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Effect of biocementation on the strength and stability of termite mounds

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Termite mounds are bioengineered granular ensembles that remain stable over decades, a vital requirement for termite societies that house millions of individual termites. An experimental study on the mechanobiology of mounds and mound soil of the fungus-growing termite *Odontotermes obesus* (Rambur) demonstrated that termites are capable engineers. Mound soil was significantly different in its physical and mechanical properties compared to the surrounding or 'control' soil. However, mound and control soils did not differ in clay mineralogy. Utilising the finer soil fraction, termites altered the soil significantly by cohering grains through their secretions into units called boluses, in the presence of water. Termites modulated the amount of water close to the plastic limit of the soil while preparing these boluses such that the soil could be effectively moulded. The cementation effected by termites using their secretions and/or excretions enhanced the strength of the soil tenfold, which may not be achievable otherwise. The soil modification achieved by the termites decreased mound susceptibility to erosion and collapse. Termites successfully cemented foreign materials, suggesting a wide range of cementation abilities. Slope stability analysis with intact mound soil revealed a significant increase in the safety factor of the mound compared to that of reconstituted soil.

Introduction

Engineers are greatly interested in biocementation and its consequences on the engineering properties of substrates, ensembles and built structures. Biocementation as a viable technique for soil improvement has recently emerged to the fore, particularly for its optimal performance and environmental sustainability. For example, microbially induced calcite precipitation (MICP) is an important technique that involves bacteria that produce calcium carbonate precipitates and introduce 'biocementation' between the sand grains (Cheng *et al*., 2013). Besides MICP, there is also recent interest in the role of bioadhesives produced by higher organisms that result in biocementation and robustly engineered structures such as the reef-building 'concrete' tubes of marine sandcastle worms (Le Cam *et al*., 2011; Sun *et al*., 2007). While MICP-induced biocementation has been studied at multiple scales – that is, from the laboratory through on-site implementation, including the micromechanics of intergrain cementation (Cheng *et al*., 2013; DeJong *et al*., 2006, 2010; Whiffin *et al*., 2007), biocementation and engineered structures resulting from bioadhesives have received almost no attention.

Termite mounds are another important, yet not well-studied, instance of biocementation and bioengineered soil structures. These above-ground mounds, especially those of the fungus-growing termites, Macrotermitinae, have generated great interest among ecologists, entomologists, architects and soil chemists (Darlington, 1985; Jouquet *et al*., 2004; Korb, 2011; Worall, 2011). Despite the dominance of termite mounds as landscape elements in several habitats, there have been scant investigations of the exact engineering of soil modifications effected by the termites for construction of the mounds. Termite mounds are ensheathed by a soil shell within which there is an intricate assemblage of tunnels and cavities, as well as chambers for fungus in species of fungus-growing termites (Korb, 2011). The mound soil has an organo-mineral structure, and the mounds are visibly resistant to loading through cycles of natural forces and exhibit long-term temporal stability (Turner, 2000). In the recent past, the fact that temperature and gases appear to be regulated in these mounds (Korb and Linsenmair, 1999, 2000; King *et al*. 2015; Noirot, 1990) has generated further interest in the engineering science of these soil structures in the context of sustainable architecture and construction. Macrotermitinae termites, especially in the savannah ecosystem in Africa, have provided the backbone for many interesting studies on the utilisation of surrounding soil for mound building (Korb, 2011).

It has been conjectured that fungus-growing termites modify the soil adequately by segregating the soil clay fraction (Jouquet *et al*., 2002, 2003, 2004); additionally, these authors demonstrated some mineralogical modification by the termites, by the creation of 'expandable clay minerals'. The resistance to weathering or erosion of termite mound soils (alluded to as a criterion of stability by these authors) is also said to be enhanced predominantly because of the particle size segregation effected by termites (Abe *et al*., 2009). Jouquet *et al*. (2003) report about 30% increase in the clay fraction between mound soil and control soil. These authors also suggest that the size segregation effects mineral modification, which allows 'weaker shrinkage behaviour' in mound soils. Despite several investigations, a clear understanding of the properties of the source soil and the modifications of the termites to this soil to build a mound has not emerged. Even though substantial literature has accumulated towards documenting the micro-scale changes in the soil achieved by the termites (Jouquet *et al*., 2003), a cohesive view of the reasons for mechanical stability of termite mounds supported by an engineering perspective is not yet available. Glandular secretions and excretions from the termites are some of the factors that are known to contribute to cementation in termite mounds. Lee and Wood (1971a) and Wood (1988) explain that saliva is used as a cementing agent in the case of nest and gallery construction, while a Macrotermitinae termite uses its excretions for the construction of the fungal combs. Gillman *et al*. (1972) extracted the organic constituents from the mound walls and reported that these contribute to the cementation process. In a similar study on several mound-building termites of Brazil, Kaschuk *et al*. (2006) investigated the modifications in the chemical composition of mound soil effected by the termites, and reported that the difference in chemical composition between the mound and control soils arose from the increased organic content in the mound soil.

The primary goal of this paper is to investigate the engineering properties of mounds built by termites. The authors studied the fungus-growing termite *Odontotermes obesus* that builds large mounds that remain stable for decades. In addition to a stability analysis of the mound, a series of experiments were conducted, which examine the geometry of the termite mound; the physical, chemical and mechanical properties of the mound soil, compaction, packing and erodability. Mound soil properties were compared with those of control or surrounding soil. The authors also conducted experiments under laboratory conditions with termites that were provided foreign building materials, such as glass beads, and pure clays to examine termite capabilities in handling these materials. These investigations provide a novel understanding of the strength and stability of the mound resulting from the biocementation activities of termites.

Materials and methods

Study organism

The authors studied mounds of *O. obesus* (Rambur), a fungus-growing termite common in India (Batra and Batra, 1966; Bose, 1984; Chhotani, 1997; Manzoor and Akhtar, 2006). These mounds were located on the campus of the Indian Institute of Science (IISc), Bangalore, India (13·01° north, 77·33° east). The topsoil in the Bangalore area is a residual red soil ranging from 1 to 4 m in depth, formed from the weathering of the gneissic parent rock (Rao and Revanasiddappa, 2002). Mineralogical studies on this gneissic bedrock have revealed presence of minerals such as quartz, mica and feldspar and some quantity of non-expansive clay minerals such as kaolinite (Ramaiah and Rao, 1969). This residual soil is also highly porous with large variation in its on-site void ratios (Rao and Revanasiddappa, 2006). The groundwater level on the campus ranges from ~1 to 3 m in depth (M. Sekhar, unpublished data). The on-site soil remains predominantly unsaturated due to alternate wet and dry seasons, low groundwater conditions and loss of water due to greater evapotranspiration relative to precipitation; these soils are also susceptible to collapse (Rao and Revanasiddappa, 2002).

Physical attributes of the mound

Initially, physical characteristics, namely overall shape, height and girth, were recorded for 12 mounds that were present on the IISc campus. In order to comprehensively understand mound structure, one specific large mound, harbouring millions of termites that had been marked for destruction for campus development activities, was selected. Since the soil distributions and the species of termites are the same throughout the campus, one representative mound was considered sufficient for some aspects of this study. In addition to recording its external features, the representative mound was sectioned horizontally at 30 cm intervals using a mechanically operated handsaw to analyse its internal structure, network of cavities and fabric. No significant variation in soil properties was found within these sections. Every section was imaged from the top of the mound using a high-resolution digital single-lens reflex camera mounted in a fixed position to document the internal network of galleries or tunnels. The magnification, the position and the field of view of the camera were kept constant for all sections.

Measurement of soil physical properties

From the perspective of contribution to mound stability, soil properties such as density, porosity and particle size were investigated as a function of mound height by extracting samples from sections obtained from the representative mound along its vertical axis. These soil properties were assumed to have insignificant variation along mound girth. About three to five samples were cored out along the girth of the specimen, and the variation in the physical and mechanical properties of the soil was found to be insignificant. Additional samples were collected from different mounds on the IISc campus along with control soil (or surrounding soil) to examine variation across mounds. Control or surrounding soils were collected at three locations near every termite mound. To determine the quantities of phase relationships such as density, specific gravity and porosity, small cylindrical mound samples with an aspect ratio (length-to-diameter ratio) of 2 were cored out along the vertical axis of the mound. Precautions during the coring process ensured minimal cavities within these cores. Samples were oven-dried for 24 h, after which their dry densities (γ_d) were estimated from their average diameter, height and mass. The specific gravity was determined using a pycnometer bottle (ASTM-D854, 2010b). By using dry density (γ_d) and specific gravity (G_s), the porosity (n) of the mound soil at these locations was determined. In this study, about 99% of the disintegrated termite mound soil passed through the 75 μm sieve. Hence, only the fine fraction was chosen for further characterisation using a hydrometer (as per ASTM-D422, 2007). These hydrometer results were further verified using a laser particle size analyser (Easysizer20). The uniformity coefficient and the coefficient of curvature (Head, 1984) cannot be explicitly measured because only the fine fractions of the two soils were considered in this particle size analysis (i.e. particles < 75 μm). Atterberg limits such as the liquid limit and plastic limit were also measured, quantifying the consistency or workability of fine-grained soils (Head, 1984; Salgado, 2008). The liquid limit was determined using a cone penetrometer (ASTM-D4318, 2010a; BSI-1377, 1990), and the plastic limit was based on standard methods (ASTM-D4318, 2010a; Head, 1984). In addition to the Atterberg limits obtained from one particular mound, tests were also performed on several other mounds to quantify the variation in soil properties.

