ENGINEERING CHARACTERISTICS OF NEST BUILDING GEOMATERIALS USED BY MUD DAUBER SPECIES

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ENGINEERING CHARACTERISTICS OF NEST BUILDING GEOMATERIALS USED BY MUD DAUBER SPECIES

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ABSTRACT

Mud dauber wasps construct their nests using soil from adjacent areas. Mud dauber nests have been studied from an entomological perspective. However, the properties of the nest material remain unexplored from a soil engineering perspective. This study investigated the physical and mechanical properties of the nest soil for use in future bio-inspired design to improve soil behavior as a construction material. To achieve this goal, nests from three mud dauber species (black and yellow, organ pipe, and steel blue) were collected from locations near Baton Rouge, Louisiana. The shape, weight, moisture content, organic content, and specific gravity of the nests were measured and analyzed using statistical analysis. The average specific gravity of the nests was relatively low (about 2.6). Mud daubers may be able to select specific soil particles for constructing their nests, such as quartz, feldspars, and calcite. Particle size analysis of the nest soil was conducted and compared to the soil's particle size distribution from adjacent areas. The comparison shows that mud daubers collect silt and sand with a small portion of clay for nest construction. The nest soil was classified as low plastic sandy silt based on the Revised Soil Classification System (RSCS). Penetrometer tests were used to investigate the unconfined compression strength of the nests. The penetrometer test results indicate that the nest soils are classified as very stiff soil, which is attributed to the unique soil structure, packing, and moisture content. The dry densities of mud dauber nests could be higher than the maximum densities achieved from the lab compaction test. This might indicate that mud dauber has a particularly effective method for compacting the nest during nest construction. Scanning Electron Microscopy (SEM) imaging showed the soil particle packing in the nest construction. Energy Dispersive Spectrum (EDS) revealed the nests' element composition, including calcium, silicon, oxygen, and carbon.
CHAPTER 1. INTRODUCTION

1.1. Overview

Recently, bio-geotechnical engineering has received considerable attention from geotechnical researchers. Many interests are drawn to use or mimic microorganisms, insects, and plant roots to improve soil engineering properties, create innovative geotechnical materials, and improve construction techniques. For example, bio-cementation is an innovative ground improvement technique that employs microorganisms to cement soil particles and improve the engineering properties of soil. The research described in this thesis focused on investigating the physical and mechanical properties of mud dauber nest soil for use in future bio-inspired design to improve the soil properties as a construction material. Mud dauber wasps are able to build durable nests using soils. Many studies on mud dauber wasps performed by entomologists and biologists have focused on the wasp behavior, type, shape, its prey, and its nest shape (Bohart & Menke, 1976; Fabre, 1921; Mazek-Fialla, 1936; Grandi, 1961; White, 1962; Dorris, 1970; and Pezzi, 1998). Some studies were performed to investigate mud dauber nest fossils to date arts on rocks (Bednarik, 2014; and Finch et al., 2019). Yet, no study approached the physical and mechanical characteristics of the mud dauber nests. Mud daubers prefer to build their nests in dry areas, such as tropical continental areas. Thirty species of mud dauber wasps were discovered in the old world (the world before discovering the America). Some of them were introduced to the new world (Bohart & Menke, 1976). Three species commonly found in the U.S. are black and yellow mud dauber (Sceliphron caementarium), steel blue mud dauber (Chalybion californicum), and organ pipe mud dauber (Trypoxylon politum) (Matthews et al., 1997). Mud dauber nests are commonly located under the eaves of houses, on the wall of houses, and in the fire-place cowls (Fabre, 1921; Grandi, 1961; White, 1962; Dorris, 1970; and Pezzi, 1998). Mud daubers have become more
associated with human dwellings because this might give mud daubers more protection from predators (Pezzi, 1998). Mud dauber nests are found on illuminated surfaces protected from direct sunlight and water (Camillo, 2002). The female wasp selects soil particles to form a mud pellet, which is as large as her head. The female mud dauber grabs the pellet using her mandible to fly back to the nest construction site. The pellet is then compacted to the nest using the wasp’s mandibles with buzzing vibration (Camillo, 2002). The female wasp constructs the first cell, provides prey (e.g., spiders) into the cell, and seals the cell before constructing the next one. Finally, a bundle of nest cells is constructed to form one durable nest cluster.

