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Review

A geotechnical perspective on soil-termite interaction: Role of termites in unsaturated soil properties

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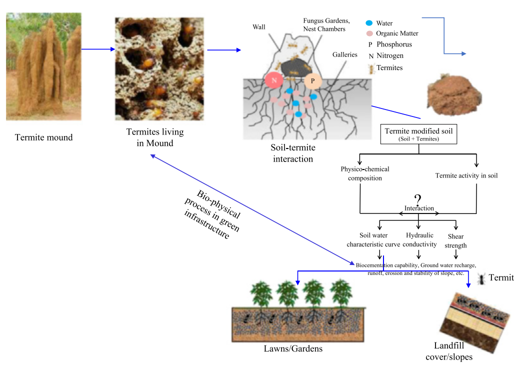
HIGHLIGHTS

- Soil-termite interaction in context to geo-environmental engineering is reviewed.
- Termites enhance soil aggregation through its secretion of enzymes.
- Aggregation influences hydraulic properties and stabilizes geo-structures.
- Influence of termites on geotechnical properties of soil warrants investigation.

GRAPHICAL ABSTRACT



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ABSTRACT

The soil-insect interaction has gathered significant attention in the recent years due to its contribution to bio-cementation. Termites, as a group of cellulose-eating insects, alter physical (texture) and chemical (chemical composition) properties of soil. Conversely, physico-chemical properties of soil also influence termite activities. It is vital to understand the soil-termite interaction and their influence on hydraulic properties and shear strength of soil, which are related to a series of geotechnical engineering problems such as ground water recharge, runoff, erosion and stability of slopes. In this study, an attempt has been made to review the latest developments and research gaps in our understanding of soil-termite interaction within the context of geo-environmental engineering. The hydraulic properties and shear strength of termite modified soil were discussed with respect to soil texture, density and physico-chemical composition. The incorporation of hysteresis effect of soil water characteristic curve, and spatio-temporal variations of hydraulic conductivity and shear strength of termite modified soil is proposed to be considered in geotechnical engineering design and construction. Finally, the challenges and future trends in this research area are presented. The expertise from both geotechnical engineering and entomology is needed to plan future research with an aim to promote use of termites as maintenance engineers in geotechnical infrastructure.

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Contents

1. Introduction

Biocementation is a process, where soil grains are bonded together into smaller aggregates in presence of moisture, micro-organisms and chemical constituents. Biocementation involves application of microbiological activity for improving the properties (hydraulic, mechanical and thermal) of soils. Biocementation is found to be feasible and sustainable solution to improve soil behaviors (DeJong et al., 2010). In general, the bacteria are employed to precipitate calcite (Martinez et al., 2013). Microbial- induced Calcite Precipitation (MICP) technique is one of the most commonly adopted bio-cementation approach for improving engineering properties of soil (Cheng et al., 2013; Feng and Montoya, 2015; Salifu et al., 2016; Tang et al., 2020; Wang et al., 2023). During MICP treatment, microorganisms react with chemical components to produce calcium carbonate ($CaCO_3$) that binds particles of soil, leading to enhanced stiffness and strength (Dagliya et al., 2022). On one hand, there have been many review studies (Mujah et al., 2017; Tang et al., 2020; Sharma et al., 2021) on the use of MICP for the treatment of soil considering application in geotechnical engineering infrastructures. Wang et al., 2023 found 20 % increase in strength and 90 % decrease in erosion due to MICP treatment. Sharma et al. (2021) showed that the MICP treated soil is resistant to episodic drying and wetting. These studies rarely consider any effects of biocementation induced by secretions of termites in geotechnical and ecological infrastructures has been hitherto neglected. Only recently have geotechnical engineers and ecologists begun to realize the effect of adhesives exuded from organisms on engineering properties of soil (Kandasami et al., 2016; Zachariah et al., 2017).

Termites came into existence during the Triassic Period while ants have appeared millions of years later. These small insects live in large communities, which are primarily found in tropical, sub-tropical and savannah regions (Yamada et al., 2006; Levick et al., 2010). As a group of cellulose-eating insects, termites construct mounds (Oberst et al., 2016). Faecal matter of termite contains partially digested cellulose (Villagran et al., 2019). Termite activities also include transportation of the fine soil from deeper profile to ground level. Mandibular gland of termite releases saliva to apply on the transported fine soil particles. Thereafter, termites deposit the mixture of saliva and fine soil particles on faecal matter. Saliva and faeces consist an important adhesive agent (i.e., glycoprotein). Stability and integrity of the termite mounds can be attributed to partially digested cellulose and glycoprotein. An increase in soil strength and changes in hydraulic properties were observed due to the bio-adhesion (Balila, 2017; Singh et al., 2019), implying that termite amended soil reveals novel compositions to improve soil properties. These new compositions are useful for adoption in geotechnical infrastructure. It is evident that contents of clay, organic content, Ca, Cu, C, Fe, K, Zn and Mg in termite mounds is 2 to 50 times higher than those in surrounding soil (Enagbonma and Babalola, 2019), and alter the physico-chemical composition of soil (Jouquet et al., 2017). On the other hand, soil physico-chemical properties have been also found to play an important role in termite activities (Jouquet et al., 2002, 2016; Xu et al., 2015). Therefore, a comprehensive understanding of soil-termite interaction is vital for geotechnical engineering and ecological practices. This research area thus needs interdisciplinary approaches linking termite activity and physico-chemical changes in soils.

Fig. 1a shows the influence of termite activity on soil porosity and permeability as investigated by Singh et al. (2019). Permeability in termite amended soil could be 100 times higher than that of normal soil, which could be attributed to the termite induced micro-cracks and small pores. Such studies need to be validated for compacted soil. However, the interaction between termites and geotechnical properties of soil in past studies have been hitherto neglected.

Fig. 1b shows the importance of interdependence between soil physico-chemical properties and termite activity in the context of various geotechnical engineering applications. The physical properties, such as grain size distribution and density, vary spatially due to transportation of soil by termites (Erens et al., 2015). In addition, the chemical composition (i.e., organic nitrogen, phosphorous, potassium etc.) of soil changes due to the presence of saliva, facial and dead termites in soil (Deke et al., 2016). On the other hand, the preference of termites to use various types of soils for constructing mounds may vary with the change in physico-chemical composition of soil (Zachariah et al., 2017).

