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Influence of hydrochar addition on the hydraulic properties of compacted soils

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ABSTRACT: Hydrochar, a biomass-derived carbon-rich material produced by the hydrothermal carbonisation (HTC) process, has been considered as a low-cost, sustainable and environmentally friendly material to amend the soil hydraulic properties. However, there is a lack of comprehensive research on how hydrochar production temperature affects soil hydraulic properties at the same compaction dry density. This study measured the hydraulic properties including saturated hydraulic conductivity (k_s) and water retention curves (WRCs) of a compacted soil amended with different mass proportions of hydrochar that were derived at two production temperatures (180 °C and 240 °C, denoted as H1 and H2) under two dry densities. At lower dry density, both the addition of H1 and H2 increased k_s. Beyond thresholds (2.5% for H1, 5% for H2), k_s decreased but remained higher than the unamended soil. At higher dry density, the threshold shifted to 1% for both H1- and H2-amended soil, with k_s falling below the unamended soil. Hydrochar addition changed soil volumetric behavior from wetting-induced collapse to swelling, with greater swelling at higher mass proportion. Drying-induced soil shrinkage was reduced by hydrochar addition at the measured suction range. Both the addition of H1 and H2 increased soil air entry value and water retention capability. As suction increased to 150 kPa, the volumetric water content of all unamended and amended specimens converged to a similar value, indicating that the enhancement effect of hydrochar on soil WRC is limited to the low suction range, making it more suitable for humid and semi-humid regions.

KEYWORDS: Hydrochar-amended soil, dry density, production temperature, saturated hydraulic conductivity, water retention curve.

1 INTRODUCTION

Soil is often heavily compacted to satisfy the load-bearing requirements, which can be a major cause of urban flooding issues. Indeed, soil compaction leads to poor drainage (Bullock and Gregory 2009) and has been determined to be responsible for the increase in flood vulnerability, especially under the negative impact of irreversible environmental change and extreme precipitation events (Alaoui et al. 2018). Extreme drought and precipitation events also exacerbate the negative impacts on the slope stability and the health of plants covering the slopes. It is thus vital to explore sustainable and environmentally friendly solutions to improve the drainage characteristics and water retention capacity of urban soils to reduce flooding risks, while also supporting plant growth.

Hydrochar is a carbon-rich material produced by the hydrothermal carbonisation (HTC) process under a temperature of 180-260 ºC with an autogenous pressure (Kambo & Dutta 2015). This process occurred in water and does not require the pre-drying procedure and produce minimal toxic gases (2%-5%, Qambrani et al. 2017). The solid yield associated with the HTC process is called hydrochar. Previous studies have demonstrated the effectiveness of hydrochar for contaminant removal (Fang et al. 2015), biofuel energy (Singh et al. 2017) and plant growth (Dieguez-Alonso et al. 2018) due to their high adsorption ability, calorific value and nutrient availability. Some previous studies have shown that hydrochar could improve the saturated hydraulic conductivity (k_s) and water retention curves (WRCs) of soil. Results of Eibisch et al. (2015) showed that both the addition of digestate- and woodchip-derived hydrochars increased the k_s and WRCs of loamy sand. And the decrease in the hydrochar HTC temperature increased the plant available water content. Kalderis et al. (2019) reported a nonlinear increase of k_s as the mass proportion of hydrochar derived from orange peel feedstock increased. Röhrdanz et al. (2016) found that the increase in HTC reaction severity (production temperature and reaction time) decreased the water holding capacity of quartz sand. However, there has been a lack of comprehensive studies examining the effects of hydrochar production temperature on both the k_s and WRC of compacted soil. Moreover, the existing studies compared the hydraulic properties of hydrochar-amended soils without controlling the void ratio. Indeed, hydrochar is normally lighter than mineral soil, and its addition could affect the initial void ratio of soils if the same compaction effort is applied to prepare soil samples. Therefore, the influence of hydrochar on the soil are co-affected by the differences in the initial void ratios and the soil microstructural changes due to the additions of hydrochar. The compaction dry density influence on the hydraulic properties of hydrochar-amended soil remained unclear.