1.2. Problem Statement

Although many researchers investigated the mud dauber wasp behavior, type, shape, prey, and nest shapes, limited studies have focused on characterizing the physical and mechanical properties of the nest soil.

1.3. Objectives

The research described in this thesis aimed to investigate the physical and mechanical properties of mud dauber nest soil to generate data and observations for use in future bio-inspired design to improve the behavior of soil as a construction material. To investigate the physical and mechanical properties of the nest soil, mud dauber nests collected in the vicinity of Baton Rouge LA (USA). Geotechnical laboratory tests, including water content, organic content, specific gravity, dry unit weight, particle size distribution, fall cone, compaction, and penetration tests were performed for nest samples. Scanning Electron Microscopy (SEM), Energy Dispersive Spectrum (EDS), and X-Ray Diffraction (XRD) were used to characterize the soil particle morphology and elemental composition of the nest soil.
1.4. Scope

The main scope of this study included three tasks: (1) geotechnical laboratory tests and statistical analysis of the results on the mud dauber nests, (2) classification of the nest soils using the Revised Soil Classification System (RSCS), and (3) micro scale analysis of the structure and elemental composition of the nest soils. The nest soils' physical and mechanical properties were characterized using several geotechnical laboratory tests followed by the statistical analysis. RSCS was used to classify the nest soils according to the particle size distribution, liquid limit, and particle roundness analysis. Finally, the soil particle packing and the elemental composition were characterized using SEM, EDS, and XRD imaging.

1.5. Outline

This study includes eight chapters. The first chapter is an introduction that gives a brief background about mud daubers, their types, and their nests, followed by the objectives and the scope. A literature review on mud daubers’ nests and other species’ soil nests is presented in chapter two. Chapter three presents the nest sample collection and locations. The physical and mechanical properties of mud dauber nest soils are presented in chapters four and five, respectively. Nest soil classification using RSCS is shown in chapter six. Chapter seven includes the microscale analysis for the nest soil. Finally, overall conclusions of this study are summarized in chapter eight.
CHAPTER 2. LITERATURE REVIEW

2.1. Mud Dauber Nests

Mud daubers are medium-sized, non-aggressive wasps from either the family of *Sphecidae* or *Eumenides*. They build their nests using soil and prey on spiders (Bohart and Menke, 1976; and Matthews et al., 1997). Mud daubers can be divided into primary and secondary nest builders. Primary builders construct their nests. Secondary builders occupy abandoned nests of primary builders (Bednarik, 2014). The mud dauber nests can commonly be found under the eaves of houses, under piles of wood, on walls of houses, and under fire-place cowls. Every nest consists of multiple tube-shaped cells. The female wasp stores prey (i.e., spiders from different families) in those tubes as nutrition for her eggs (Grandi, 1961; Bohart and Menke, 1976; and Jocqué, 1988). In the United States, there are three main mud dauber species as shown in Figure 2.1: (a) Black and yellow mud dauber (*Sceliphron caementarium*), (b) Steel blue mud dauber (*Chalybion californicum*), and (c) Organ pipe mud dauber (*Trypoxylon politum*) (Matthews et al., 1997). Each species of mud dauber builds its nest in a unique shape (Figure 2.1 d, e, and f). Black and yellow mud daubers are a black wasp with yellow markings. Its nest can be recognized by its clustered, rectangular structure. Steel blue mud dauber has a distinctive metallic blue body, which renovates and reuses the nests of black and yellow mud daubers (Krombein et al., 1979). Hence, the steel blue and black and yellow mud dauber nests are very similar in shape. The pipe organ mud dauber has black body coloration and builds distinctive tubular mud nests (Evans, 2007). Even though mud dauber nests are widely distributed globally, they are typically found in tropical or subtropical areas (Bednarik, 2014). These favorable places offer favorable spots where mud daubers are able to build their nests (Shafer, 1949; and Cross et al., 1975). In early to mid-summer, mud daubers come out of last year's nests. After mating, females start to build nests near a location where she
Figure 2.1. Mud dauber species and their nests
can easily find a source of water, mud, and plenty of spiders. Each female organ pipe mud dauber begins nest-building by constructing a single mud tube. This nest-building process might take from three hours to a full-day labor. The female wasp can collect 3 to 18 spiders before she stops working. She stores those collected spiders inside the nest cell, followed by laying one egg per cell, then seals the nest using extra mud (Mathews et al., 1997).

