionally, it is noteworthy from Figure 5 and Figure 6 that the margin of decrease in temperature value of BAS concerning bare soil was noted to be reduced with an increase in radial distance from the heat source for all elapsed time. A minimal difference in temperature reduction value was observed between the 100 mm and 125 mm radial distances for bare and BAS. A probable reason for this can be credited to the critical influence zone of the heat source. Therefore, it is suggested to provide the insulation of the BAS layer up to a certain thickness only, as there is not much difference in the temperature reduction of BAS compared to bare soil after a certain radial distance from the heater source.

A systematic investigation of the microstructure of soil-biochar composite was carried out to comprehend the mechanics behind the thermal insulation efficiency of soil-biochar composite through micrographical analysis. FESEM was utilized to examine the surface morphology of soil-biochar composite on a Zeiss Gemini 300 (Oberkochen, Germany) instrument. A small amount of sample was taken out from the soil column of BAS after the completion of both the heating and ambient cooling cycle. The sample was oven-dried using a hot air oven, mounted on an aluminum stub, and the sample was coated with a 20 nm gold coating for SEM analysis. From Figure 7, it is evident that the biochar particles are entrapped between the soil grains, posing a barrier to heat transfer and increasing the thermal insulation efficiency of BAS.

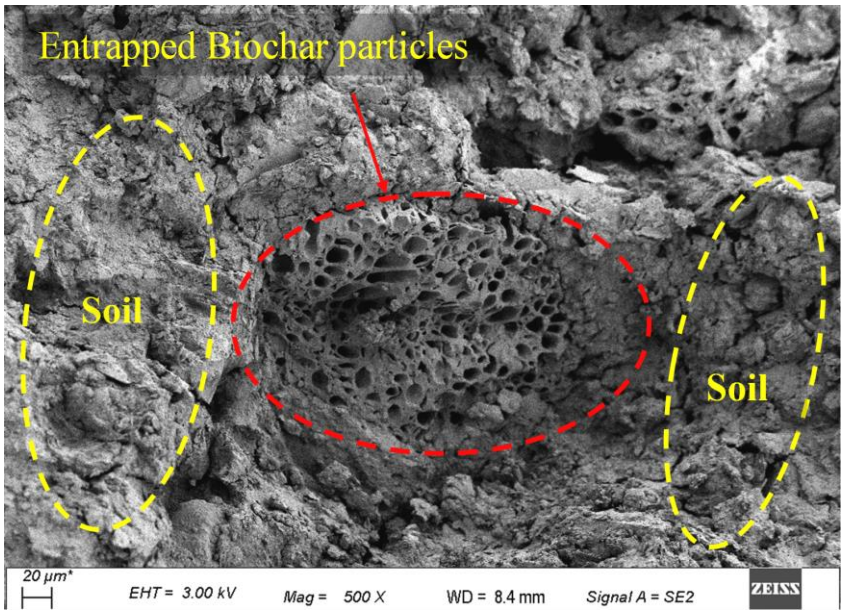


Figure 7. *FESEM micrographs of BAS sample highlighting the intra-porous biochar-soil matrix*

Figure 8 presents the temperature variation with radial distance in bare soil and soil amended with different biochar content at the elapsed time of 0.5, 1, 10, and 100 hours in the first cycle of heating. It can be seen from the figure that the temperature decreases with an increase in radial distance from the heat source in both bare and BAS.