It goes without saying that the determination of soil water characteristic curve (SWCC) and hydraulic conductivity, both are critical for geotechnical engineers and ecologists to capture water movement features in soil (Gadi et al., 2016, 2017, 2018a, b). This further helps to analyze water infiltration and runoff in bare and grass lands (Leung et al., 2015; Gadi et al., 2018a, b). The Richards equation combined with sink term is generally used to estimate the ground water recharge through bare or grass lands (Deb et al., 2013). On the other hand, the shear strength of soil is another important feature that is used to resist failure and sliding along shear planes. The

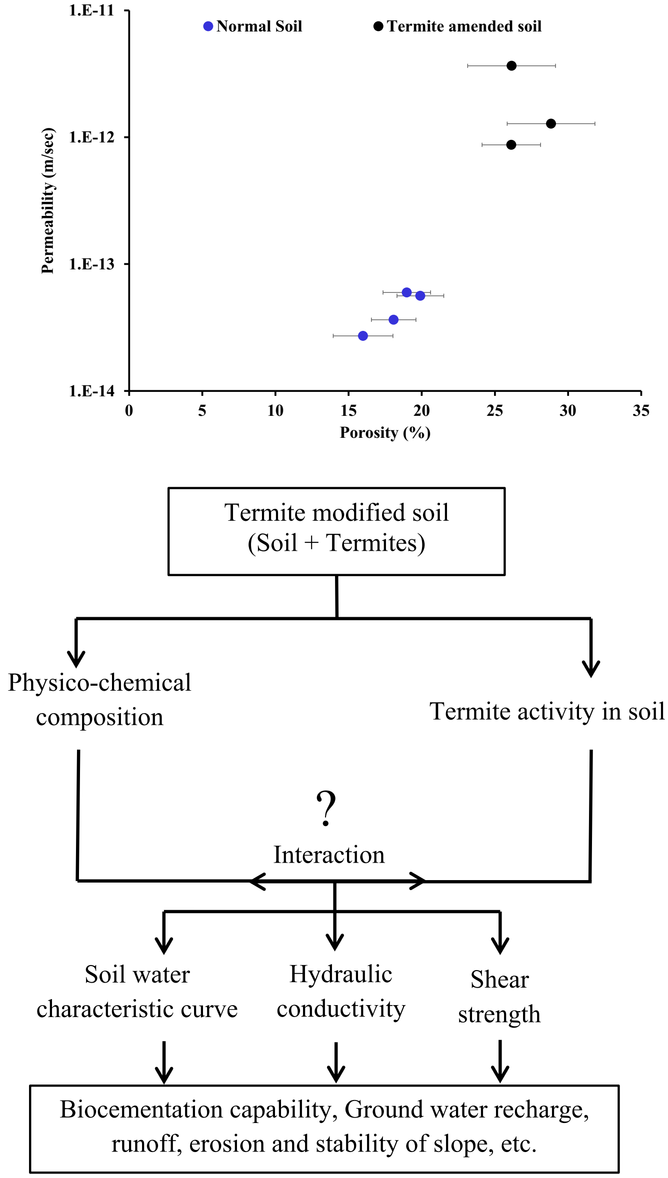


Fig. 1. (a) Effect of soil-termite interaction on porosity and permeability (after Singh et al., 2019) and (b) Linkage between unsaturated soil properties and physico-chemical properties of termite modified soil.

shear strength and hydraulic properties of soil govern the erosion and stability of geotechnical and ecological infrastructures (Fredlund and Xing, 1994). Numerous studies have been conducted to determine the engineering properties of bare soil regardless of the effect of termites (Ghasabkolaei et al., 2017; Soldo et al., 2020; Zhang et al., 2020). However, the physico-chemical composition of termite modified soil, has been scantily investigated. It should be noted that very few investigations have been conducted to study the interdependence of physico-chemical composition of soil and termite activity (soil-termite interaction) and its effect on ground water recharge, runoff, erosion and stability of slopes.

Therefore, the overarching aim of this study is to provide a comprehensive overview of the interaction between termite activity and physico-chemical properties of soil. Specifically, we attempt to highlight the changes in particle size distribution, density and chemical composition of soil due to termite activities. In addition, the changes in termite activity due to the variation of grain size distribution and density are also discussed. The limitations in the use of geotechnical instrumentation to monitor soil-termite interaction are also described briefly.

2. Soil properties

In general, the soil in termite mound is partially saturated. The soil existing in surroundings of termite mounds may be dry, partially saturated or fully saturated. In a partially saturated or unsaturated condition, soil exists in a three-phase system i.e., pore spaces are occupied by air and water (Lu and Likos, 2004). This section demonstrates the vital parameters of soil, which is a reference for discussing the interdependence between soil and termite properties in further sections.

2.1. Soil water characteristic curves

The water retention ability of soil is generally defined by SWCC, which is a graphical illustration of the mathematical relationship between volumetric water content (VWC, θ) or degree of saturation (S_r) or void ratio (e) and soil suction (Ψ). It is well known that the total soil suction is a combination of matric suction (Ψ_m) and osmotic suction (Ψ_o). Adsorptive and capillary forces induce matric suction while osmotic suction is induced by contaminants or salts (Arifin and Schanz, 2009). Various methods and instruments used for measuring total suction and matric suction are summarized in Table 1. The osmotic suction is hard to measure and hence, it is usually evaluated by calculating the difference between total and matric suctions (Krahn and Fredlund, 2009).

A laboratory study was conducted by Leung et al. (2015) to obtain SWCC, where the authors compacted a soil sample to the desired density in a mould. Tensiometers (1 kPa - 80 kPa) and heat dissipation matric potential sensors (> 50 kPa) were installed in the soil to measure the suction. It must be noted that cavitation may occur in the tensiometer at a suction larger than 80 kPa. Hence, the heat dissipation matric potential sensors were installed to measure suction larger than 50 kPa. In addition, the commercially available sensors were employed to measure the soil moisture content. Fig. 2a shows the typical drying and wetting SWCCs, which were fitted using the closed form equation (Van Genuchten, 1980). This model is expressed as:

$$\theta(\Psi) = \theta_r + \frac{\theta_s - \theta_r}{\left[1 + (\alpha|\Psi|)^n\right]^{1-\frac{1}{n}}} \tag{1}$$

where $\theta(\Psi)$ refers to the water retention curve, $|\Psi|$ refers to the suction, θ_s represents the saturated water content, θ_r represents the residual water content, α is related to the inverse of air entry suction, n is the measure of pore-size distribution and $m = 1 - \frac{1}{n}$.