This study aims to investigate the influence of hydrochar on the hydraulic properties (k_s and WRC) of a silty-clay sand. The effects of compaction dry density, hydrochar production temperature and particle size on the k_s of soil were examined using a flexible wall permeameter. The WRCs of soils amended by hydrochar of different production temperatures were measured using a volumetric pressure-plate extractor. Mercury intrusion porosimetry (MIP) tests were conducted to assist in the interpretation of experimental results. This study could inform the application of hydrochar-amended soils in urban and ecological engineering scenarios.

2 MATERIALS AND METHODS

2.1 *Test materials*

The tested soil was an orangish brown completely decomposed volcanic (CDV) taken from a construction site in Hong Kong. The soil was composed of 83.6% sand (2 mm ~ 63 μm), 12.7% silt (63 μm ~ 2 μm), and 3.7% clay (⩽ 2 μm). The liquid limit and plasticity index were 36.5% and 12.1%, respectively. Based on the standard (ASTM 2011), the soil was classified as SC-SM (silty, clay sand). The soil had a maximum dry density of 1.7 g/cm^3 with an optimum water content of 21.1%.

The hydrochar was produced using clippings of *Axonopus compressus* grass. The feedstock was immersed in water and heated to a temperature of 180 or 240 ºC using a stirred pressure reactor. After production, the solid yield was filtered and oven dried. The hydrochar was milled, sieved, and proportioned to replicate the soil's particle size distribution: 83.6% sand (2 mm ~ 63 μm) and 16.4% fine fraction (⩽ 63 μm), aiming to isolate the particle size effects on the k_s. The derived hydrochar at 180 and 240 ºC were denoted as H1 and H2, respectively. Increasing HTC temperature decreased the hydrochar particle size due to the more severe particle breakage by the stirrer and the more pronounced hydrolysis reactions (Li et al. 2018). The hydrochar produced at higher temperature of 240 ºC was passed through 0.025 mm sieve to obtain finer particles (denoted as H2(f)) to investigate the particle size effects. Basic physiochemical properties of hydrochar are summarised in Table 1.

Table 1. Physicochemical properties of tested hydrochar.

Type	Specific gravity	Specific surface area (m^2/g)	Ash Content	pH
H1	1.55±0.04	4.23±0.09	9.73±0.32	4.59±0.12
H2	1.63±0.04	5.12±0.07	16.40±0.97	4.80±0.09

Note: Analysis performed in three replicates (mean±standard deviation).

2.2 *Specimen preparation*

The soil was mixed with H1, H2 or H2(f) at four different mass proportions (f_H) of 0, 1%, 2.5%, 5% and 10%. Water was added to the mixtures to reach the optimal moisture content of 21.1%. The wet mixtures were passed through a 2 mm sieve and stored for 24 h for moisture equalisation. Two target dry densities of 1.4 and 1.6 g/cm^3 (i.e., corresponding to 80% and 95% degree of compaction of the unamended soil, respectively) were selected for investigation. Specimens were statically compacted to the target dry density to form specimens that have the same dimension of 70 mm for the diameter and 70 mm for the height. Detailed test program for k_s tests is summarised in Table 2.

For WRC tests, two dry densities of 1.4 and 1.6 g/cm^3, two hydrochars of H1 and H2, and three mass proportions of 0, 5% and 10% were considered. Specimens were statically compacted in three layers using an oedometer ring with a diameter of 61.8 mm and a height of 20 mm. Each specimen was sandwiched by a pair of filter paper and a pair of porous stones using a clamp, after which the assembly was placed inside a chamber for saturation under vacuum pressure. Each specimen was weighted to check its degree of saturation, and all specimens showed a degree of saturation larger than 97%. Then each specimen was transferred to a pressure plate extractor for WRC measurement. Detailed test program and as-compacted properties are summarised in Table 3.

Table 2. Test program for k_s tests.