Measurement of compaction and packing properties of soil

The Proctor compaction test provides a relationship between the packing (or dry density) of soil in the presence of water (measured as water content) at a known or constant mechanical energy input. Proctor compaction tests (ASTM-D698, 2012; Germaine and Germaine, 2009) were conducted on destructured termite mound soil (manually with a wooden mallet) and control soils. These soils were mixed thoroughly with different amounts of water (estimated as a fraction of the weight of soil, i.e. 2–20% water content), cured overnight and compacted with a calibrated Proctor hammer.

Measurement of soil chemical/mineralogical properties

Pulverised samples of both mound and control soils were subjected to X-ray diffraction (XRD), from which their mineralogical composition was obtained. Samples were heated for 24 h at 100°C before XRD measurements. The organic content of mound and control soils was measured by loss on ignition (LOI) tests. Soil samples were oven-dried and ignited in a muffle furnace at 440°C (ASTM-D2974, 2014). The percentage loss in mass due to ignition provided an estimate of the organic content of soil samples. While the mineralogical analyses were restricted to only a few samples, measurements of pH and LOI were performed on multiple samples (four samples per termite mound). For pH, soil-water mixtures of 10 g of soil and 25 ml distilled water (ASTM-D4972, 2013) were stirred for 1 h and the aqueous solutions tested with a pH meter.

Measurement of soil engineering properties

Permeability depends on a number of factors, such as particle size, shape, texture, nature of fluid, temperature, porosity, type of flow and arrangement of the soil particles (i.e. soil fabric) (Cedergren, 1997). Assuming laminar flow of water (Reynolds number <1) through the soil and the validity of Darcy's law (rate of flow in direct proportion to hydraulic gradient), falling-head permeability tests were performed (Head, 1994) to measure hydraulic conductivity. A reconstituted sample of the termite mound (8·5 cm dia. and 2 cm height) was compacted to its on-site density and was saturated completely for this test. Similarly, experiments were carried out on control soils reconstituted to their maximum dry density. Different hydraulic heads were used, and the average hydraulic conductivity of the soils was estimated.

Since soils fail under a combination of normal and shear stresses, shear strength was also measured. In a direct shear test, for a given magnitude of normal stress, shear stresses are monotonically applied on the horizontal plane until failure. Soil collected from a termite mound in the form of clumps was disintegrated and compacted to a density of 1·68 g/cm^3 and water content of 17%. This density was closest to the maximum on-site density, with water content on the wet side of the optimum (see 'Results' section). The soil was monolithically placed into the direct shear box (6 cm × 6 cm). A horizontal displacement rate of 0·125 mm/min (ASTM-D3080, 2011a) was applied to the upper half of the box, and shear forces were measured at three different normal loads (the corresponding normal stresses were 50, 100 and 150 kPa). For different magnitudes of normal stresses, the corresponding shear stresses at failure were plotted and a linear fit was made. Unconfined compression tests were also performed on on-site samples, having a standard aspect ratio of 2, cored out of various sections of the mound and oven-dried for 24 h. A minimum sample diameter of 30 mm was maintained, and an axial deformation rate of 0·5%/min (ASTM-D2166, 2006) was employed during these tests. Control soils were compacted to the maximum dry density at an optimum moisture content and tested under unconfined compression conditions after oven drying for 24 h.

The collapse or erodability of soils was also measured. Collapse in residual soils, of the type that occur in the study site, was earlier measured by compacting the soil into an oedometer ring and loading it under unsaturated conditions. In such tests, a slow ingress of water is allowed into the loaded oedometer ring, inducing a collapse (Rao and Revanasiddappa, 2006) and the collapse potential is determined. Additionally, tests proposed by Le Bissonnais (1996) using fast wetting, slow wetting and stirring after pre-wetting have been used to determine the aggregate stability of soils (see Jouquet *et al*., 2002, for termite mound soils). These methods provide an estimate of the aggregate stability of the soil and the breakdown of capillary bonds in the presence of water. In this study, collapse or erodability was measured by subjecting on-site samples of termite mound soil to alternate cycles of wetting and drying (akin to the crumb test for dispersive clays (Head, 1984)). Differently sized samples (150–200 g) were soaked in water for specified periods of time (2, 4, 8, 16, 32, …, 100 min) and then dried before weighing. These alternate wetting and drying cycles were repeated with increasing immersion/soaking time until the entire sample was completely disintegrated. The loss of weight was related to the failure of the intergranular contacts due to the presence of water.

Behavioural experiments on termites to examine their utilisation of mound-building materials

Experiments with termites were conducted in plastic containers (25 cm × 15 cm × 7 cm) lined with black paper to simulate the dark internal conditions of the mound. The base of the containers was lined with waterproof sandpaper to provide traction for termite locomotion. The containers were subjected to ultraviolet radiation for 45 min to sterilise them. They were lined with sterilised plastic piping containing water with small perforations to facilitate water availability to termites for bolus construction. The biological term *bolus* is a collection of soil particles accumulated by individual termites to form a ball-shaped structure using its secretions, which are used in mound building. Two small vials each containing 5 g of sodium bicarbonate ($NaHCO_3$) for carbon dioxide (CO_2) production and two vials each containing 19 g of zinc sulfate heptahydrate ($ZnSO_4{\cdot}7H_2O$) for the maintenance of humidity were placed within these containers. To each vial, 10 ml of distilled water was added. Weighed amounts of the following materials were provided in different paired combinations to termites: control soil, glass beads, pure kaolinite, pure montmorillonite and sieved red soil at three different particle sizes (<75, 75–150 and 150–300 μm). A small quantity of fungal comb was placed in the centre of the container with the two choices of building materials on either side, to stimulate the termites to cover it with the materials provided. For each experiment, based on the success of earlier trials and to achieve results within a reasonable time, 155 termites (85 major workers, 40 minor workers and 30 soldiers) were released into each box. For all experiments, termites from only one mound (I23) from the IISc campus were used. The containers were closed, and the termites were allowed to use the building materials. The usage of the material by the termites was recorded qualitatively. The paired choices were so selected so that it could be determined by texture or colour which material had been employed by termites. For example, a visually indistinguishable paired choice of soil of <75 μm and that of 150–300 μm was not provided. Each experiment was run for 24 h.

Results

Physical attributes of termite mounds

Two specific shapes of mounds, conical and dome shaped, were identified at the study site. The height-to-girth ratio of the mounds (measured at the base) was between 1 and 2. The mean aspect ratio is approximately 1·57 ± 0·26 standard deviation (results from 12 mounds). A typical mound is featured in Figure 1(a). This mound had a basal diameter of 105 cm and a height of 210 cm; it had eight arms (i.e. projections) from the central core. For simplicity, this mound was approximated as a right circular cone with an overall volume of $6{\cdot}1 \times 10^5$ cm^3. This mound (Figure 1(a)) was sectioned horizontally at 30 cm intervals (Figures 1(b)–1(f); image captures in plan). The sections provide an insight into the network of galleries and tunnels created in the construction. The mound consists of an outermost shell with thick walls (4–5 cm) at the base of the mound and thinner walls at the apex (1 cm). Section images were superimposed by controlling their transparencies and collated to identify the vertical continuity of cavities in the mound (Figure 1(g)). A large central cavity was present throughout the height of the mound. Several vertical cavities also occurred in all arms. The bottom most section of the central region of the mound had a large cavity where the fungi are predominantly grown and chambers for the secondary queens were present.

Soil physical properties

The mound soil was denser at the base, and its dry density gradually declined with mound height. The density was approximately 1·42 g/cm^3 at the top of the mound and increased to about 1·68 g/cm^3 at the base (Figure 2(a)). The higher density at the base can be attributed to the increased densification (or consolidation) of the soil due to the effects of gravity with time. The porosity of mound soil varied from 37% to 47%, with porosity increasing with mound height (Figure 2(b)). The specific gravity of both the mound soil and the control soil was found to be 2·67.

In order to examine the particle size distribution of the mound soil, percentage fractions by weight smaller than a series of particle sizes are plotted as particle size curves (Figure 2(c)). The termite mound soil was characterised by a mean particle size of ~6 μm, while the control soil had a mean particle size of ~20 μm. Very little variability was observed in particle size through the height of the mound (see Figure 3).