Nachtigall (2001) reported that the female wasp inspected the site first. Then, she gathered some soil particles to form a sphere of soil (pellet) and took the pellet back for building the nest construction. The cells in the nests range from 1 to 54 sausage-shaped cells. The cells are typically constructed next to each other to form one nest bundle (Camillo, 2002). The nest soil consists of clay, silt, sand, and some organics. Other inclusions that were reported in the nest soil include pollen grains, spores, sponge spicules, phytoliths, carbon particles (charcoal), starch grains, and parts of gramine and dicotyledons (Bednarik, 2014). After collecting 103 mud dauber nests from nine farms, Polidori et al. (2005) did a granulometric analysis and used several geological methods to investigate these nests' properties. They reported that the nests were composed of discrete fabric units (e.g., amorphous organic material) inserted with homogeneous material (soil elements). The main components of the nest soil include quartz, other soil minerals (i.e., feldspar, plagioclase, and epidotes), and portions of organic material (plant fragment) (Polidori et al., 2005). The micro scale analysis showed that the wasps built their nests around the lumen of the nest, instead of building along the longitudinal direction. This observation was confirmed by the images showing the horizontal section (the one transversal to the shortest axis of the cell) and the vertical section (the one transversal to longest axes of the cell) as shown in Figure 2.2. The horizontal and vertical sections of the nests have the same typology but with a more chaotic distribution in the horizontal section as shown in Figure 2.2, which means that the nest was constructed around its lumen.
(Polidori et al., 2005). The granulometric analysis curves (i.e., particle size distribution curves) of the nests showed there were no significant differences in the soil particle size distributions between the mud dauber nests. This observation confirms the hypothesis that the wasps can collect the specific soil particle size, and the nest soil size is independent of the surrounding soil. The small amount of organic content that was found in the nests may indicate the absence of saliva in the nests (Polidori et al., 2005).

Figure 2.2. Mud dauber nest sections: (a) transversal section to the longest axis of the cell, (b) transversal section to the shortest axis (our research data)

2.2. Soil Nests Built by Other Species

Animals and insects who build their nests from soil always target specific soil types. For example, burrow-nesting birds target sedimentary soil substrates since it is easy for them to dig the sedimentary soil that provides stability to the nests (Smalley et al., 2013). Many species use soil to build their nests, including Hirundine species (Papoulis et al., 2018), termites (Jouquet et
al., 2016), Campo Miners (Heneberg and Simecek, 2004), bee-eaters (Heneberg et al., 2004), and kingfisher (Heneberg, 2004).