Table 2 lists the parameters of the Van Genuchten model fits, using the least squares method. The air entry value (AEV) refers to the suction that

Table 1
Summary of instruments used for measuring soil suction (after Gadi et al., 2016).

Method	Total suction	Matric suction	Suction range (MPa)	Equilibration time	Manufacturer
Thermocouple psychrometer	Yes	No	0.3–0.7	60 min	Campbell Scientific
Transistor psychrometer	Yes	No	0.1–10	60 min	Soil Mechanics Instrumentation
Chilled mirror psychrometer	Yes	No	0.5–30	10 min	Meter group
Filter paper method	Yes	No	0.05–30	5–14 days	Whatman, Schleicher and Schuell
Thermal conductivity sensor	No	Yes	0.001–1.5	Hours to Days	Campbell Scientific
Electrical conductivity sensor	No	Yes	0.05–1.5	0.25–2 days	Soil Moisture Equipment
Tensiometer	No	Yes	0.001–0.1	In minutes	Meter group

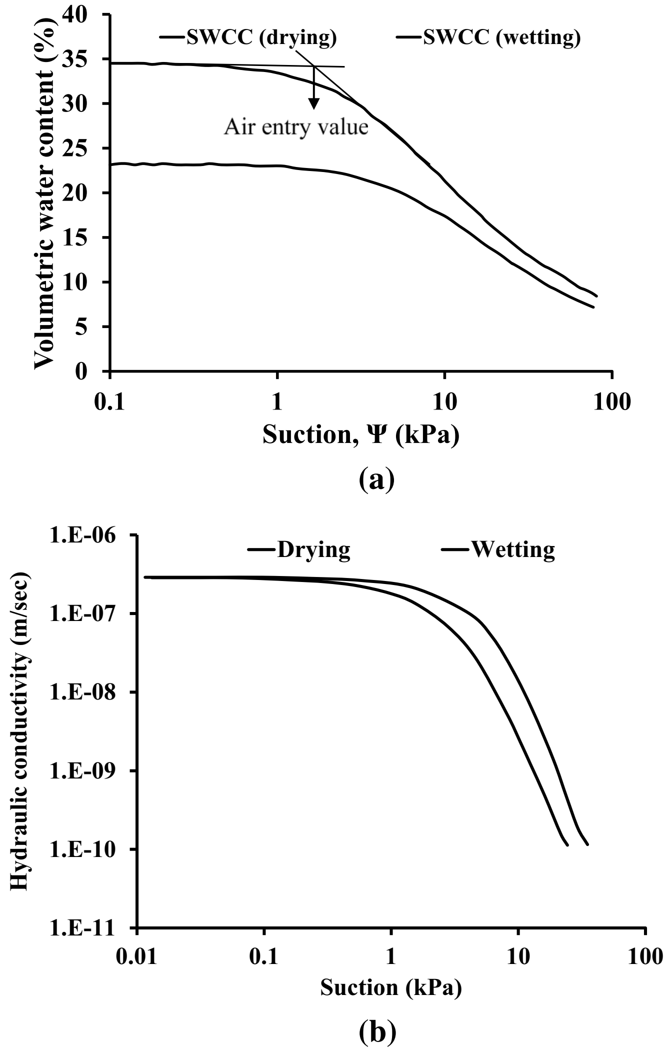


Fig. 2. (a) Hysteretic soil water characteristic curves (after Leung et al., 2015) and (b) predicted hydraulic conductivity for silty sand (using Van Genuchten, 1980 approach).

should be exceeded before air enters into the pores of soil (Fredlund and Xing, 1994). The residual water content represents water content corresponding to the highest suction. The residual air content refers the water content corresponding to suction around 0 kPa.

The desorption curve represents the drying cycle and the adsorption curve represents the wetting cycle, while it is well established that the soil type and density significantly affect SWCC (Gallage and Uchimura, 2016). In addition, the drying and wetting cycles also play a vital role in determining SWCC. Numerous theoretical models (Arya and Paris, 1981) and statistical equations (Gardner, 1958; Gupta and Larson, 1979; McKee and Bumb, 1984; Ahuja et al., 1985) were developed to predict the variation of SWCC due to the change in grain size distribution and density. Furthermore, several correlations were developed using empirical equations by previous researchers (Saxton et al., 1986; Fredlund et al., 2000; Torres Hernandez, 2011). Accurate measurement of SWCC is vital to analyze shear strength and hydraulic conductivity accurately (Gadi et al., 2017).

2.2. Hydraulic conductivity

It is well known that the hydraulic conductivity represents the ability of the soil to allow water to pass through it, which is important for understanding the workability of soil and conducting ground improvement measures. In addition, hydraulic conductivity governs the water balance in farmlands, forests, slopes and river banks, and is vital to devise irrigation schedule and drainage schemes and maintain green space (Mubarak et al., 2009; Bouwer, 1966). The hydraulic conductivity of unsaturated soil is commonly predicted using Van Genuchten (1980) approach:

$$K(\Psi) = K_s S_e^j \left[1 - \left(1 - S_e^{1/m}\right)^m\right]^2 \tag{2}$$

where K_s is saturated hydraulic conductivity, S_e represents effective degree of saturation and j is pore connectivity parameter (Mualem, 1976). Fig. 2b shows the hydraulic conductivity deduced using Van Genuchten (1980) approach. A higher hydraulic conductivity can be seen in the case of wetting as compared to that during drying.