The Atterberg limits of control soil and termite mound soil obtained from different sections along the height axis of the experimental mound were investigated. The liquid limit and the plastic limit of both mound and control soil were 33% and 17% respectively. The Atterberg limits were remarkably consistent for all mound sections and also for other mounds present in the study area (see Figure 4). The unified soil classification (ASTM-D2487, 2011b) was used to classify the soil based on the liquid and

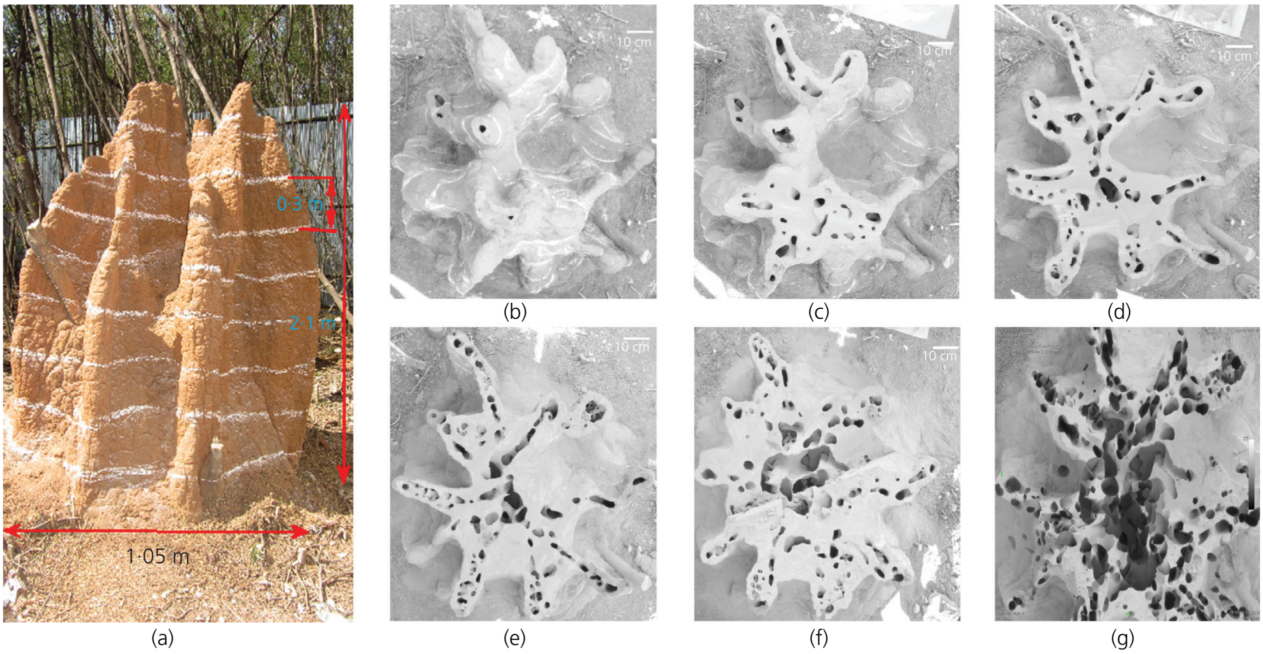

Figure 1. (a) Typical termite mound used in this study for sectioning and studying the galleries/tunnel patterns. The white lines indicate the interval (0·3 m) between the sections. (b–f) Sequence of sections of a termite mound shown in (a) to identify the tunnels and galleries. (g) Collated images of (b)–(f) used to identify the continuity of the cavities found in the termite mound. The cavities or voids that pervade the length of the mound are highlighted as dark regions in this collated image

plastic limits; both the mound and control soils were found to be inorganic clay with low compressibility. A set of fresh samples of termite-manipulated soil (collected immediately after an intentional breach was made in the mound and the termites started to seal the opening) was collected from termite mounds. The on-site moisture content of these samples was about 17%, which is equal to the plastic limit of the soil. This water content appears ideal for moulding the soil to the required shape, and the termites agglomerate the soil particles in the presence of moisture along with their secretions into an almost spherical structure, which is referred to in this study as a 'bolus' and which the termites employ as the basic mound-building unit. A scanning electron micrograph of a bolus is presented in Figure 2(d); in general, the bolus size is about 100–200 times the mean soil particle size. This bolus is the unitary structure of the termite mound construction, and boluses are used to build the entire mound structure. A bolus can therefore be construed as being similar to a brick in a masonry structure.

Compaction and packing of the soil

In the compaction tests, the range of densities achieved with different moisture contents results in a typical bell-shaped curve (Figure 5) about the highest density (or OMC). The laboratory standard Proctor compaction curves obtained also include a zero-air void line, indicative of the achievable densities when no air voids (complete saturation) are present at given water content. The destructured termite mound soils (soils that were completely homogenised) and control soils when compacted in the laboratory had a maximum dry density of 1·85 g/cm^3, corresponding to an OMC of 14% (Figure 5). Termites therefore prepare their boluses at water contents (i.e. 17%) that are greater than the OMC – that is, on the wet side of optimum. The dry density measured from a sample extracted from the wall of a mound (on site) was between 1·68 and 1·42 g/cm^3 – that is, about 9–23% lower than the maximum achievable dry density in the laboratory.

Soil chemical/mineralogical properties

In general, the mineralogical analysis showed no major difference between the mound soil and the control soil, with quartz and kaolinite being the major constituents; a sample XRD result is presented in Figure 6. No other major minerals were identified in both soils. The organic content was 4–5% in both the mound and control soils. Therefore, the mound soil is not significantly different in clay mineralogy from the control soil. The pH of the termite mound samples varied from 6 to 7, indicating a slightly acidic soil (similar to the studies performed by Dhembare, 2013, on termite mound soils). The changes in the pH primarily depend on the species and soil type. The mineralogical composition, the pH and the organic content measured from different mounds (presented Table 1) in the study area suggests that the soils of different mounds have similar mineralogical properties in addition to physical properties such as grain size and Atterberg limits.

Soil mechanical properties

The physical and chemical properties of a soil mirror the engineering/mechanical properties of that soil. As the Atterberg

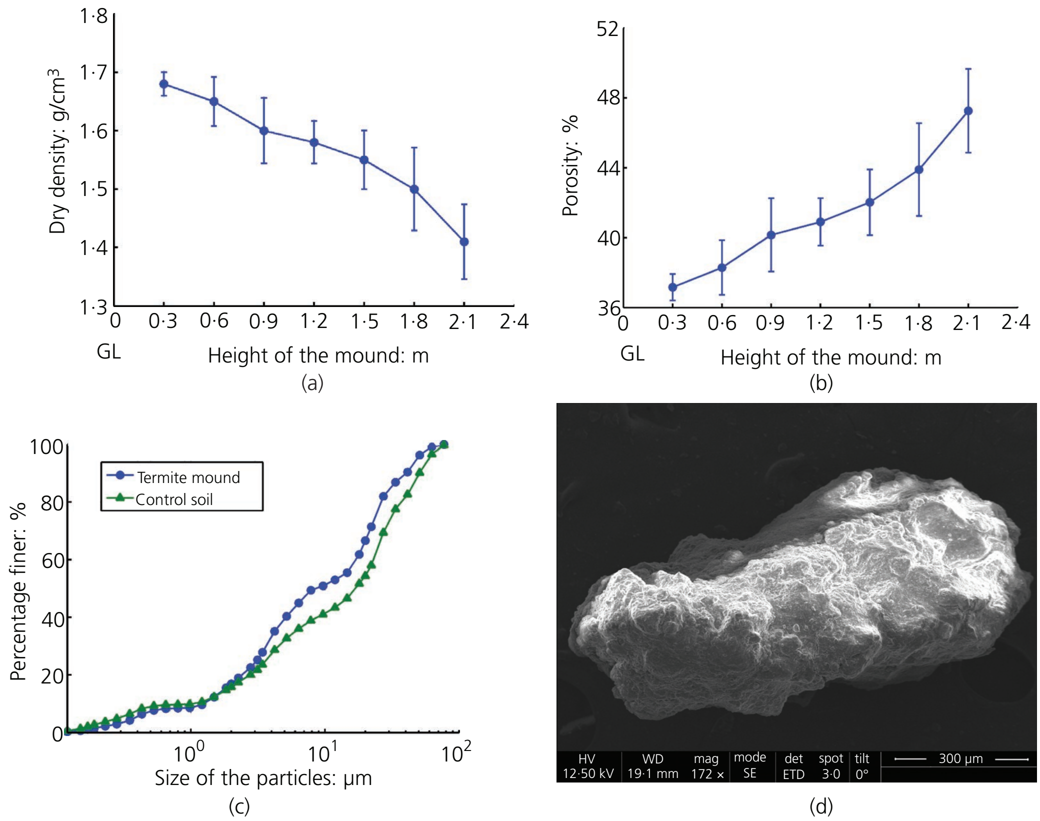

Figure 2. (a) Variation of dry density in mound with elevation. The abscissa shows the height of the termite mound from ground level (GL). (b) Variation of porosity at different levels of the mound. The abscissa shows the height of the termite mound from ground level (GL). (c) Cumulative particle size distributions of mound soil (shown in Figure 1(a)) and control soil obtained using particle size analyzer. (d) Scanning electron micrograph of a bolus (building unit of termite mounds) which is about 100 to 200 times the mean grain size (taken from (c))

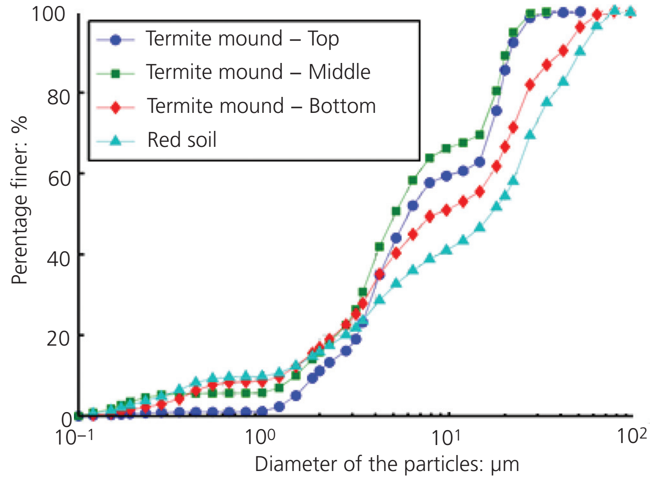

Figure 3. Particle size distributions of the mound soil (top, middle and bottom) and the control soil. The mean particle size of the termite mound soil is three to four times smaller than that of the control soil