2.2.1. Nests Built by Hirundine

Hirundine species (House Martin, Barn Swallow, and Red-rumped Swallow) are small birds from the swallow and martin family. They build their nests from mud as shown in Figure 2.3. It was confirmed that the Barn Swallows prefers to choose silt and lower amount of sand for building their nests (Kilgore and Knudsen, 1977). Even though the sand improves the workability of the mud, Barn Swallows prefer silt because silt improves the stability of the nests (Kilgore and Knudsen, 1977). In general, Hirundine species tend to collect fine-grained sediments from loose deposits. The sediments should be wet enough to ease constructing the nests (Papoulis et al., 2018). Particle size analysis on Hirundine species’ nests showed no significant difference in the soil particle sizes between different Hirundine species (i.e., Barn Swallow, Red-Rumped swallow, and House Martin). All Hirundine species use silt (particle size less than 63 μm) as a primary building material. The portion of very fine to medium sand (62.5 - 500 μm) is always lower than 50% (4.2 - 48.1%). The coarse to very coarse sand percentage (500 - 2000 μm) is always below 10%. The dominant soil of the nest is silt with the percentage ranging from 24.2% to 81.3%. The mineralogical analysis of the nests confirmed the existence of several clay minerals and non-clay minerals. They all have low specific gravity values (less than 2.8). The non-clay minerals are quartz, calcite, and feldspars (Papoulis et al., 2018).

The mineralogical analysis of the nest soil of different Hirundine species showed two mineral groups. The first group is the minerals that are used as the aggregate with low plasticity. The other group is the minerals used as the cement with high plasticity (Papoulis et al., 2018). The cementation between soil particles maintains the nest cohesion. The most suitable material for this
purpose is clay due to its high plasticity (Smalley et al., 2013). Generally, the percentage of clay minerals in most of the nests is less than 30%, which means that those Hirundine species can select their preferred soil particle sizes and minerals (Kilgore and Knudsen, 1977; and Papoulis et al., 2018).

![Image of Hirundine species and their nest]

Figure 2.3. Hirundine species and their nest

### 2.2.2. Termites Mounds

Termite mounds are good examples of bioengineered soil structures built from mud as shown in Figure 2.4. Termite mounds are durable for many decades, which is required by the termite society (Erens et al., 2015). Termite mounds have a bi-layered structure with a durable dense core and porous periphery. The factor of safety of mound structure is higher than those of human-made structures (Zachariah et al., 2020). It has been shown that termites can modify clay fraction by performing soil segregation (Jouquet et al., 2002; Jouquet et al., 2003; and Jouquet et al., 2004). It was proven that the termite mounds have 30% clay fraction, which is more than the surrounding soil due to the soil segregation by termites (Jouquet et al., 2003).
Termites can perform soil modification to improve the weathering resistance and stability of the mounds (Abe et al., 2009). Termites secrete glandular secretions when building their mounds. These secretions have a crucial contribution to cementing soil particles (Lee and Wood, 1971; and Wood, 1988). Analysis of organic contents of the mounds shows that termite mounds have higher organic content than the surrounding soil. Termites cement soil particles together using water and their glandular secretion into one unit. This unit is analogous to bricks used in human-made construction and termed as ‘boluses’ (Zachariah et al., 2020). Termites can prepare the boluses by mixing the soil with a specific amount of water to turn the soil to the plastic state, which is easier for termites to strengthen the mound structure (Kandasami et al., 2016). If the soil has a very low moisture content (less than 15%), it is difficult for termites to cement the soil together. If the soil has a high moisture content (higher than 60%), it is also difficult for termites to walk on it. The average diameter of these boluses depends on the caste of termites (major and minor workers) (Zachariah et al., 2017). The major workers can handle boluses with volume 3.7 times larger than the boluses by minor workers. These soil boluses are 0.25-0.3 times of the head size of two termite castes, and their weights are 17% and 9% of the body weights of major and minor workers, respectively. The ease of handling these boluses depends on soil properties, including the particle sizes, shape, chemical compositions, and the presence of organic matters (Zachariah et al., 2017).

The chemical composition of the mounds is not the same with the surrounding soil (Gillman et al., 1972; and Kaschuk et al., 2006). The study by Kandasami (2016) raised questions about the ability of termites to modify particle mineralogy. Kandasami (2016) compared the Atterberg limits (indicator of the clay mineralogy) between termite mounds and the control soil and concluded that there was not any difference of Atterberg limits between the mounds and the
control soil. The XRD analysis also showed that the mineralogy of the mounds stayed unchanged comparing to the control soil. Rao and Revanasiddappa (2006) supported the above finding on the mineralogy and added that the predominant minerals were quartz and kaolinite. It seems that termites are interested in the same soil mineralogy with Hirundine and mud dauber species.