2.3. Shear strength

The shear strength (τ) is the measure of the shear stress that soil can resist. The shear strength of an unsaturated soil is expressed as below (Fredlund et al., 1978)

$$\tau = c' + \sigma' \tan\varphi' + (u_a - u_w) \tan\varphi^b \tag{3}$$

where c' is cohesion of soil, σ' is effective stress, (u_a-u_w) is suction, φ' is friction angle with respect to changes in σ' when suction is held constant (angle of internal friction) and φ^b is friction angle with respect to changes in suction when effective stress is held constant. Electrostatic forces and cementation property (due to ferric oxide, sodium chloride etc.) cause the cohesion. Angle of internal friction is the measure of resistance to shear stress. Suction is one of the important factors which affect shear strength (Vanapalli et al., 1996). Generally, two different types of tests are conducted to measure shear strength of soil: (i) suction controlled test and (ii) undrained triaxial tests. As the stress conditions can be controlled in suction controlled test, it is usually adopted to determine the shear strength of unsaturated soils. It should be noted that shear strength may not increase with the increase of suction in residual zone (Sheng et al., 2011).

3. Effects of termites on physico-chemical composition of soil

This section highlights the role of termites in changes in texture, density and proportions of fine and coarse particles, which subsequently alter the soil properties discussed in Section 2. The possible changes in soil properties are presented using observations of previous research on unsaturated soil mechanics. This section helps the scientific community to conduct parametric studies to enhance interdisciplinary understanding.

3.1. Effect of termites on texture of soil

Fig. 3a shows the fractions of sand, clay and silt at 2 cm and 26 cm depths from the *Amitermes obeuntis* termite mound (Debruyn and Conacher, 1995). The soil composition at control site (without termites) is also shown for comparison. Fraction of fine particles in *Amitermes obeuntis* is significantly higher (i.e., 14 % higher) than that of control soil at 2 cm depth. Whereas, fine fraction is higher in control soil than termite infested

Table 2
A summary of fitting coefficients for drying and wetting SWCCs using Van Genuchten (1980) equation (after Leung et al., 2015).

Soil type	θ_s [m^3/m^3]	θ_r [m^3/m^3]	α [m^{-1}]	n [−]	m [−]
Drying SWCC	0.345	0.01	2.2	1.52	0.342
Wetting SWCC	0.23	0.01	1.2	1.58	0.367

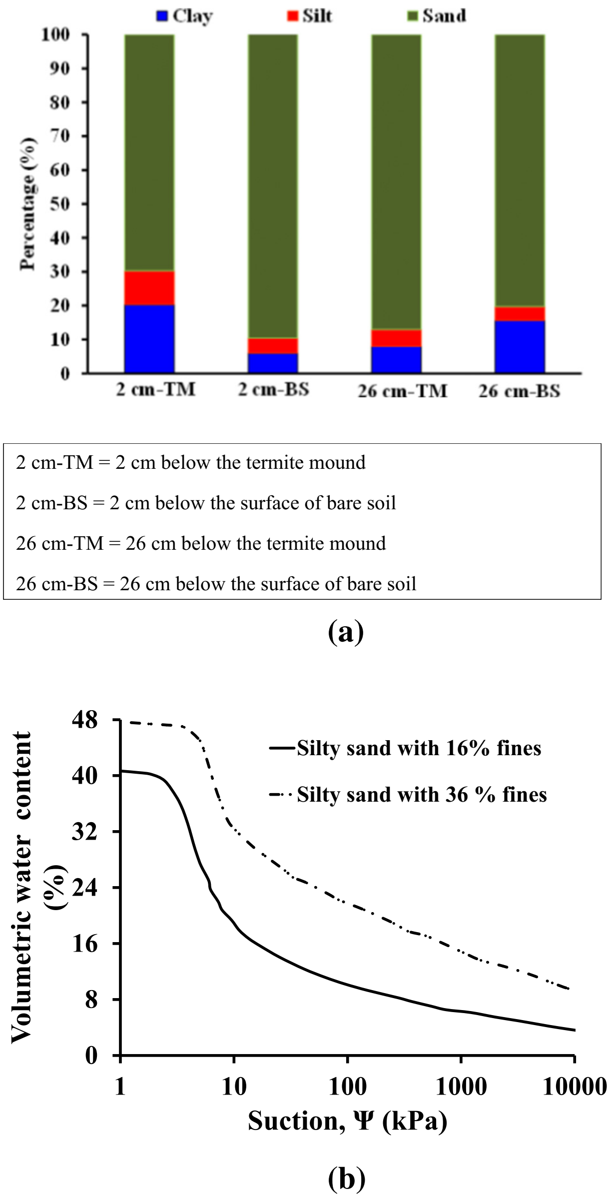


Fig. 3. (a) Soil texture of termite-modified soil (after Bruyn and Conacher, 1990) and (b) effect of soil texture on soil water characteristic curve (after Gallage and Uchimura, 2016).

soil at 26 cm depth. The trend of variation of fraction of sand is opposite to that of fine particles fraction. This may be attributed to transportation of fine particles from deeper layer of soil profile. Previous studies showed that termites collect and transport fine particles from depth up to 20 m (Holt and Lepage, 2000). In addition, fine content transported by termites is spatially heterogeneous (Whitford, 1996). Therefore, one would expect the parameters cohesion (c), angle of internal friction (ϕ) and suction (Ψ) are spatially heterogeneous. However, the spatial heterogeneity of soil composition were rarely explored in the literature.

Effect of grain size distribution on SWCC is shown in Fig. 3b to highlight the importance of understanding spatial heterogeneity of soil composition due to termite activity. Fig. 3b presents the SWCCs of two soils with dissimilar fine contents (Gallage and Uchimura, 2016). The soils are classified as silty sand according to USCS (ASTM D2487-10, 2010). It has been found that residual suction and air entry values are relatively high for soil with more fine content, which could be attributed to the pore size difference between two types of soils. Size of pores in the soil containing less fine content would be large (Indrawan et al., 2006; Indrawan et al., 2007). Soil containing more large pores desaturates faster than that with less pores (Ahuja et al., 1998). Fig. 3b also shows that the water retention capacity of soil with higher fine content is greater than that with less fine content.

3.2. Effect of termites on density of soil

Fig. 4a shows the variation of dry density with respect to the height of termite mound (Kandasami et al., 2016). Dry density was found to increase with height of the mound. The authors reported the likely reason to be consolidation or densification of soil at the base of the mound (Kandasami et al., 2016). The dry density of soil has been found to decrease by 21 % with the increase of the height of termite mound. In addition, few studies have also reported that dry density changes spatially below the termite mound (Eggleton and Taylor, 2008). A much earlier study by Potineni and Veeresh (1989) showed that difference in dry density between the base of the mound and 20 cm below the mound could be up to 19 %. This density variation implies the significant changes of other properties of soil. However, previous researchers rarely explored the spatial variation of soil density due to termite activity in large areas.