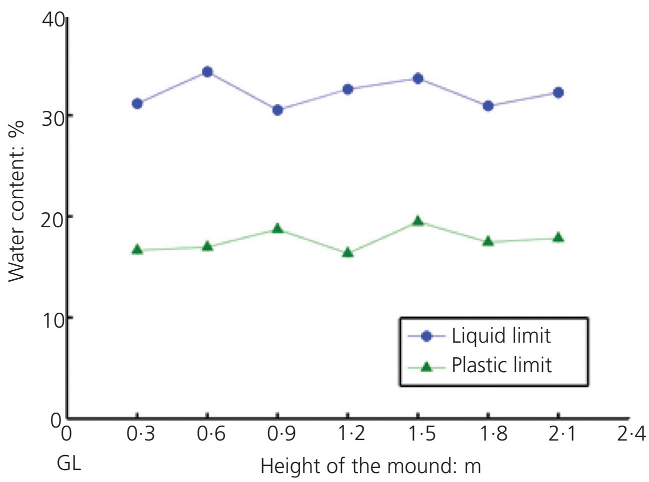

Figure 4. Atterberg's limits at obtained from different locations of the mound. The liquid limit and the plastic limit are almost constant throughout the mound

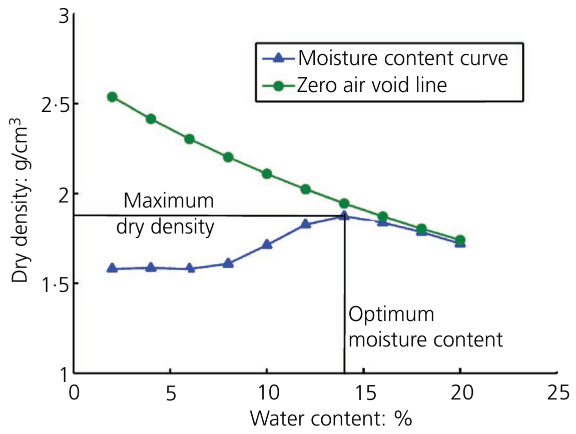

Figure 5. Compaction results indicating the maximum dry density and OMC of the reconstituted mound soil. The experiments were performed by applying a controlled energy to the soil-water mixture to achieve the densest packing possible

limits and chemical properties did not vary in the area of study across mounds, the authors concluded that the mechanical properties would also not vary through the different mounds. The study was therefore restricted to only one mound; however, the results on the mechanical behaviour of termite mounds are equally applicable and valid for other mounds in this area of study, since the source soil of these mounds remained the same.

The hydraulic conductivity of the termite mound soil obtained from the falling head permeability test was 5×10^{-5} to 6×10^{-5} cm/s (Table 2). However, these tests when performed on the control soil at its maximum dry density resulted in a permeability of about 3×10^{-5} to 4×10^{-5} cm/s, which was slightly lower than that of the termite mound soil (Table 2). The permeability of water through the soil indicates an upper bound for the movement of other fluids of lower viscosity through the soil sample. The control soils with lower density are highly permeable compared to the mound soil and the control soil with maximum dry density. The cohesion and the friction angle determined for the destructured termite mound soil, when reconstituted at the on-site density, were 20 kPa and 25° respectively, as determined from the peak shear stress and normal stresses in direct shear tests (Figure 7(a)). However, the control soil, when reconstituted to its maximum density, had a cohesion value of 40 kPa and a friction angle of 27°. The cementation provided by the termites to the soil was destroyed once the soil was remoulded; hence, reliable estimates of the frictional resistance were obtained from these tests. Cylindrical specimens cored out from the termite mound (such that the cavities, fissures etc. are minimised to a great extent) were used to estimate the on-site compressive strength of the mound soil using an unconfined compression test where the cohesion component in the soil was estimated to be half the strength in uniaxial compression ($C = q/2$). During the unconfined compression of a soil sample, the stress gradually increases up to a peak value, after which it decreases. As is typical in the case of

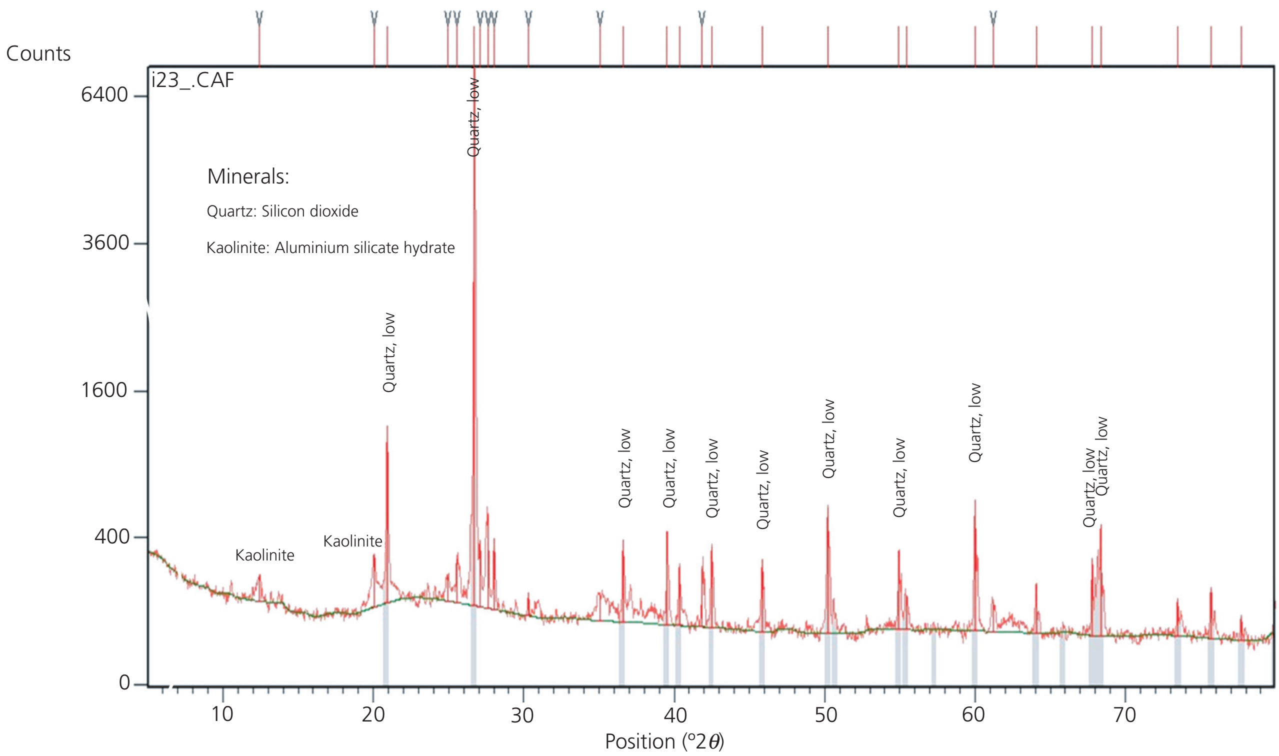

Figure 6. The inorganic mineralogical composition of the termite mound soil as illustrated with a sample XRD result

Mound number	Liquid limit	Plastic limit	Plasticity index	XRD	pH	Organic content
I10	34·6	17·85	16·75	Quartz and kaolinite	7·53	5
I12	35	16·67	18·33	Quartz and kaolinite	6·52	4·93
I27	34·47	15·38	19·09	Quartz and kaolinite	6·98	4·82
5	33·7	16·98	16·72	Quartz and kaolinite	—	—
2	36·21	18·32	17·89	Quartz and kaolinite	—	—

Table 1. Physical and chemical properties obtained from various mounds in the IISc campus. Since the soil in this specified area is the same, the mound properties are also very similar

any cohesive-frictional granular ensemble (Mitchell and Soga, 2005), the load is resisted initially by the cohesion between the soil particles. On further loading, the cohesion between the particles breaks down, and this can be identified from the peak of the stress-strain curve, beyond which a drastic reduction of the stress is usually recorded.

The peak strength of the material was about 1500 kPa (Table 2). Uniaxial compression test results obtained from cores at the top and bottom of the mound are presented in Figure 7(b). Samples obtained from the bottom of the mound had a slightly elevated magnitude of strength due to increased density (Figure 2(a)) and reduced porosity (Figure 2(b)). There was nearly a 25% increase in peak compressive strength at the bottom of the termite mound compared to the top (Figure 7(c)), with strength values ranging from 1200 to 1800 kPa (Table 2). Unconfined compression tests performed on the control soil remoulded and packed at the maximum dry density had strength values between 125 and 150 kPa (Table 2), indicating a tenfold decrease from the strength of intact termite mound soil.