Series	Target dry density (g/cm^3)	Mass proportion f_H (%)	Specimen ID
Soil	1.4 (low density)	0	S-L
Soil + H1		1	H1-1%L
		2.5	H1-2.5%L
		5	H1-5%L
		10	H1-10%L
Soil + H2		1	H2-1%L
		2.5	H2-2.5%L
		5	H2-5%L
		10	H2-10%L
Soil + H2(f)		1	H1(f)-1%L
		2.5	H2(f)-2.5%L
		5	H2(f)-5%L
		10	H2(f)-10%L
Soil	1.6 (high density)	0	S-H
Soil + H1		1	H1-1%H
		2.5	H1-2.5%H
		5	H1-5%H
		10	H1-10%H
Soil + H2		1	H1-1%H
		2.5	H2-2.5%H
		5	H2-5%H
		10	H2-10%H

Table 3. Test program and as-compacted properties of the specimens for WRC tests.

Series	Target dry density (g/cm^3)	Specimen ID	Initial void ratio e_0	Saturated void ratio e_sat	Saturated water vontent w_sat
Soil	1.36	S-L	0.907	0.895	0.338
Soil + H1		H1-5%L	0.846	0.873	0.345
		H1-10%L	0.801	0.908	0.369
Soil + H2		H2-5%L	0.858	0.873	0.344
		H2-10%L	0.809	0.901	0.366
Soil	1.62	S-H	0.607	0.635	0.242
Soil + H1		H1-5%H	0.549	0.655	0.260
		H1-10%H	0.516	0.706	0.286
Soil + H2		H2-5%H	0.562	0.611	0.241
		H2-10%H	0.522	0.611	0.248

2.3 *Test instrument and procedures*

2.3.1 *k_s tests*

The k_s of unamended and hydrochar-amended soil was measured by a flexible wall permeameter. After specimen setup, a small confining pressure of 20 kPa was applied for 24 h. The specimen was bottom-up and then back-pressure saturated to achieve a B-value higher than 0.95. Following the standard (ASTM 2016), a hydraulic gradient was applied and maintained to be less than 10 during measurement. In each test, when the ratio of water inflow rate to outflow was between 0.75 to 1.25, a steady-state measurement of k_s was taken. At least four measurements were made and the final value of k_s was determined by averaging any three measurements with a variation less than ±10%. The k_s value was calculated based on the falling head- rising tailwater method.

2.3.2 *WRC tests*

The WRC of unamended and hydrochar-amended soil was measured using a volumetric pressure-plate extractor with a 2-

bar ceramic disk. To obtain more accurate measurements, suctions lower than 6 kPa were controlled by the hanging-column method. For suctions larger than 6 kPa, the suction was applied and controlled, in steps, by changing the air pressure of the airtight chamber of the extractor. Any vertical displacement of each specimen was measured by a dial gauge that has a resolution of 0.001 mm. Suction equilibrium was deemed to be reached when the variations of water content of each specimen with time was less than 0.04%/day (Sivakumar 1993).

After WRC tests, MIP tests were conducted on both unamended and hydrochar-amended specimens with varying dry densities and mix proportions.

3 RESULTS AND DISCUSSION

3.1 *Effects of hydrochar temperature on the k_s*

Figure 1 illustrates the effects of incorporating H1 and H2 on the k_s of soil at the lower density of 1.4 g/cm^3. As the mass proportion increased to 2.5%, k_s increased from 2.8×10^{-7} (S_L) to 1.6×10^{-6} m/s (H1-2.5%L) and 1.2×10^{-6} m/s (H2-2.5%L), respectively. This could be attributed to the increase in large pore volume by hydrochar addition (Dong et al. 2024). As the mass proportion increased to 5%, the k_s of H1-5%L started to drop while the k_s of H2-5%L reached its highest value of 3.1×10^{-6} m/s. The k_s of H2-amended soil decreased as the mass proportion further increased to 10%. The reduction in k_s was related to the pore filling effects of hydrochar particles and the pore compression induced by increased compaction energy (Dong et al. 2023). Considering that both H1 and H2 has a smaller specific gravity than the soil, and H1 has a smaller gravity than H2 (Table 1), a larger pore volume of H1 was needed to replace the soil at the same mass compared to H2. Consequently, achieving the same dry density required a higher compaction energy for H1-amended soil, which led to more pronounced compression of large macro-pores. As a result, H2 exhibited a higher k_s and a higher threshold mass proportion (5%) compared to H1 (2.5%). The higher specific surface area of H2 also contributed to the larger k_s in H2-amended soil compared to that in H1-amended soil (Table 1).