Fig. 4b shows the SWCCs of silty sand samples compacted at two dissimilar densities (Gallage and Uchimura, 2016). The saturated moisture content is much lower when density is higher and this could occur due to the low void ratio of densely compacted soil. Water drains quickly through large pore radii as compared to small pore radii. Hence, air entry value at lower density is relatively less than that at higher density. At a considered

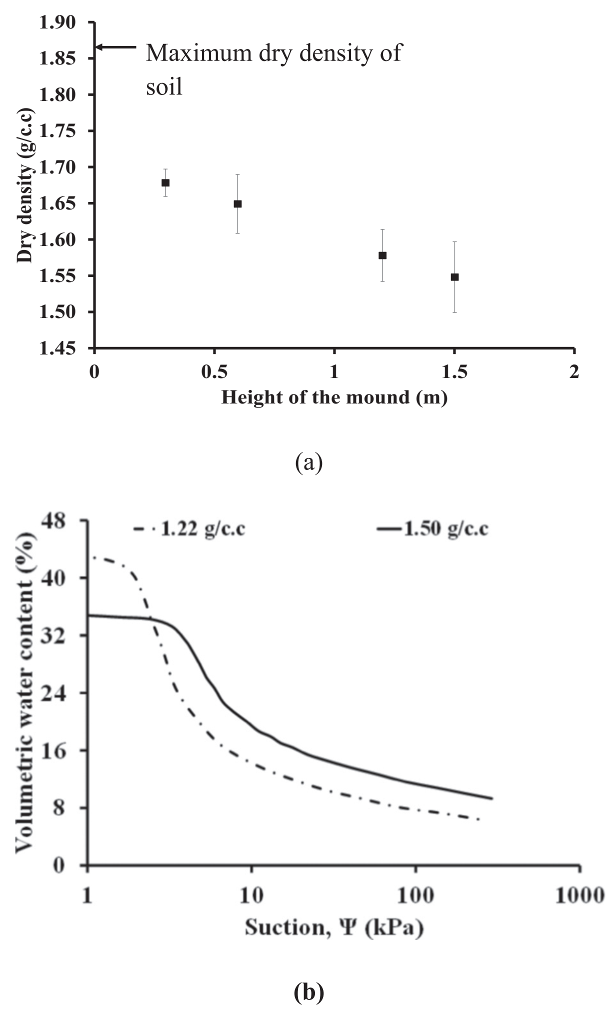


Fig. 4. (a) Variation of dry density in the mound with height (Kandasami et al., 2016) and (b) effect of density on soil water characteristic curve (Gallage and Uchimura, 2016).

water content, suction was found to be high when void ratio is low. This trend can be observed at suction beyond air entry value. The higher suction due to relatively small pores can be understood from the capillary equation (Fredlund and Rahardjo, 1993) below:

$$\Psi_i = \frac{2\gamma \cos \Theta}{\rho_w \, g r_i} \tag{4}$$

where Ψ_i is soil suction, γ is surface tension of water, Θ is contact angle of particles, ρ_w is density of water, g is acceleration due to gravity, r_i is mean pore radius.

3.3. Effect of termites on composition of soil

Fig. 5a shows the comparison of carbon, phosphorous and potassium contents in termite modified soil and bare soil (under the absence of termites; after Debruyn and Conacher, 1995). It can be observed that proportions of carbon, phosphorous and potassium are higher in termite modified soil as compared to those of bare soil. This chemical enrichment of termite modified soil can be explained from termite activity. For example, the high carbon, phosphorous and potassium contents were derived from materials ingested to extract nutrients (Breznak and Brune, 1994). Organic substance is formed from biochemical processes in digestive tract of termites (Breznak and Brune, 1994). Thus, it is conceivable that high values of carbon, phosphorous and potassium could potentially exist due to saliva and faecal matter. It is evident that changes in organic content greatly alter the soil properties as observed in studies reported by Zema et al., 2021 and Schroeder et al., 2022.

Fig. 5b highlights the influence of organic matter on desaturation (Dexter, 2004). Slope of the SWCC was presented using Van Genuchten parameter n, which was found to increase up to 1.3. Thereafter, the increase in slope was relatively low. The increase in slope could be well attributed to enhanced cohesion due to presence of organic matter. It must be noted that the soil density did not vary along with change in organic content in the study of Dexter (2004). In addition, density and organic content vary simultaneously with time (Blanco-Canqui et al., 2009; Murphy, 2015). However, the spatio-temporal variation of density and organic content in termite mound and its surroundings was rarely investigated previously.

3.4. Effect of termites on stress strain behavior of soil

In unconfined compression test, stress increases slowly and reaches a peak value (Kandasami et al., 2016). Thereafter, stress decreases due to breakage of bond between particles. Fig. 6 shows the variation of stress against strain due to unconfined compression. It was found that peak stress at bottom of the termite mound was higher than that at the top of the mound. This may be due to densification and consolidation of soil at bottom of the termite mound. It can be observed that brittle failure occurs at the bottom of the mound, while plastic failure is found at the mound top. It must be noted that termite modifies the density and texture along the depth and width in the surroundings of termite mound (Nutting et al., 1987). This indicates that the stress-strain behavior may vary spatially and temporally in termite modified soil, which needs further investigation. Furthermore, time and load required to over consolidate or normally consolidate the soil in deeper profile may also change with time and this aspect also remains to be explored.