Termite mound samples disintegrated about 20% when soaked in water for around 100 min, after which the collapse was rapid (Figure 8). Erosion in the presence of water occurred at a much

Properties	Termite soil	Control soil
Physical properties		
■ Particle size	5–75 µm; mean 6–10 µm	5–250 µm; mean 20–25 µm
■ Atterberg limits		
■ Liquid limit ■ Plastic limit	Liquid limit 33–36%; plastic limit 16–18%. No spatial variation of the Atterberg limits was found.	Liquid limit 33–36%; plastic limit 1–18%
■ Dry density	1·42–1·68 g/cm^3. The on-site density varied with height of the mound.	The on-site density measurements are not applicable here.
■ Porosity	37–47%	
Chemical properties	Predominantly silicate and kaolinitic minerals	Predominantly silicate and kaolinitic minerals
Mechanical properties		
■ Unconfined compressive strength	1200–1800 kPa. The on-site compressive strength varied with height of the mound.	125~150 kPa. The compressive strength was measured at maximum dry density.
■ Hydraulic conductivity	5×10^{-5} to 6×10^{-5} cm/s	3×10^{-5} to 4×10^{-5} cm/s
■ Shear strength parameters		
■ Cohesive intercept (c) ■ Internal angle of friction (ϕ)	$\phi = 25°$ and $c = 20$ kPa when termite mound soil was reconstituted to the maximum on-site density	$\phi = 27°$ and $c = 40$ kPa when termite mound soil was reconstituted to the maximum dry density

Table 2. A compilation of the soil properties of both the termite mound soil and the control soil

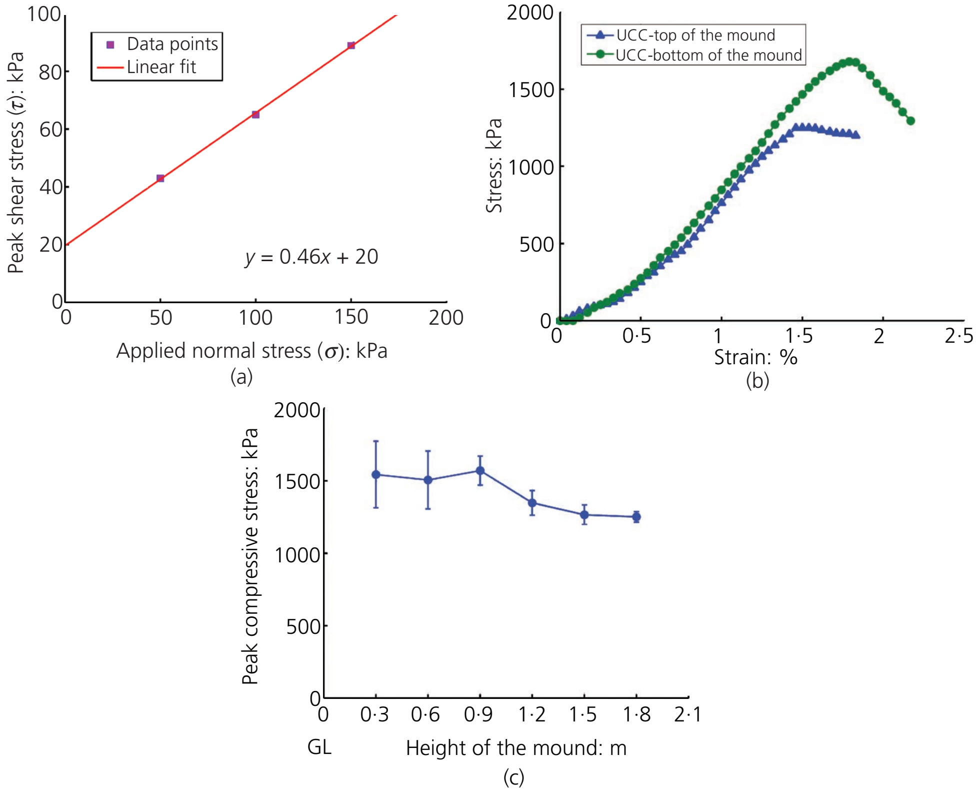

Figure 7. (a) Direct shear test performed at three normal loads to determine the shear strength parameters (cohesion and friction angle). The y intercept gives the cohesion value, and the slope of the linear fit gives the friction angle. (b) Variation of stress against strain obtained by testing under unconfined compression (UCC). Samples were tested from the top and the bottom of the mound. The stress gradually increases up to a peak value, after which it decreases. (c) Variation of the peak compressive strength at different elevations of the termite mound from ground level (GL)

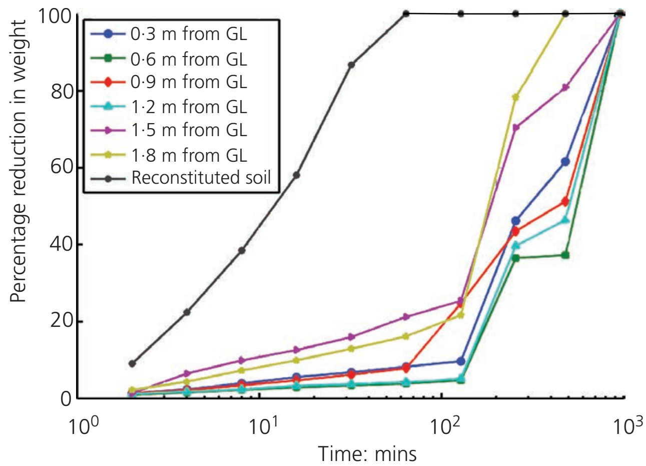

Figure 8. Weathering experiments (alternate wetting and drying) to determine the stability of the mound performed on the mound soil obtained from different parts of the mound with increasing time intervals (wetting time interval) and compared with the reconstituted soil. The legend in the figure indicates that the samples were collected at different heights from ground level (GL)

faster rate at the top of the mound, where the density was low and the porosity was high. When the mound soil was disintegrated, reconstituted to its on-site dry density and subjected to alternate wetting and drying tests, a dramatic collapse at a much faster rate (100% collapse in 60 min; Figure 8) was observed for the reconstituted sample when compared to the termite mound samples. The on-site termite mound samples exhibited increased resistance to weathering due to termite-induced cementation. The on-site resistance to erosion is expected to be greater as the complete immersion of the mound in water is likely to be a rare event under natural conditions. A compilation of all the properties of the termite mound soil and the control soil obtained in this study is provided in Table 2.

Behavioural experiments on termites to examine their utilisation of mound-building materials

Termites (major and minor workers) used the materials offered to them to make boluses as they do with natural soil. Individual termites (with the exception of soldiers) collected material and cemented them into boluses. Further, they aggregated these boluses into piles that covered the fungus comb and also deposited them on the walls and floor of the experimental boxes in some

Choice of samples given (choices within one set were done on the same day)	Quantitated by	Qualitative results
Soil against kaolinite	Weight/weight	Both materials utilised
Montmorillonite against soil		Both materials utilised. In this set, montmorillonite was used relatively more often than kaolinite.
Mixture of kaolinite and glass beads on both sides	Volume/volume	Small clusters made
Kaolinite against glass beads		Both utilised
Soil <75 μm on both sides	Weight/weight	Began to cover fungal comb
Soil 75–150 μm on both sides		Began to cover fungal comb
Soil 150–300 μm on both sides		Fungal comb almost completely covered

Table 3. Experiments on the choice of building material by termites

cases. Termites were able to utilise all the materials offered to them to build a covering over the fungus comb in the experimental boxes (Table 3). This suggests that they can provide cementation for the entire range of materials that were employed in these tests and could utilise them for building. Even with materials other than soil, termites formed boluses of these foreign materials and agglomerated these boluses to cover the fungus comb.

Discussion

Termite mounds are a dominant feature of open grassland and savannah-woodland landscapes in the tropics (Korb, 2011), where they can reach a density of 200 mounds per hectare (Lepage and Darlington, 2000). The impressive mounds of the Macrotermitinae termites can tower to 8 m (Korb, 2011) and house millions of termites, their fungus chambers, termite brood and mature reproductive individuals (Evans *et al*., 1998). Considering the energy that must be expended in mound building at this scale, the quantity of building material handled and the fact that the mound serves as a shelter for millions of individuals, a necessary feature of such mounds is their long-term temporal stability (that can endure for at least up to two decades (RM Borges, personal observation). Natural selection acting over millions of years on these termite builders (Nobre *et al*., 2011) has consequently resulted in stable housing that has enabled termites to occur in vast areas in the tropics. The results of this study have not only helped to elucidate an engineering framework that termites must employ for the building of such a mound but have also suggested constraints that termites face during this construction. For example, the mounds of *O. obesus* examined in this study collapse under certain regimes of wetting, which suggests that such termite mounds can be restricted only to drier climatic zones or those where rainfall spells are not prolonged. It is therefore not surprising that the Macrotermitinae termites such as *O. obesus*, although very common in India (Chhotani, 1997), are more common in regions where soils are not waterlogged (Sen-Sarma, 1974) and in deciduous forest types, which receive moderate rainfall (Roonwal and Chhotani, 1989).