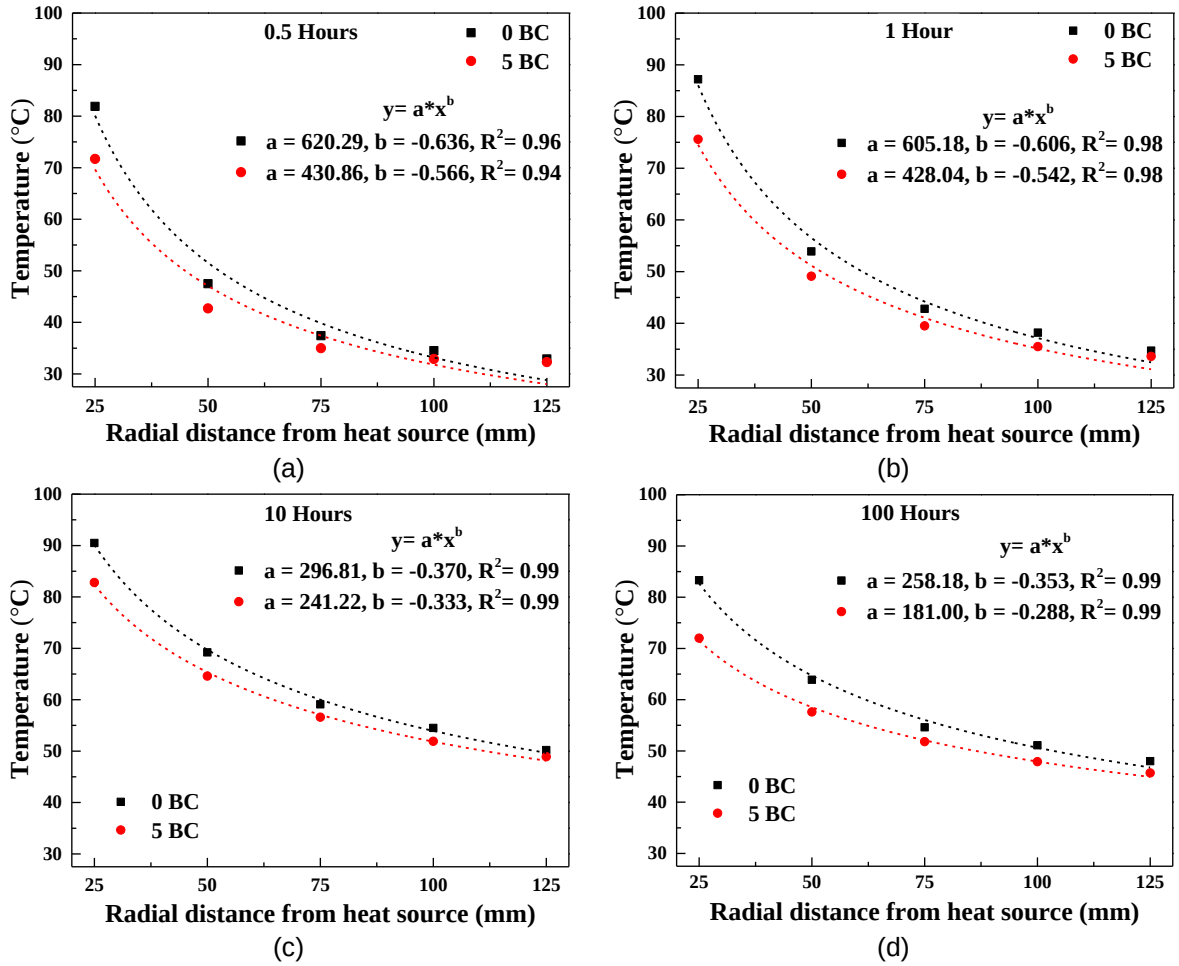


Figure 8. *Temperature variation according to radial distance from heater rod (a) 0.5 hours; (b) 1 hour; (c) 10 hours; and (d) 100 hours*

The test results were best fitted, and a non-linear inverse power function correlation ($R^2 > 0.95$) between temperature and radial distance was observed for bare soil and BAS. Moreover, it is remarkable to point out from Figure. 8 that the margin of decrease in temperature value of BAS with respect to bare soil was noted to be reduced with an increase in radial distance from the heat source for all elapsed time. A probable reason for this can be credited to the critical influence zone of the heat source.

4 CONCLUSIONS

This study explores the investigation of heat migration in biochar-amended soil (BAS). A soil column was fabricated by mixing the soil with hardwood biochar and compacted at the dry density of 95% of maximum dry density and optimum moisture content condition in an acrylic mold. Thereafter, the heater rod and temperature sensors were installed in the mold to measure temperature distribution during heating and ambient cooling. The following results can be drawn based on the investigation:

1) The BAS exhibits lower temperatures compared to bare soil at all radial distances and times for both the heating and cooling cycles. This is mainly ascribed to the entrapment of biochar particles between the soil particles that have lower thermal conductivity and thermal diffusivity than bare soil.

2) An increase in temperature lag was found in BAS than in bare soil, primarily due to the lower thermal conductivity and thermal diffusivity of biochar.

3) The margin of decrease in temperature value of BAS with respect to bare soil was noted to be reduced with an increase in radial distance from the heat source. Thus, it is suggested to provide the insulation of the BAS layer up to a certain thickness only. Further studies are needed to recommend the threshold thickness.
4) A non-linear inverse power function correlation ($R^2 > 0.95$) between temperature and radial distance was observed for both bare soil and BAS.

The finding of the study unravels the potential of biochar-based thermal backfill to restrict heat transfer from energy storage facilities. Therefore, the proposed BAS can be utilized effectively as a thermal backfill material for buried crude oil pipelines, crude oil storage tanks, and subsurface cold storage to improve their performance.

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REFERENCES

Abu-Hamdeh, N. H., & Reeder, R. C. (2000). Soil thermal conductivity effects of density, moisture, salt concentration, and organic matter. Soil science society of America Journal, 64(4), 1285-1290.

ASTM. 2007. Standard test method for particle-size analysis of soils. ASTM D422-63. West Conshohocken, PA: ASTM.