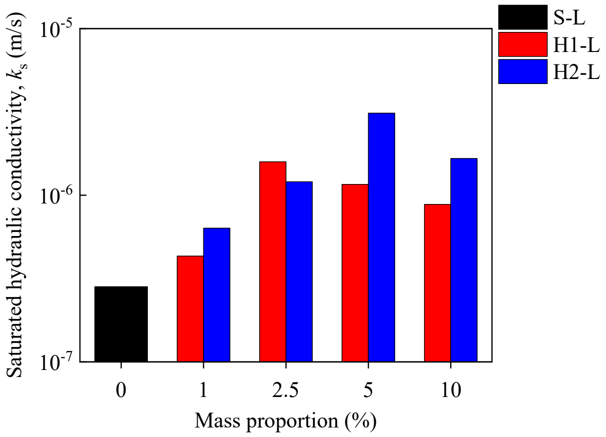

Figure 1. Saturated hydraulic conductivity of soil amended by H1 and H2 at a lower dry density of 1.4 g/cm^3.

3.2 *Effects of dry density on the k_s*

Figure 2 shows the effects of H1 and H2 addition on the k_s of soil at the higher density of 1.6 g/cm^3. The unamended soil (S-H) had a k_s of 1.9×10^{-7} m/s. The addition of 1% of H1 and H2 increased the k_s by 58% and 47% to 3.0×10^{-7} m/s (H1-2.5%H) and 2.8×10^{-7} m/s (H2-2.5%H), respectively. When the mass proportion exceeded 1%, a further increase in the mass proportion decreased the k_s of both H1- and H2-amended soils.

A higher compaction dry density caused the threshold to appear earlier in hydrochar-amended soils. This was because an increase in compaction dry density reduced the macro-pore volume and increased the micro-pore volume of the soil (Chen et al. 2020a). The filling and compression of deformable hydrochar particles into soil macro-pores were more significant in samples with higher dry density than in those with lower dry density, thus reducing the threshold value to 1%. Beyond this threshold, the larger the mass proportion, the smaller the macro-pore volume and hence the lower the k_s. When the mass proportion increased to 10%, k_s reduced by approximately 72% and 37% to 5.3×10^{-8} m/s (H1-10%H) and 1.2×10^{-7} m/s (H2-10%H), respectively.

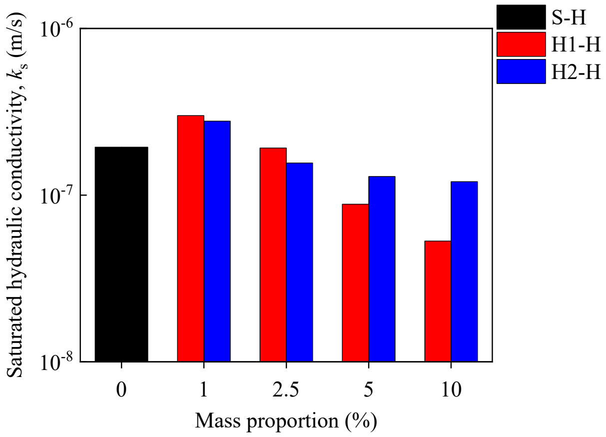

Figure 2. Saturated hydraulic conductivity of soil amended by H1 and H2 at a higher dry density of 1.6 g/cm^3.

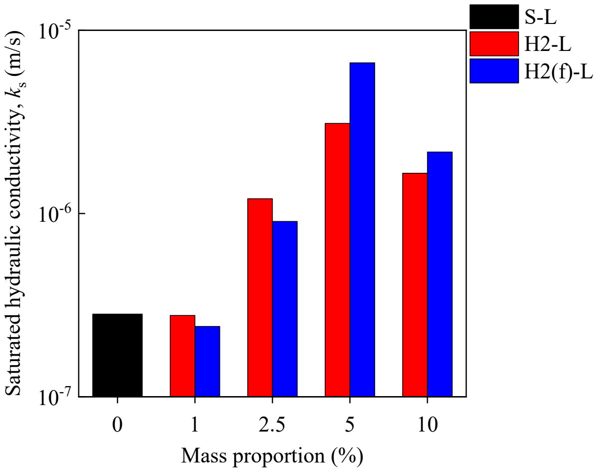

Figure 3. Saturated hydraulic conductivity of soil amended by H2 of different particle sizes at a lower dry density of 1.4 g/cm^3.