These experiments are relevant for an understanding of the hierarchical particle arrangement (or fabric structure) in the structure-function relationship of the mound system. The termites utilise the finer fraction of the soil, as indicated in the results of the particle size distribution; the mean particle size of the mound soil is almost four times smaller than that of the control soil (as shown in Figure 2(c) and Table 2). It is clear that among the modifications effected by the termites, employing soil of a tighter particle size distribution is distinctive. While the use of the soil finer fraction has been noted in prior studies of mound soil properties (Abe *et al*., 2009; Jouquet *et al*., 2002, 2003, 2004), this study found that the Atterberg limits (which are commonly used as signatures of clay mineralogy) were not different between the two soil types (mound and control). This confirms that termites are not effecting any changes in clay mineralogy of the mound soils, contrary to what has been suggested by some researchers (Jouquet *et al*., 2002). The Atterberg limits also mirror the engineering properties of these soils, as widely reported in the soil mechanics literature (Atkinson, 2007; Craig, 2004; Lambe and Whitman, 1969; Salgado, 2008). Udoeyo (2000) performed a series of compaction tests on *Macrotermes bellicosus* termite mound soils in Nigeria. This clayey sand exhibited a liquid limit of 40–50% and a plastic limit of 19%, which is slightly greater than the Atterberg limits obtained from the non swelling clayey termite mound soil used in this study. Additionally, Udoeyo (2000) obtained the OMC of about 18% through a series of compaction tests and this value of OMC was found to be greater than the OMC observed in this study. This is not surprising since the Atterberg limits and the compaction characteristics are inherent soil characteristics. The XRD studies reaffirm that the mineralogy remains by and large unaltered after manipulation by the termites; similar observations have also been reported using extensive chemical/mineralogical characterisation by Kaschuk *et al*. (2006). Rao and Revanasiddappa (2006) have also reported the same mineralogy as seen here in these results – that is, predominant presence of quartz and kaolinite. This finer clay fraction probably contributes to a more efficient capillary action

(Mitchell and Soga, 2005) that allows movement of water to the upper reaches of the mound (Turner, 2000). It is conjectured in this study that the termites agglomerate this fine soil into a unitary structure or bolus in the presence of moisture. These boluses are prepared by moderating the ambient water availability to a water content that is almost equal to the plastic limit of the soil, which, as stated earlier, is perhaps most suitable for moulding the soil. These unitary structures or boluses are handled by the termites and utilised for construction of the extended phenotype of their mound. The average size of the bolus formed by the termite seems to depend on the caste of the termite (N. Zachariah, unpublished results). Under this schema, the mound is an agglomeration of boluses, which in turn are made from cementation of soil particles. The boluses are also most likely held together by the cohering action of glandular secretions and/or excretions from the termites to form different features of the mound. This biocemented fine-grained soil with its hierarchical fabric exhibited enhanced properties when compared to the control soil. Additionally, this enhancement of strength is also aided by the significant matrix suction present due to unsaturated conditions (Mitchell and Soga, 2005) in the mound. Studies on the nature of these boluses, the chemistry of the material of termite origin causing the cementation between boluses and their correspondence with soil manipulation by the different castes of termites are currently being investigated.

When termite mound soil was subjected to unconfined uniaxial compression testing after oven-drying, it exhibited a strength of about 1500 kPa compared to the control oven-dried soil samples, whose strength was about 150 kPa. This hierarchical termite soil fabric structure therefore imparted a tenfold increase in strength, which is quite remarkable. When the termite soil was reconstituted (or remoulded to remove the cementation due to secretions), it did not differ significantly in frictional strength from the control soil as determined by the direct shear tests, suggesting that it is the cementation effect of the secretions and particle segregation that contributed in most part to the tenfold strength increase. Manuwa (2009) also showed a slight increase in the strength of the remoulded mound soil as compared to the control soil through a series of Proctor compacted specimens using vane shear.

Interestingly, these mound soils also show an enhanced resistance to erosion or weathering when compared to the control soil or the remoulded soil. Also, studies on the hydraulic conductivity (Dowuona *et al*., 2012) of both termite mound soil and control soil revealed that the termite mound soil is less permeable than the control soil, akin to this study's results. The control soil, which is a residual soil (soils formed due to the weathering of underlying gneissic rock), demonstrated an increased propensity to collapse under wetted loads (Rao and Revanasiddappa, 2002). Studies by Ackerman *et al*. (2007) on the water retention characteristics of the mound soil showed that it has a lower water retention capacity and higher water repellency due to the intrinsic bonds that are developed due to the organic material (saliva and excretions) present in the soils. Structural stability, particularly under partially saturated conditions, is probably imparted to a collapsible soil by matrix suction that stabilises the intergrain contact. Addition of more water, or saturation of the soil, could weaken the capillary bonds and cause the intergranular contacts to fail, resulting in collapse (Burland, 1961).

The ability of a granular ensemble to resist loads is predominantly derived from intergrain friction. The fabric of the termite mound soil has an additional component of cohesion that can only be effected by material of termite origin that is added to the soil during bolus manipulation. This cohesive-frictional granular ensemble is further strengthened by the matrix suction in the clay fabric. The authors conjecture that such a fabric is likely to have enhanced resistance to structural degradation and weathering of the mound. Perhaps the chemistry of the termite materials and their interaction in the presence of varying amounts of water will throw light on this unique soil fabric. This presence of matrix suction in the fine soil and the stability it confers can perhaps be used to explain the predominance of mounds in the drier savannahs of Africa and central India, where they are often believed to be built where the groundwater level is suitable (Mège and Rango, 2010). Therefore, the epigeal (or above-ground) termite mounds are likely to be stable in drier climatic zones, where they are dominant (Davies *et al*., 2014; Dawes-Gromadzki, 2008).

The authors also find it significant that termites, when provided with a choice of materials with largely different mineralogy (i.e. chemical properties) (Table 3), did in fact use the availability of water to form boluses with clay minerals such as kaolinite (slightly plastic clay with liquid and plastic limits of 58% and 36% respectively) and montmorillonite (highly plastic clay with liquid and plastic limits of 600% and 100% respectively) (Mitchell and Soga, 2005). This suggests that the Macrotermitinae termites, which are widely distributed in India, may be able to utilise diverse soil types and adjust their water contents accordingly to build their mounds.

Stability analyses of termite mounds

In order to understand the significance of biocementation in the fabric of mound soil, a simple theoretical exercise of limit equilibrium slope stability analysis was conducted. The soil properties estimated from the results of this study were used for this exercise. The geometry of the slope was modelled as a cone, using mound dimensions of height 210 cm and a base width of about 105 cm (similar to the mound examined in Figure 1(a)). Observations from different mound geometries confirm that the aspect ratio of termite mounds lies between 1 and 2. This means that the slopes of the mounds were anywhere between 45° and 75°. This steep slope may not be optimally stable, particularly under saturated conditions, considering only frictional properties. The stability of the slope depends not only on the geometry of the slope but also on the shear strength parameters (cohesion and friction) of the soil. A two-dimensional analysis was performed under axisymmetric conditions using cohesion (obtained from the unconfined compression experiments) and friction (obtained from direct shear experiments) under saturated soil conditions. The steep mound geometry and saturated conditions of the soil, under which the slope stability analysis was performed, present an ‘extreme situation’ under which mound stability was modelled. In actuality, conditions are likely to be much less stringent. This analysis was carried out based on the method of slices, where the sliding mass above the failure surface was divided into a number of slices and a force balance was performed to calculate the factor of safety. A limit equilibrium approach, employing methods such as those of Bishop, Janbu and Spencer (Salgado, 2008) for the stability analysis (all based on method of slices) was used here. In this study, the limit equilibrium method is used because of its simplicity and accuracy and also for its easy implementation.

A circular failure surface was selected for the stability analysis and a safety factor calculated using this analysis (Figure 9). The safety factor, obtained when the mound geometry and the ion-site mound soil properties were used, was about 89, indicating that the slope (mound) would remain extraordinarily stable even under these extreme conditions (Figure 9). However, it must be noted that this analysis indicates an upper bound in stability since termite mounds have a large number of voids, tunnels and cavities in them, which will reduce the overall mound stability. Future studies will take into account the presence of these voids in stability analyses. A safety factor of only 3 was obtained when the reconstituted mound soil properties were employed (Figure 10). The 30-fold difference in safety factor values obtained between intact and reconstituted mound soil suggests that the increased stability of the mound results from the presence of cohesion in the soil imparted by the termites. Therefore, the hierarchical structure of the termite mound, comprising a fine-grained soil with intergrain cementation, a bolus structure and interbolus cementation, appears to be a major contributory factor to stability.