According to Kandasami (2016), the unconfined compression teste results show that the strength of the termite mounds could reach to 10 folds increase comparing to the control soil. Kandasami (2016) concluded that the higher strength of the mounds is due to the particle segregation and the granular secretions by termites. For optimum packing, termites use boluses (a small rounded mass of soil formed by the termites) of major and minor workers. Termites can cement the large-size boluses together by filling the voids by the small size boluses. This optimum packing should have significant contribution in strengthening and stabilizing the mound structure (Zachariah et al., 2017). Other studies on the water retention characteristics of termite mounds proved that the mound soil has lower water retention and higher water repellency, which is attributed to the glandular secretions (Ackerman et al., 2007). Lower water retention is a beneficial property for termite mounds because more water can debilitate the capillary bonds between soil particles and break the intergranular contact (Burland, 1961). Also, the fabric of the termite mound soil may have a contribution in cohesion that is contributed by the boluses. The matrix suction of these clay fabrics could increase the strength of the cohesive-frictional granular ensemble (Kandasami et al., 2016), which can be used to illustrate the presence of termite mounds in a dry area (drier Savannah in Africa) to improve the stability of the mound structure (Mège and Rango, 2010; Davies et al., 2014).
2.2.3. Ant Tunneling

Some insects excavate soil to build their nests, such as ants (Monaenkova et al., 2015). Ants construct tunnels by soil removal instead of soil piling (Tschinkel, 2005). The excavation rate of ants varies from 0.02–2 cm³ day⁻¹ ant⁻¹ (Espinoza and Santamarina, 2010). Ants were described in the literature as professional geotechnical engineers due to their extraordinary capabilities of
excavation. Ants have their distinctive and methodical capability of tunnel excavation. It was reported that ant tunnels could exist in different soils, including fine-grained, silty, sandy, and even gravel soils (Bonte et al., 2003; MacMahon et al., 2000; and Nagel, 1970). This fact demonstrates that ants can adapt their nest construction to different soils. Harvester ants tend to live in wet and sun covered areas because the shortage of water results in ant desiccation and death. However, plenty of water leads to tunnel collapse (Johnson, 2001; Gregg, 1963; MacMahon et al., 2000; Nagel, 1970; and Wheeler, 1910). The precipitation and soil characteristics that can affect water retention directly relate to ants’ behavior (Johnson, 2001). The water content of the tunnel soil has a range between 4-20%. Lower water content and soil temperature affect ant digging behavior (Nagel, 1970; and Bollazzi et al., 2008). Ants can move soil particle size based on their mandible size. They can collect particles with the same size as their heads (2-5 mm particle size) (Nagel, 1970; Johnson, 2000; Wheeler and Wheeler, 1963; and Hooper-Bui et al., 2002). Ants may generate glandular secretion (similar to termites) to cement soil particles for improving the stability of the ant tunnel (Gregg, 1963).

A study by Espinoza and Santamarina (2010) provided a detailed investigation of the relationship between grain size, water content, and the digging behavior of ants. Three parameters control the particle removal, including grain size (d), mandible size (M), and water content. For silts and clayey soils, ants set the particles up in loose particle conglomerates when the soil has very low water content. For soil with higher water content, the ants can remove bundled soil particles (can reach 3 mm). For dry sands, ants can remove three particles of 20/30 sand and 13 particles of finer sands (F110). If water is present, it was easier for ants to make more stable pellets. For gravels, ants excavate only one particle regardless of the water content. The degree of saturation and particle size also affect the excavation patterns. Ants excavate short tunnels in fine-
grained clay. However, they excavate wider and longer tunnels in sands at low and medium moisture contents. For dry sand and gravel, the ant excavation causes sliding (Espinoza and Santamarina, 2010).