3.3 *Effects of hydrochar particle size on the k_s*

Figure 3 displays the effects of particle size on the k_s of H2-amended soil at the dry density of 1.4 g/cm^3. Both the addition of H2 with same particle size as soil and H2 with finer particles (< 0.025 mm, denoted as H2(f)) increased the k_s of soil. At mass proportions of 1% and 2.5%, the k_s of H2(f)-amended soil was slightly lower than that of H2-amended soil. This is consistent with the study of Edeh and Mašek (2022), who found that the addition of fine biochar particles led to a less significant increase in the k_s of loamy sand compared to coarse biochar at the same mass proportion, due to the lower proportion of macro-pores in soil amended with fine biochar. As the mass proportion increased to 5%, k_s of H2(f)-amended soil became larger than that of H2-amended soil. This indicates that more macro-pores appeared in H2(f)-5%L. Results of Chen et al.

(2020b) showed that a decrease in biochar particle size increased the maximum dry density of soil at the same mass proportion of 10%. This means that less compaction energy was required for H2(f)-amended soil to reach the same dry density as H2-amended soil. Therefore, H2(f)-amended soil at relatively higher mass proportion of 5% and 10% exhibited larger k_s than H2-amended soil. On the other hand, both H2-L and H2(f)-L exhibited the same threshold of 5%. The threshold value was mainly related to the hydrochar temperature and dry density rather than hydrochar particle size.

3.4 *Effects of hydrochar on the volumetric behaviour*

Figure 4 illustrates the variations of void ratio with matric suction for unamended and amended soils by H1 and H2 at a lower dry density of 1.4 g/cm^3. At the same dry density, the addition of H1 or H2 reduced the initial void ratio (e_0) because both H1 and H2 have a much smaller specific gravity than the soil (Table 3). The e_0 of S-L decreased by 1.5% upon saturation, possibly associated with the wetting-induced collapse due to the presence of some unstable large inter-aggregate pores after specimen compaction. However, all of the amended soils swelled after saturation (i.e. increase from e_0 to e_{sat}; Table 3). The wetting-induced specimen swelling could be attributed to the expansion and distortion of aggregates when subjected to water uptake (Sivakumar et al. 2006). Moreover, the higher the hydrochar mass proportion, the greater the increase in e_0 would be. This was because the addition of hydrochar decreased the specific gravity of the amended-soils and hence increased the saturated water content (w_{sat} in Table 3). As the initial water content (21.1%) was same for all the amended soils, the increase in the mass proportion caused the increase in the water content that needed to saturate the specimens. It was possible that more water entered the aggregate pores and led to more significantly sample swelling during saturation. When subjected to drying as suction increased from zero to 150 kPa, the e_0 of S-L marginally reduced by 0.7%. Except the values of initial e_0 and saturated e_{sat}, the addition of hydrochar, regardless of type (i.e. H1 or H2) or mass proportion, reduced e_{sat} by 1.5% to 2%, a reduction two to three times higher than that of S-L along the drying path. And a yield point at the suction of approximately 30 kPa existed where a significant reduction in the void ratio appeared for all the specimens.