Conclusion

This paper presents a series of experimental results examining and quantifying the enhancement of engineering properties of the mound soil effected by termites. While this information is in itself of value for a deeper understanding of phenomena such as termite mounds, the importance of the results for other types of bioengineered constructions cannot be overlooked (Kraus *et al.*, 2013). Quantitative studies of the agglomeration of the soil into boluses, packing of the boluses and the emergence of the eventual stable mound structure present very interesting problems at multiple length scales ranging from a few microns (particles) to the boluses to the mound (manifold increase), and should enable development of the theory of biocementation in termite mound soils. It also observed that the termites are capable of utilising other materials in the presence of water for building their mounds. It is possible that the insights presented in this paper will provide new bioengineering constraints and approaches to understanding the distribution of termites, which have hitherto been explained by conventional ecological factors such as termite feeding ecology and ecophysiology (Eggleton and Tayasu, 2001). The termite system will also provide interesting insights into the

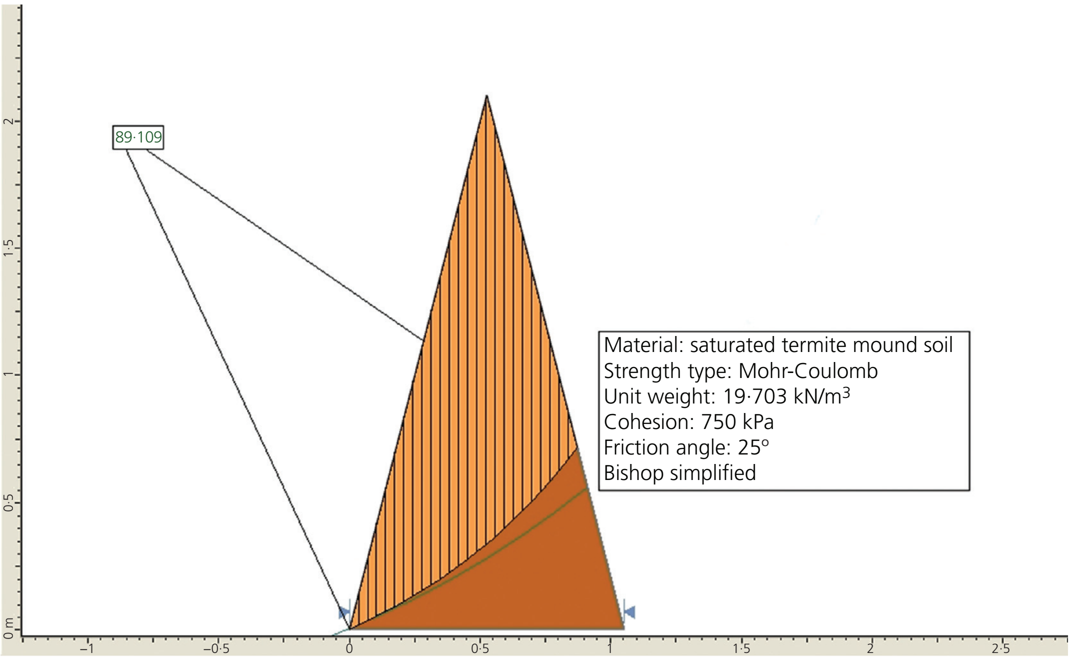

Figure 9. Slope stability analysis performed at on-site conditions using the limit equilibrium package Slide to obtain the factor of safety against failure. The value of 89·109 indicates the safety factor

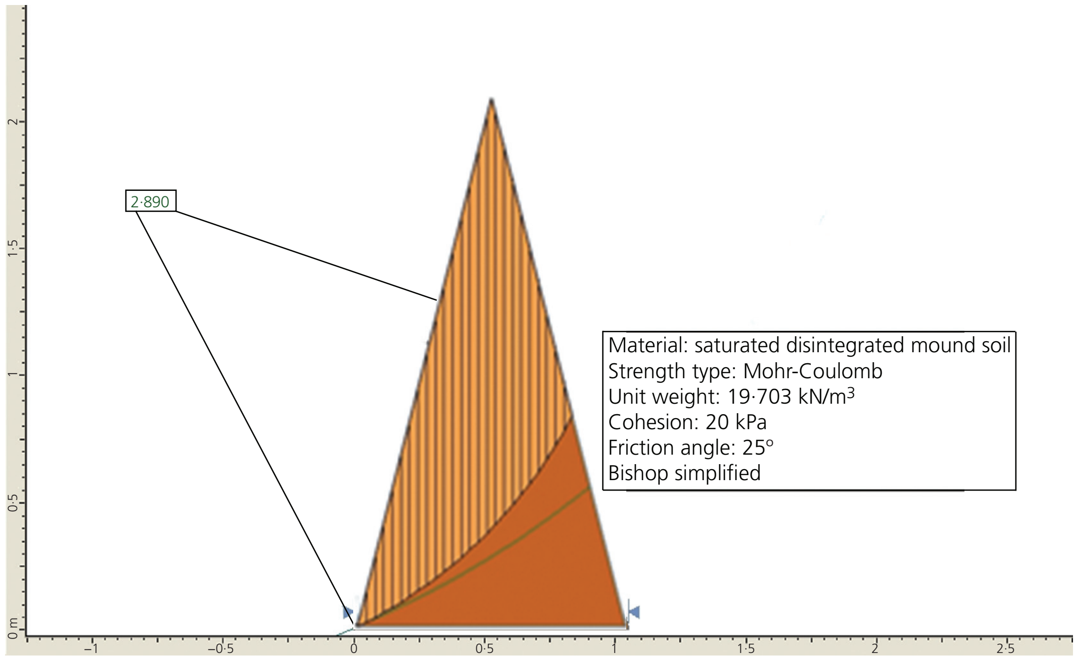

Figure 10. Slope stability analysis performed with the remoulded termite mound soil properties obtained from direct shear using Slide to obtain the factor of safety against failure

biocementation to robust structures such as the giant reefs built by sandcastle worms (Endrizzi and Stewart, 2009; Stewart *et al*., 2011) or deep ocean crusts impregnated with marine worm clay castings which effect pipeline stability (Kuo and Bolton, 2013).

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REFERENCES

Abe SS, Yamamoto S and Wakatsuki T (2009) Soil-particle selection by the mound-building termite *Macrotermes bellicosus* on a sandy loam soil catena in a Nigerian tropical savanna. *Journal of Tropical Ecology* **25**: 449–452, http://dx.doi.org/10.1017/S0266467409006142.

Ackerman IL, Teixeira WG, Riha SJ, Lehmann J and Fernandes EC (2007) The impact of mound-building termites on surface soil properties in a secondary forest of Central Amazonia. *Applied Soil Ecology* **37(3)**: 267–276, http://dx.doi.org/10.1016/j.apsoil.2007.08.005.

ASTM (2006) D 2166: Standard test method for unconfined compressive strength of cohesive soil. ASTM International, West Conshohocken, PA, USA.

ASTM (2007) D 422: Standard test method for particle-size analysis of soils. ASTM International, West Conshohocken, PA, USA.

ASTM (2010a) D 4318: Standard test methods for liquid limit, plastic limit, and plasticity index of soils. ASTM International, West Conshohocken, PA, USA.

ASTM (2010b) D 854: Standard test methods for specific gravity of soil solids by water pycnometer. ASTM International, West Conshohocken, PA, USA.

ASTM (2011a) D 3080: Standard test method for direct shear test of soils under consolidated drained conditions. ASTM International, West Conshohocken, PA, USA.

ASTM (2011b) D 2487: Standard practice for classification of soils for engineering purposes (unified soil classification system). ASTM International, West Conshohocken, PA, USA.

ASTM (2012) D 698: Standard test methods for laboratory compaction characteristics of soil using standard effort. ASTM International, West Conshohocken, PA, USA.

ASTM (2013) D 4972: Standard test method for pH of soils. ASTM International, West Conshohocken, PA, USA.

ASTM (2014) D 2974: Standard test methods for moisture, ash, and organic matter of peat and other organic soils. ASTM International, West Conshohocken, PA, USA.

Atkinson J (2007) *The Mechanics of Soils and Foundations*. CRC Press, Boca Raton, FL, USA.

Batra LR and Batra SW (1966) Fungus-growing termites of tropical India and associated fungi. *Journal of the Kansas Entomological Society* **39**: 725–738, http://dx.doi.org/10.2307/25083581.

Bose G (1984) *Termite Fauna of Southern India*. Zoological Survey of India, Calcutta, India.

BSI (1990) EN 1377:1990. Methods of test for soils for civil engineering purposes classification tests. BSI, London, UK.

Burland JB (1961) *The Concept of Effective Stress in Partially Saturated Soils*. MSc thesis, University of the Witwatersrand, Johannesburg, South Africa.

Cedergren HR (1997) *Seepage Drainage and Flow Nets*. Wiley, New York, NY, USA.

Cheng L, Cord-Ruwisch R and Shahin MA (2013) Cementation of sand soil by microbially induced calcite precipitation at various degrees of saturation. *Canadian Geotechnical Journal* **50(1)**: 81–90, http://dx.doi.org/10.1139/cgj-2012-0023.

Chhotani OB (1997) *Fauna of India*. Isoptera (Termites). Zoological Survey of India, Calcutta, India, vol. 2.

Craig RF (2004) *Craig's Soil Mechanics*. CRC Press, Boca Raton, FL, USA.

Darlington JPEC (1985) The structure of mature mounds of the termite *Macrotermes michaelseni* in Kenya. *Insect Science and Its Application* **6**: 149–156.

Davies AB, Levick SR, Asner GP *et al.* (2014) Spatial variability and abiotic determinants of termite mounds throughout a savanna catchment. *Ecography* **37**: 1–11, http://dx.doi.org/10.1111/ecog.00532.

Dawes-Gromadzki TZ (2008) Abundance and diversity of termites in a savanna woodland reserve in tropical Australia. *Australian Journal of Entomology* **47**: 307–314, http://dx.doi.org/10.1111/j.1440-6055.2008.00662.x.

DeJong JT, Fritzges MB and Nüsslein K (2006) Microbially induced cementation to control sand response to undrained shear. *Journal of Geotechnical and Geoenvironmental Engineering ASCE* **132(11)**: 1381–1392, http://dx.doi.org/10.1061/(ASCE)1090-0241(2006)132:11(1381).

DeJong JT, Mortensen BM, Martinez BC and Nelson DC (2010) Bio-mediated soil improvement. *Ecological Engineering* **36(2)**: 197–210, http://dx.doi.org/10.1016/j.ecoleng.2008.12.029.