4. Effect of composition of soil on termite activity

The activity of termites is likely to differ for different types of materials due to their different compositions. Termite activity can be observed from the weight and volume of boluses fabricated by them to build mounds. Fig. 7a shows the ease of activity of termites in terms of weight and volume of boluses (Zachariah et al., 2017). Termites could be present on various materials i.e., stainless steel, agar, glass, burnt-soil, sand, kaolinite, red soil and crushed hydrogel. It is known that termites require more time to walk on smooth surfaces. It must be noted the friction could influence the termite activity (Zachariah et al., 2017). Due to high plasticity of agar (Rhim, 2011), the termites could not bite the agar easily with mouth. In addition, bolus exaction from agar is a slow process. Hence, normalized weight and volume of boluses are minimum for the case of agar. Weight and volume of granular materials were found to be relatively high. This is

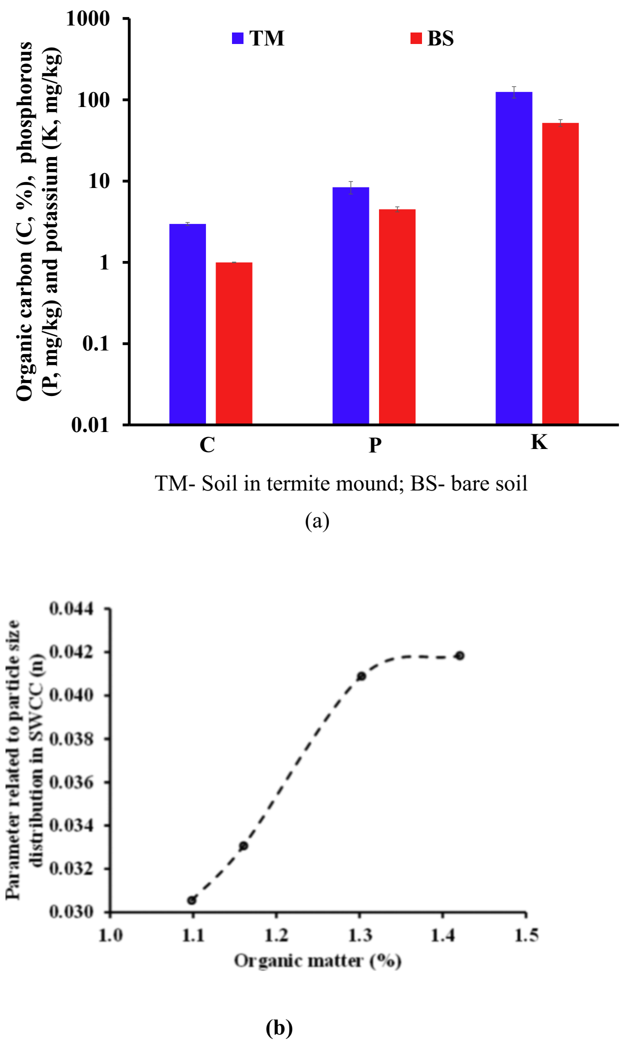


Fig. 5. (a) Chemical composition of termite modified soil (after Bruyn and Conacher, 1990) and (b) effect of organic matter on SWCC (after Dexter, 2004).

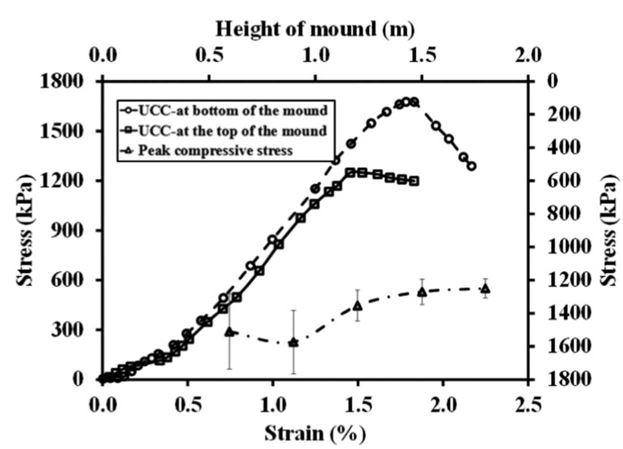
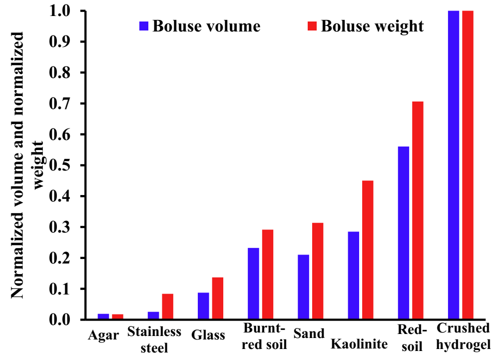
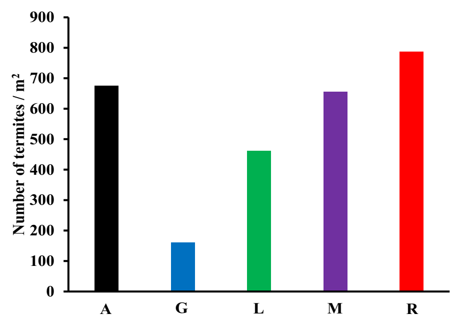


Fig. 6. Variation of stress-strain relationship at top and bottom of the mound and peak compressive strength at various elevations (after Kandasami et al., 2016).



(a)



A- Aciw prunings, G- Gliricidia prunings, L- Leucaena prunings, M- Maize stover and R- Rice straw

(b)

Fig. 7. Effects of (a) physical and (b) chemical composition on ease of termite activity in various types of soils (after Zachariah et al., 2017).

because excavation of boluses is not needed in the case of granular materials. Unlike other materials, secretions may not be needed significantly to aggregate the particles of crushed hydrogel. This may attribute to the highest weight and volume of boluses in crushed hydrogel. Weight and volume of unburnt soil is higher than that of burnt soil, and this could be attributed to the fragile behavior of burnt soil (Zachariah et al., 2017).

Wide range of soil types exist in various geotechnical infrastructures. For example, Zachariah et al. (2017) showed that weight and volume of boluses can be increased up to 10^4 times due to raise in size of glass crusts, implying that size of soil particles affect the termite activity. However, the influence of soil particle size distribution on termite activity was rarely studied for various types of soil. Angle of internal friction varies with change in mineralogy and composition of soil and angle of internal friction could be up to 40° (Zachariah et al., 2017). There is also a dearth of information on the effect of change in internal friction of soil on termite activity. The fine content of soil is the key factor that affects its plasticity. Thus, soil plasticity needs to be taken into account to quantify the weight and volume of the boluses, but to-date this aspect has not been investigated.