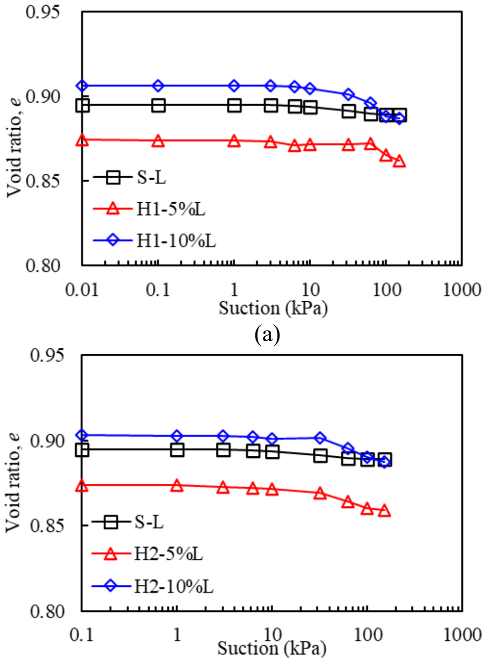

Figure 4. Relationships between void ratio and matric suction of unamended and amended soils by (a) H1; and (b) H2 at a lower dry density of 1.4 g/cm^3.

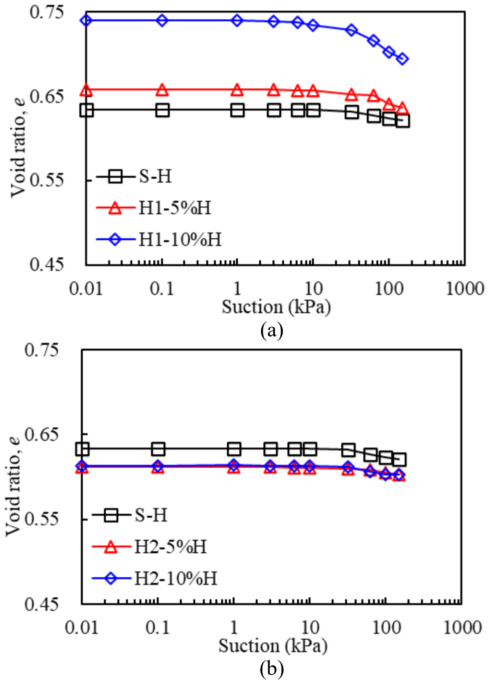

Figure 5. Relationships between void ratio and matric suction of unamended and amended soils by (a) H1; and (b) H2 at a higher dry density of 1.6 g/cm^3.

Figure 5 shows the variations of void ratio with matric suction for unamended and amended soils by H1 and H2 at a higher dry density of 1.6 g/cm^3. Swelling of the specimens at high density due to saturation was more significant than that observed at low density (Table 3). The value of e_0 of S-H, H1-5%H and H1-10%H was increased by 5.7%, 19% and 127%, respectively, after saturation. The increase in the swelling amount with the increase in the mass proportion was related to the increase in the required saturated water content (w_{sat}) due to the reduction of the specific gravity (Table 1). The swelling potential of aggregate pores in H1-amended soil was much larger than that of H2-amended soil (8.8% and 16.5% increase of e0 for H2-5%H and H2-10%H). H1-amended soils had lower specific gravity and required more water to reach saturation compared with H2-amended soils at the same mass proportion (Table 1 and 3), which could be one possible reason of the more significant swelling of H1-amended soil. A yield point at the suction of approximately 30 kPa existed for all the specimens at high density. It seems that yield point was independent of the dry density or hydrochar addition (Figures 4 and 5), which is an interesting phenomenon that needs to be studied in the future.

3.5 *Effects of hydrochar on the WRC*

Figure 6 illustrates the drying WRCs for unamended and amended soils by H1 and H2 at a lower dry density of 1.4 g/cm^3. The air entry value (AEV) where a significant drop in volumetric water content (θ) occurred was determined by the graphical method (Fredlund and Xing 1994). The AEV of unamended soil (S-L) was 1 kPa. From Figure 6(a), amending the soils with 5% of H1 and 10% of H1 increased the AEV to approximately 3 kPa and 6 kPa, respectively. Because AEV refers to the minimum suction required to drain the pore water from the largest pores in the soils, the increase in AEV by hydrochar addition indicates that hydrochar can fill the largest soil pores to enhance water retention capability. From Figure 6(b), the addition of H2 increased both the AEV and the θ in the suction range between the AEV and 150 kPa. H2-5%L and H2-10%L exhibited similar AEVs of approximately 2 kPa, and the increase in the mass proportion of H2 from 5% to 10% resulted in a negligible increase in the WRC. The increase in AEVs due to hydrochar addition was supported by the observed decrease in macro-pore peak diameter, as evidenced by MIP results presented in Figure 8.