ASTM. 2010. Standard test methods for liquid limit, plastic limit, and plasticity index of soils. ASTM D4318-10. West Conshohocken, PA: ASTM.

ASTM. 2011. Standard practice for classification of soils for engineering purposes (unified soil classification system). ASTM D2487. West Conshohocken, PA: ASTM.

ASTM. 2012. Standard test methods for laboratory compaction characteristics of soil using standard effort. ASTM D698-12. West Conshohocken, PA: ASTM.

ASTM. 2014. Standard test methods for specific gravity of soil solids by water pycnometer. ASTM D854. West Conshohocken, PA: ASTM.

Başer, T., Dong, Y., Moradi, A. M., Lu, N., Smits, K., Ge, S., ... & McCartney, J. S. (2018). Role of nonequilibrium water vapor diffusion in thermal energy storage systems in the vadose zone. Journal of Geotechnical and Geoenvironmental Engineering, 144(7), 04018038.

Blanco-Canqui, H. (2017). Biochar and soil physical properties. Soil Science Society of America Journal, 81(4), 687-711.

Danielewicz, J., Śniechowska, B., Sayegh, M. A., Fidorów, N., & Jouhara, H. (2016). Three-dimensional numerical model of heat losses from district heating network pre-insulated pipes buried in the ground. Energy, 108, 172-184.

Howard AK (1996) Pipe bedding and backfill geotechnical training manual no. 7 Second Edition. In: United States Dep. Inter. Bur. Reclam. https://www.usbr.gov/tsc/techreferences/mands/mandspdfs/pipebed.pdf

Lehmann, J., and S. Joseph, eds. 2015. Biochar for environmental management: Science, technology and implementation. New York: Routledge.

Li, K. Q., Li, D. Q., Chen, D. H., Gu, S. X., & Liu, Y. (2021). A generalized model for effective thermal conductivity of soils considering porosity and mineral composition. Acta Geotechnica, 16(11), 3455-3466.

Liu, Z., Xu, J., Li, X., & Wang, J. (2018). Mechanisms of biochar effects on thermal properties of red soil in south China. Geoderma, 323, 41-51.

Lu, S., Ren, T., Gong, Y., & Horton, R. (2007). An improved model for predicting soil thermal conductivity from water content at room temperature. Soil Science Society of America Journal, 71(1), 8-14.

Moradi, A., Smits, K. M., Massey, J., Cihan, A., & McCartney, J. (2015). Impact of coupled heat transfer and water flow on soil borehole thermal energy storage (SBTES) systems: Experimental and modeling investigation. Geothermics, 57, 56-72.

Moradi, A., Smits, K. M., Lu, N., & McCartney, J. S. (2016). Heat transfer in unsaturated soil with application to borehole thermal energy storage. Vadose Zone Journal, 15(10), 1-17.

Otomi, O. K., Onochie, U. P., & Obanor, A. I. (2020). Steady state analysis of heat transfer in a fully buried crude oil pipeline. International Journal of Heat and Mass Transfer, 146, 118893.

Patwa, D., Chandra, A., Ravi, K., & Sreedeep, S. (2021). Influence of biochar particle size fractions on thermal and mechanical properties of biochar-amended soil. Journal of Materials in Civil Engineering, 33(9), 04021236.

Patwa, D., Bordoloi, U., Dubey, A. A., Ravi, K., Sekharan, S., & Kalita, P. (2022a). Energy-efficient biochar production for thermal backfill applications. Science of The Total Environment, 833, 155253.

Patwa, D., Muigai, H. H., Ravi, K., Sreedeep, S., & Kalita, P. (2022b). A novel application of biochar produced from invasive weeds and industrial waste in thermal backfill for crude oil industries. Waste and Biomass Valorization, 13(6), 3025-3042.

Patwa, D., Ravi, K., & Sreedeep, S. (2022c). Influence of initial molding parameters and natural moisture migration on biochar-based soil composite for thermal backfills applications. Acta Geophysica, 1-19.

Reddy, K. R., Yaghoubi, P., & Yukselen-Aksoy, Y. (2015). Effects of biochar amendment on geotechnical properties of landfill cover soil. Waste Management & Research, 33(6), 524-532.

Sah, P. K., & Sreedeep, S. (2014). Evaluation of bentonite-based thermal backfill materials. Environmental Geotechnics, 1(3), 179-188.

Tong, B., Kool, D., Heitman, J. L., Sauer, T. J., Gao, Z., & Horton, R. (2020). Thermal property values of a central Iowa soil as functions of soil water content and bulk density or of soil air content. European Journal of Soil Science, 71(2), 169-178.

Zhang, J., Chen, Q., & You, C. (2015). Numerical simulation of mass and heat transfer between biochar and sandy soil. International Journal of Heat and Mass Transfer, 91, 119-126.