Fig. 7b shows the influence of various plant residues on termite activity (Tian and Brussaard, 1993). The chemical composition of the considered plant residues is shown in Table 3. Effect of rice straw was found to be significant among various types of plant residues. Any relationship between polyphenol, N and lignin in plant residues and number of termites was not found. However, number of termites was found to increase with decrease in decomposition rate. It has been reported that decomposition rate depends on various factors such as moisture content, temperature etc. (Couteaux et al., 1995). Additionally, seasonal variation may also alter the decomposition rate (Chapin et al., 2002). These factors were rarely considered in analyzing the properties of termite modified soil in the past studies. It should be noted that natural and artificial fiber reinforcement are adopted to enhance the strength and hydraulic properties of various infrastructures. These fibers consist various proportions of lignin, cellulose etc. (Bordoloi et al., 2017). Hence, termite activity in various types of fiber reinforced soil compacted at different densities warrant further investigation.

Table 3
Composition of the considered residues of plants (after Tian and Brussaard, 1993).

Residues of plants	Nitrogen (%)	Lignin (%)	Polyphenols (%)	SiO_2 (%)
Acioa	1.61	47.6	4.09	2.71
Gliricidia	3.60	11.6	1.62	0.59
Leucaena	3.55	13.4	5.02	0.53
Maize stover	1.00	6.8	0.56	2.22
Rice straw	0.84	5.2	0.55	11.35

5. Discussion and future scope

Termites are one of the most efficacious groups of insects, colonizing most of the landmasses on Earth (Leponce et al., 1997). Research on soil-termite interaction is gaining momentum in the recent years. Detailed summary of existing studies that deal with termites is provided in Table 4. The summarized studies are discussed as per termite activity, texture, density, SWCC and chemical composition of soil and instrumentation used for monitoring. Based on these studies some key limitations are identified. Within the context of ecological engineering, soil science and geotechnical engineering, these limitations are emphasized in the next section and future scope has been proposed.

5.1. Instrumentation for monitoring suction

It can be observed from Table 4 that only limited number of studies are available on measurement of suction in termite modified soil. It is also

Table 4
Overview of the parameters considered in the studies of soil-termite interaction.

Reference	Soil type	Termite type	SWCC		UH		Shear strength		Infiltration	Suction	Suction device	Chemical composition
			SS	MS	SS	MS	SS	MS				
Kandasami et al. (2016)	Quartz and kaolinite mixture	*O. obesus*	×	×	×	×	✓	✓	×	×	×	✓
Abe et al. (2009)	Sandy loam	Macrotermes bellicosus	×	×	×	×	×	×	×	×	×	✓
Jouquet et al. (2004)	Clayey	Isoptera and Macrotermitinae	×	×	×	×	×	×	×	✓	Tensiometer	✓
Manuwa (2009)	×	×	×	×	×	×	✓	✓	×	×	×	✓
Sarcinelli et al. (2009)	×	Termitinae, Nasutitermitinae and Apicotermitinae families	×	×	×	×	×	×	×	×	×	✓
Léonard and Rajot (2001)	Sandy	×	×	×	×	×	×	×	✓	×	×	✓
Udoeyo et al. (2000)	×	Macrotermes Bellicosus	×	×	×	×	✓	✓	×	×	×	✓
Jouquet et al. (2002)	×	Odontotermes nr. Pauperans	×	×	×	×	×	×	×	×	×	✓
Bonachela et al. (2015)	×	×	×	×	×	×	×	×	✓	×	×	✓
Sileshi et al. (2010)	×	Hodotermes	×	×	×	×	×	×	✓	×	×	✓
Eggleton and Taylor (2008)	×	Coptotermes acinaciformis	×	×	×	×	×	×	✓	×	×	✓
Ptáček et al. (2013)	×	Various species	×	×	×	×	×	×	×	×	×	✓
Brune and Dietrich (2015)	×	Various species	×	×	×	×	×	×	×	×	×	✓
Dronnet et al. (2006)	×	Reticulitermes santonensis Feytaud	×	×	×	×	×	×	×	×	×	✓
Verma et al. (2009)	×	Various species	×	×	×	×	×	×	×	×	×	✓
Kinyuru et al. (2013)	×	M. subhylanus, *P. militaris*, M. bellicosus and *P. spiniger*	×	×	×	×	×	×	×	×	×	✓
Scharf (2015)	×	Various species	×	×	×	×	×	×	×	×	×	✓
Zhou et al. (2007)	×	*R. flavipes*	×	×	×	×	×	×	×	×	×	✓
Nakashima et al. (2002a)	×	*Coptotermes formosanus* Shiraki	×	×	×	×	×	×	×	×	×	✓
Nakashima et al. (2002b)	×	*Coptotermes formosanus*	×	×	×	×	×	×	×	×	×	✓
Warnecke et al. (2007)	×	Nasutitermes ephratae and *N. corniger*	×	×	×	×	×	×	×	×	×	✓
Hongoh et al. (2008)	×	×	×	×	×	×	×	×	×	×	×	✓
Hayashi et al. (2007)	×	*Coptotermes formosanus* Shiraki	×	×	×	×	×	×	×	×	×	✓
Bauer et al. (2000)	×	*R. flavipes* and Nasutitermes arborum	×	×	×	×	×	×	×	×	×	✓
Yang et al. (2005)	×	Reticulitermes santonensis	×	×	×	×	×	×	×	×	×	✓
Fisher et al. (2007)	×	*Reticulitermes flavipes*	×	×	×	×	×	×	×	×	×	✓
Stingl et al. (2005)	×	Reticulitermes santonensis	×	×	×	×	×	×	×	×	×	✓
Noda et al. (2005)	×	*C. formosanus* and Termitogeton planus	×	×	×	×	×	×	×	×	×	✓
Husseneder (2010)	×	Reticulitermes and Coptotermes	×	×	×	×	×	×	×	×	×	✓
Freymann et al. (2008)	×	Various species	×	×	×	×	×	×	×	×	×	✓
Sarr et al. (2001)	Stony ferruginous sandy loams	×	×	×	×	×	×	×	✓	×	×	✓
Zachariah et al. (2017)	Various types of soil	Odontotermes obesus termites,	×	×	×	×	×	×	×	×	×	✓

(×) - Not Considered, (✓) – Considered.
*UH- Unsaturated hydraulic conductivity, MS- mound soil, SS- surrounding soil.

evident that only tensiometers was used to measure suction in previous studies. There is an intrinsic shortcoming in utilizing the tensiometer, as it could only measure suction between 0.001 and 0.1 MPa (see Table 1). Given that soil with higher fine content induces large suction (> 1 MPa), a combination of instruments needs to be installed to measure suction accurately. In this perspective, installation of tensiometer coupled with thermal conductivity sensor (see Table 1) can be appropriate to measure high suction range.