2.3 Summary

Investigating the nests’ structure and geo-properties used by different organisms is an exciting topic of bio-geotechnical engineering. Although different species build their nests from the soil, their nests have some common characteristics. For instance, mud dauber, Hirundine, and termite species are interested in picking specific minerals during their nest construction, including quartz, calcite, and kaolinite. They are also interested in the similar size of particles; most of the nests are made of silt and sand with a small portion of clay. Yet, those species might differ in some characteristics, such as the high organic content within the termite mounds, which confirms the presence of the glandular secretions in the termite nests. The nest properties reported herein provided additional insights and guidance for improving our human-made building materials.

This research focuses on investigating the physical and mechanical properties of the mud dauber nest soils for use in future bio-inspired design to improve soil behavior as a construction material. To investigate the physical and mechanical properties of the nest soils, we collected the nests at several places around the Baton Rouge area. The nest samples were then subjected to the geotechnical laboratory tests, including water content, organic content, specific gravity, dry unit weight, particle size distribution, fall cone, compaction, and penetration tests. To investigate the presence of any glandular secretions in the nest, Scanning Electron Microscope (SEM), Energy Dispersive Spectrum (EDS), and X-Ray Diffraction (XRD) were used to characterize the soil particle morphology and elemental compositions of the nests.
CHAPTER 3. SAMPLING OF MUD DAUBER NESTS

3.1. Sample Collection

Mud dauber nest samples (n=69) were collected from different locations in Louisiana in winter 2019. Table 3.1 shows the locations of the collected mud dauber nest samples. Figure 3.1 shows the nest locations on a Google map. The nests were removed carefully with a putty knife (to avoid breaking the nests), placed into plastic bags, and labeled with sample information in detail. After sample collection, physical, mechanical, and microscopic tests were performed on the mud dauber nests. The testing plan is shown in Figure 3.2. Penetrometer tests were first performed, followed by the collection of the nest contents. The nest contents (larva, pupa, and spiders) were weighed and preserved into 50 ml tubes filled with 95% ethanol for future investigation. Then the empty nests were weighted and put in the jars and labeled. Moisture content, organic content, specific gravity, and dry density tests were then performed to investigate the physical properties of the nest soil. After those physical property tests, micro scale tests (e.g., optical microscope, SEM, EDS, and XRD) were conducted to investigate the soil structure and mineral composition of the nests. To classify the nest soil, hydrometer and fall cone tests were conducted to measure soil particle size distribution and Atterberg limits. Then, the Revised Soil Classification System (RSCS) was used to classify the nest soil.

The sample numbering system consists of three symbols as shown in Figure 3.3. The first symbol is an English alphabet, which represents the site where the sample was collected. The second number represents the sample number from the same place. The third is a Latin number representing the mud dauber type, which I was assigned to the pipe organ mud dauber (*Trypoxylon politum*), and II was given to the black and yellow mud dauber (*Sceliphron caementarium*) and steel blue mud dauber (*Chalybion californicum*). Black and yellow and steel blue mud dauber nests
were assigned with the same Latin number II because, as mentioned earlier, they have the same nest shape. The steel blue mud dauber usually uses the abandoned black and yellow nests (Bednarik, 2014). Steel blue mud daubers might modify the nests by making the nest shape uneven. However, it is still difficult to distinguish the nests between black and yellow and steel blue mud daubers. Only two places (Locations A and C) had type I and II mud daubers. However, the rest locations only had type II mud daubers.