Figure 7 shows the drying WRCs for unamended and amended soils by H1 and H2 at a higher dry density of 1.6 g/cm^3. As expected, the denser unamend soil had a much higher AEV of approximately 10 kPa than that of the looser counterpart (1 kPa). The increase in dry density resulted enhanced AEV and water retention capacity, attributed to the reduction in pore volume, particularly in macro-pores with diameters exceeding approximately 4 μm. From Figure 7(b), the addition of H1 significantly increased the saturated volumetric water content due to the increased e_{sat} and w_{sat} as the mass proportion increased (Table 3). However, the addition of H1 into the denser soils did not result in a significant change in AEV: the AEV of H1-5%H and H1-10%H remained approximately 10 kPa. In contrast, when soil was amended by H2 (Figure 7(b)), the AEV changed much more significantly, from 10 kPa to 33 kPa for H2-5%H and H2-10%H. This indicates that the H2-amended soils might have fewer large macro-pores than H1-amended soils, as evidence in Figure 8. Overall, at any given mass proportion and dry density, H1 induced a slightly larger increase in soil WRC than H2. However, the degree of increase in soil WRC became less significant as suction exceeded the AEV. At suction of 150 kPa, θ of all unamended and amended specimens converged to the same value (except H2-5%H). This indicates that the enhancement effect of hydrochar on the soil WRC is confined to the low suction range, making it more suitable for humid and semi-humid regions.

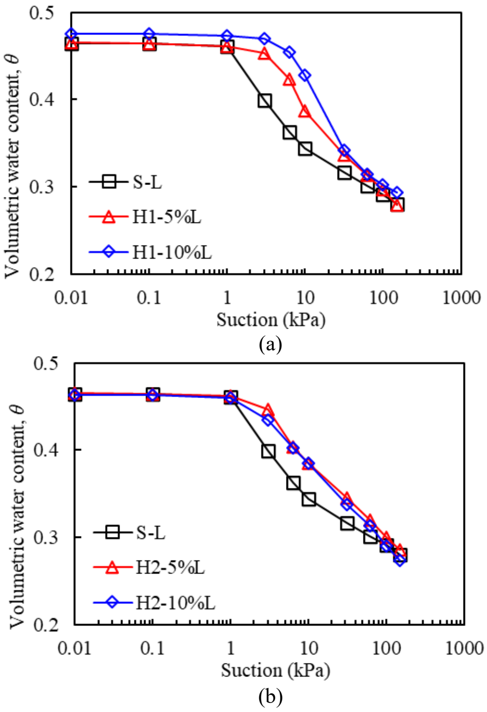

Figure 6. Water retention curves of unamended and amended soils by (a) H1; and (b) H2 at a lower dry density of 1.4 g/cm^3.

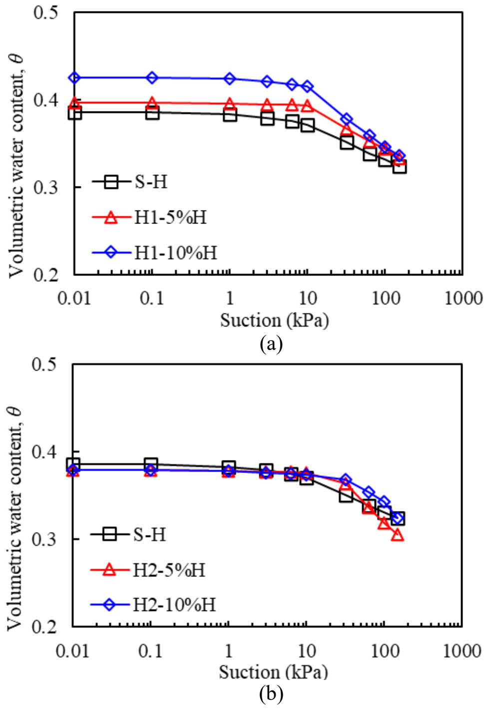

Figure 7. Water retention curves of unamended and amended soils by (a) H1; and (b) H2 at a higher dry density of 1.6 g/cm^3.