5.2. Potential effects of termite actions on soil properties

Table 4 shows that spatio-temporal variation of void ratio due to termite activity which was another area which have been hitherto neglected by past researchers. A model for void ratio of a root permeated soil was proposed earlier based on the consideration that roots occupy soil pore space, thus, reducing the pore size (Ng et al., 2016). However, termite burrowing increases the void spaces in soil, thus increasing the void ratio. Taking this into consideration, the existing model has been modified to obtain a new model for void ratio of a termite mound soil:

$$e_{t(x,z)} = \frac{e_0 + V_{t(x,z)}(1 + e_0)}{1 - V_{t(x,z)}(1 + e_0)}$$

where e_0 is void ratio of original unsaturated soil, V is the volume of pores burrowed by termites per unit time, $V_{t(x,z)}$ is the variation of volume of pores with changes lateral (x) and longitudinal distances from the mound (z) and time (t). Pores burrowed by termites include forage galleries and ventilation channels. Furthermore, the developed relation can be used to predict the hydraulic and strength properties of termite modified soil.

5.3. Field monitoring of termite modified soil

Some of the previous studies conducted field monitoring in termite modified soil to understand the effect of termite activity on infiltration and runoff (Léonard and Rajot, 2001; Sarr et al., 2001; Mando et al., 1996). For instance, Elkins et al. (1986) showed that infiltration through termite modified soil could be up to 10 times higher than that under the absence of termites. In addition, number of foraging holes per square meter could also affect the significance of above-mentioned difference in infiltration. Infiltration was not measured during the entire period of termite mound construction to draw the above-mentioned conclusions. Another important factor to consider is the height of termite mound which increases with time (Kandasami et al., 2016), as it increases the fine content in termite mound (Léonard and Rajot, 2001). Infiltration decreases with increased fine content. In addition, soil cementation caused by saliva and faecal material may also decrease the hydraulic conductivity. Therefore, long term field monitoring is required to understand the hydraulic conductivity variation through termite modified soil. Such monitoring could help analyze the erosion and stability of termite modified soil or slopes accurately. Erosion of termite mounds also plays vital role in amendment of hydraulic and strength properties of surrounding soils (Mando et al., 1996). In addition, rate of erosion depends of composition texture, density and chemical composition of termite mound. Furthermore, stability of the termite mound also varies due to change in above mentioned soil parameters. These effects on erosion and stability were widely studied by geotechnical engineers for the case of slopes (Liu et al., 2015; Li and Yang, 2019; Scaringi and Loche, 2022), however, the stability of termite mounds was rarely analyzed in the past studies.

5.4. Efficacy of termite modified soil and termite activity in engineering applications

A few studies (Udoeyo et al., 2000; Adepegba, 1979) showed that properties of termite mounds possess characteristics of good construction materials. Biocementation is emerged as feasible approach to enhance performance and sustainability of geotechnical infrastructure. Udoeyo et al. (2000) observed that termite activity could double the unconfined compressive strength of the soil. Hence, soil from termite mound is used as construction material to build light weight structures such as cottages (Udoeyo et al., 2000). It should be noted that strength and hydraulic properties termite also depend on various types of termites and soil properties as discussed in Section 3. However, such dependence was rarely investigated in the past studies.

Consideration of type of termites and soil properties help to propose a novel physico-chemical composition of soil to amend the hydraulic and strength properties of soil. Termite mounds are foremost land scape features in grass lands (Pringle et al., 2010). Nutrients in termite mound are gradually mixed into surrounding soils due to erosion (Smith and Yeaton, 1998). This could increase the nutrient content by 7 times in the soil. In addition, nitrogen fixation is generally done by termites through their digestive tract (Zhou et al., 2008). Furthermore, nitrogen in termite biomass is released upon death of termites (Lilburn et al., 2001). Bonachela et al. (2015) and Sileshi et al. (2010) showed that termite activity can improve the robustness of deserts by enabling vegetation growth, implying that termites promote the vegetation growth when available water content is very low. It is known that maintenance of green infrastructure includes watering and nutrient supplementation. Establishment of termites can be studied by considering the soil parameters. It is evident that termites develop nests in the soil matrix. These nests may increase hydraulic conductivity and subsequent seepage flux (Weijin et al., 2004). Such increase in infiltration could likely reduce the stability and safety of the geotechnical infrastructure, and thus this aspect needs to be considered while developing field specific guidelines for termite application.

6. Conclusions

This study aims to explore and promote use of living termites (an insect species) as a facilitator for enhancing certain soil properties (water retention and strength) and growth of vegetation. Presence of termites can enhance soil aggregation in long term through its secretion of enzymes. Such aggregation enhances strength and also reduces permeability. Further, presence of termites, increases porosity, which can be crucial for water retention during rainfall. Future studies in both control (laboratory) and field are required to systematically analyze influence of termites on geotechnical properties of compacted engineered soil under various testing conditions (soil grain size, soil density and drying-wetting cycles). This may also help in ecological restoration of green infrastructure. The expertise from both geotechnical engineering and entomology is needed to plan future research with an aim to promote use of termites as maintenance engineers in geotechnical infrastructure.

CRediT authorship contribution statement

Ankit Garg: Conceptualization, co-supervision of second author and editing the original manuscript.

Vinay Kumar Gadi: Writing the original manuscript draft, preparation of figures and conceptualizing the research tasks.

Hong-Hu Zhu: Reviewing/editing and conceptualizing the methodology.

Ajit K Sarmah: Re-analysis of the results, technical guidance related to termite influence on soil, reviewing/editing and proof reading the final manuscript and correspondence.

P Sreeja: Supervision and mentor for the second author and review.

Sreedeep Sekharan: Technical guidance on hydrological effects of termites on soil, reviewing/editing.

Data availability

The authors are unable or have chosen not to specify which data has been used.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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