Dhembare AJ (2013) Physico-chemical properties of termite mound soil. *Archives of Applied Science Research* **5(6)**: 123–126.

Dowuona GN, Atwere P, Dubbin W *et al.* (2012) Characteristics of termite mounds and associated acrisols in the coastal savanna zone of Ghana and impact on hydraulic conductivity. *Natural Science* **4(07)**: 423, http://dx.doi.org/10.4236/ns.2012.47058.

Eggleton P and Tayasu I (2001) Feeding groups, life types and the global ecology of termites. *Ecological Research* **16**: 941–960, http://dx.doi.org/10.1046/j.1440-1703.2001.00444.x.

Endrizzi BJ and Stewart RJ (2009) Glueomics: an expression survey of the adhesive gland of the sandcastle worm. *Journal of Adhesion* **85**: 546–559, http://dx.doi.org/10.1080/00218460902996457.

Evans TA, Lenz M and Gleeson PV (1998) Testing assumptions of mark-recapture protocols for estimating population size using Australian mound-building, subterranean termites. *Ecological Entomology* **23**: 139–159, http://dx.doi.org/10.1046/j.1365-2311.1998.00114.x.

Germaine JT and Germaine AV (2009) *Geotechnical Laboratory Measurements for Engineers*. Wiley, Hoboken, NJ, USA.

Gillman LR, Jefferies MK and Richards GN (1972) Non-soil constituents of termite (*Coptotermes acinaciformis*) mounds. *Australian Journal of Biological Sciences* **25**: 1005–1013, http://dx.doi.org/10.1071/BI9721005.

Head KH (1984) *Manual of Soil Laboratory Testing: 1, Soil Classification and Compaction Tests*. ELE International, Bedfordshire, UK.

Head KH (1994) *Manual of Soil Laboratory Testing: 2, Permeability, Shear Strength and Compressibility Tests*. Pentech Press, London, UK.

Jouquet P, Lepage M and Velde B (2002) Termite soil preferences and particle selections: strategies related to ecological requirements. *Insectes Sociaux* **49**: 1–7, http://dx.doi.org/10.1007/s00040-002-8269-z.

Jouquet P, Mery T, Rouland C and Lepage M (2003) Modulated effect of the termite *Ancistrotermes cavithorax* (Isoptera, Macrotermitinae) on soil properties according to the structures built. *Sociobiology* **42**: 403–412.

Jouquet P, Tessier D and Lepage M (2004) The soil structural stability of termite nests: role of clays in *Macrotermes bellicosus* (Isoptera, Macrotermitinae) mound soils. *European Journal of Soil Biology* **40**: 23–29, http://dx.doi.org/10.1016/j.ejsobi.2004.01.006.

Kaschuk G, Santos JCP, Almeida JA, Sinhorati DC and Berton-Junior JF (2006) Termite activity in relation to natural grassland soil attributes. *Scientiaagricola* **63(6)**: 583–588, http://dx.doi.org/10.1590/S0103-90162006000600013.

King H, Ocko S and Mahadevan L (2015) Termite mounds harness diurnal temperature oscillations for ventilation. *Proceedings of the National Academy of Sciences* **112(37)**: 11589–1159, http://dx.doi.org/10.1073/pnas.1423242112.

Korb J (2011) Termite mound architecture, from function to construction. In *Biology of Termites: a Modern Synthesis* (Bignell DE, Roisin Y and Lo N (eds)). Springer, Heidelberg, Germany, pp. 349–373.

Korb J and Linsenmair KE (1999) The architecture of termite mounds: a result of a trade-off between thermoregulation and gas exchange. *Behavioral Ecology* **10**: 12–31, http://dx.doi.org/10.1093/beheco/10.3.312.

Korb J and Linsenmair KE (2000) Ventilation of termite mounds: new results require a new model. *Behavioral Ecology* **11**: 486–494, http://dx.doi.org/10.1093/beheco/11.5.486.

Kraus C, Hirmas D and Roberts J (2013) Microbially indurated rammed earth: a long awaited next phase of earthen architecture. *ARCC Conference Repository* 58–65.

Kuo MY and Bolton MD (2013) The nature and origin of deep ocean clay crust from the Gulf of Guinea. *Geotechnique* **63**: 500–509, http://dx.doi.org/10.1680/geot.10.P.012.

Lambe TW and Whitman RV (1969) *Soil Mechanics*. Wiley, New York, NY, USA.

Le Bissonnais (1996) Aggregate stability and assessment of soil crustability and erodibility: I. theory and methodology. *European Journal of Soil Science* **47**: 425–437, http://dx.doi.org/10.1111/j.1365-2389.1996.tb01843.x.

Le Cam JB, Fournier J, Etienne S and Couden J (2011) The strength of biogenic sand reefs: visco-elastic behaviour of cement secreted by the tube building polychaete *Sabellaria alveolata*, Linnaeus, 1767. *Estuarine, Coastal and Shelf Science* **91(2)**: 333–339, http://dx.doi.org/10.1016/j.ecss.2010.10.036.

Lee KE and Wood TG (1971a) *Termites and Soils*. Academic Press, New York, NY, USA.

Lepage M and Darlington JPEC (2000) The population dynamics of termites. In *Termites: Evolution, Sociality, Symbioses, Ecology* (Abe T, Bignell DE and Higashi M (eds)). Kluwer Academic, Dordrecht, the Netherlands, pp. 333–361.

Manuwa SI (2009) Properties and shear strength of *in situ* and compacted termite mound soil (TMS) in Akure, South-western Nigeria. *Tarım Makinaları Bilimi Dergisi* **5(4)**: 415–421.

Manzoor F and Akhtar MS (2006) Morphometric analysis of population samples of soldier caste of *Odontotermes obesus* (Rambur) (Isoptera, Termitidae, Macrotermitinae). *Animal Biodiversity and Conservation* **29**: 91–107.

Mège D and Rango T (2010) Permanent groundwater storage in basaltic dyke fractures and termite mound viability. *Journal of African Earth Sciences* **57**: 127–142, http://dx.doi.org/10.1016/j.jafrearsci.2009.07.014.

Mitchell JK and Soga K (2005) *Fundamentals of Soil Behaviour*. Wiley, Hoboken, NJ, USA.

Nobre T, Koné NA, Konaté S, Linsenmair KE and Aanen DK (2011) Dating the fungus-growing termites' mutualism shows a mixture between ancient co-diversification and recent symbiont dispersal across divergent hosts. *Molecular Ecology* **20**: 2619–2627, http://dx.doi.org/10.1111/j.1365-294X.2011.05090.x.

Noirot C (1990) Evolution of the aeration systems in some higher termites. In *Social Insects and Environment* (Veeresh GK, Mallick B and Viraktamath CA (eds)). Oxford & IBH Publishing Co., New Delhi, India, pp. 680–681.

Ramaiah BK and Rao SK (1969) Soil distribution and engineering problems in Bangalore area. *Research Bulletin*. Golden Jubilee, Bangalore University, Bengaluru, India, pp. 1–102.

Rao SM and Revanasiddappa K (2002) Collapse behaviour of a residual soil. *Géotechnique* **52**: 259–268, http://dx.doi.org/10.1680/geot.2002.52.4.259.

Rao SM and Revanasiddappa K (2006) Influence of cyclic wetting drying on collapse behaviour of compacted residual soil. *Geotechnical and Geological Engineering* **24**: 725–734, http://dx.doi.org/10.1007/s10706-004-5077-4.

Roonwal ML and Chhotani OB (1989) *The Fauna of India and the Adjacent Countries, Isoptera (Termite)*. Zoological Survey of India, Calcutta, India, vol. 1.

Salgado R (2008) *The Engineering of Foundations*. McGraw-Hill, New York, NY, USA.

Sen-Sarma PK (1974) Ecology and biogeography of the termites of India. In *Ecology and Biogeography in India* (Mani MS (ed.)). Dr. W. Junk Publishers, The Hague, the Netherlands, pp. 421–472.

Stewart RJ, Wang CS and Shao H (2011) Complex coacervates as a foundation for synthetic underwater adhesives. *Advances in Colloid and Interface Science* **167**: 85–93, http://dx.doi.org/10.1016/j.cis.2010.10.009.

Sun C, Fantner GE, Adams J, Hansma PK and Waite JH (2007) The role of calcium and magnesium in the concrete tubes of the sandcastle worm. *Journal of Experimental Biology* **210(8)**: 1481–1488, http://dx.doi.org/10.1242/jeb.02759.

Turner JS (2000) *The Extended Organism*. Harvard University Press, Cambridge, MA, USA.

Udoeyo FF, Cassidy AO and Jajere S (2000) Mound soil as construction material. *Journal of Materials in Civil Engineering* **12(3)**: 205–211, http://dx.doi.org/10.1061/(ASCE)0899-1561(2000)12:3(205).

Whiffin VS, van Paassen LA and Harkes MP (2007) Microbial carbonate precipitation as a soil improvement technique. *Geomicrobiology Journal* **24(5)**: 417–423, http://dx.doi.org/10.1080/01490450701436505.

Wood TG (1988) Termites and the soil environment. *Biology and Fertility of Soils* **6**: 228–236, http://dx.doi.org/10.1007/BF00260819.

Worall M (2011) Homeostasis in nature: nest building termites and intelligent buildings. *Intelligent Buildings International* **3**: 87–95, http://dx.doi.org/10.1080/17508975.2011.582316.