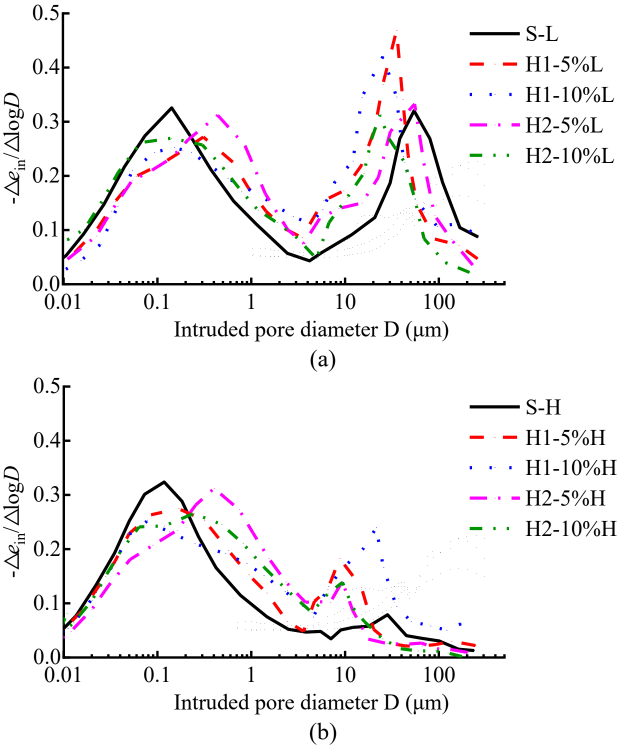

Figure 8. Pore size density functions of unamended and amended soils by H1 and H2 at dry densities of (a) 1.4 g/cm^3; (b) 1.6 g/cm^3.

4 CONCLUSIONSS

The hydraulic properties including saturated hydraulic conductivity (k_s) and water retention curves (WRCs) of a compacted silty, clay sand amended with different mass proportions of hydrochar that were derived at two different production temperatures (180 °C and 240 °C, denoted as H1 and H2) were measured. The effects of compaction dry density on k_s and WRC was investigated.

At the lower dry density of 1.4 g/cm^3, the addition of either H1 or H2 increased the soil k_s, even at a small mass proportion of 1%. However, beyond a threshold (2.5% for H1-amended soil and 5% for H2-amended soil), the k_s dropped, though its magnitude remained higher than that of the unamended soil, due to the increased compaction energy and the compression of large macro-pores. At the higher dry density of 1.6 g/cm^3, the threshold occurred earlier at the mass proportion of 1%. Beyond 1%, the k_s for both H1- and H2-amended soil dropped below that of the unamended soil, attributed to the more significant reduction in soil macro-pores and the more extensive pore filling by hydrochar particles. For H2-amended soil at the lower dry density, the decrease in hydrochar particle size led to a less significant increase in soil k_s when the mass proportion was smaller than 2.5%. However, when the mass proportion increased to 5% and 10%, the decrease in hydrochar particle size increased the k_s of H2-amended soil.

Upon saturation, the addition of hydrochar changed the soil volumetric behaviour from wetting-induced collapse to swelling. For any given dry density, the higher the hydrochar mix proportion, the greater the increase in swelling of amended soils, due to the increased saturated water content. The swelling potential of aggregate pores in H1-amended soil was larger than that in H2-amended soil, probably because H1-amended soil had lower specific gravity and required more water to reach saturation. Within the measured suction range, drying-induced soil shrinkage was reduced by the addition of hydrochar. Upon drying, soil amendment with either H1 or H2 increased the air entry value (AEV) and the soil volumetric water content (θ). At the same mass proportion and dry density, the improvement in water retention capacity from H1 addition was slightly higher than that from H2, due to the higher saturated θ and proportion-dependent influence on AEV of the former. As suction increased to 150 kPa, the volumetric water content of all unamended and amended specimens converged to a similar value, indicating that the enhancement effect of hydrochar on soil WRC is confined to the low suction range, making it suitable for humid and semi-humid regions.

5 ACKNOWLEDGEMENTS

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