Figure 3.1. Sample collection locations on Google map
Table 3.1. Summary of mud dauber nests collection

<table>
<thead>
<tr>
<th>Location No.</th>
<th>Address</th>
<th>Sample Number</th>
<th>Species</th>
</tr>
</thead>
<tbody>
<tr>
<td>A</td>
<td>1255 Jean Lafitte Blvd, 70067, Lafitte.</td>
<td>25, 14, 25, 27, 29</td>
<td>I</td>
</tr>
<tr>
<td>A</td>
<td>1255 Jean Lafitte Blvd, 70067, Lafitte.</td>
<td>1, 3-13, 15-24, 26, 30</td>
<td>II</td>
</tr>
<tr>
<td>B</td>
<td>LSU, Seaman hall, Baton Rouge.</td>
<td>1, 2</td>
<td>II</td>
</tr>
<tr>
<td>C</td>
<td>LSU, Chopin hall, Baton Rouge.</td>
<td>1</td>
<td>I</td>
</tr>
<tr>
<td>C</td>
<td>LSU, Chopin hall, Baton Rouge.</td>
<td>2</td>
<td>II</td>
</tr>
<tr>
<td>D</td>
<td>LSU, Life science building, Baton Rouge.</td>
<td>1-8</td>
<td>II</td>
</tr>
<tr>
<td>E</td>
<td>LSU, Parking Garage, Baton Rouge.</td>
<td>1-10</td>
<td>II</td>
</tr>
<tr>
<td>F</td>
<td>LSU, Student Union, Baton Rouge.</td>
<td>1-9</td>
<td>II</td>
</tr>
<tr>
<td>G</td>
<td>Oct street, Rayne.</td>
<td>1-3</td>
<td>II</td>
</tr>
<tr>
<td>H</td>
<td>741 Portula avenue, 70820, Baton Rouge.</td>
<td>1</td>
<td>II</td>
</tr>
<tr>
<td>I</td>
<td>12110 Lake estates, 70810, Baton Rouge.</td>
<td>1</td>
<td>II</td>
</tr>
</tbody>
</table>
Figure 3.2. Testing flow chart for the mud dauber nests
Figure 3.3. Illustration of the sample numbering system

A

1

I

Nest Site
From A to I

Nest Number

Nest Type
I for pipe organ mud dauber
II for black and yellow and steel blue mud dauber
CHAPTER 4. PHYSICAL PROPERTIES OF NESTS

4.1. General Nest Shape

Mud dauber nests were photographed first once received as sown in Figure 4.1. The nests of the organ pipe mud dauber consist of several sausage shape cells connected side-by-side, as shown in Figure 4.1 (a, b, and c). Each cell was provisioned with one egg and several spiders by the female mud dauber (Grandi, 1961; Bohart and Menke, 1976; and Jocqué, 1988). The dimension of the organ pipe nests ranged from 50 to 100 mm in length and width, and 10 to 50 mm in height. Black and yellow mud dauber nests build extra layers of mud on the nest. The nests of the black and yellow and steel blue mud daubers are shown in Figure 4.1 (d, e, and f). Black and yellow and steel blue mud dauber nests have the same shape because steel blue mud dauber renovates and reuses the abandoned nests of black and yellow mud daubers (Krombein et al., 1979). The nest shape is amorphous and not specified compared to the organ pipe nests due to the extra mud layers that the black and yellow mud dauber build over the nest surface. The dimension of the black and yellow wasp nests ranged from 20 to 120 mm in length and width and 10 to 40 mm in height.

4.2. Nest Weight

After the contents in the nests (e.g., eggs and spiders were collected), the nest contents and the nest soil were weighed separately on a 0.01 g accuracy scale. All the nest weights were recorded separately according to the specimen number. SAS programming model was used for statistical analysis of the nests’ physical properties. Figure 4.2 shows a histogram of the distribution of all the nest weights regardless of the place or the nests' type. The most frequent values of mud dauber nest weights are between 20 and 50 g. Table 4.1 shows that the mean of the nest weights is 60.29 g, with a standard deviation of 39.84 g, which indicates that the nest weights
are widely distributed. The minimum and maximum weights of nest weight are 9.27 and 184.26 g, respectively, as shown in table Table 4.1.

Figure 4.1. Mud dauber nests: (a, b, and c) for pipe organ nest, (d, e, and f) for black and yellow and steel blue nests. Distribution of the weights of the nest samples.
Figure 4.2. Distribution of the weights of the nest samples

Table 4.1. Statistical analysis of the nest weights

<table>
<thead>
<tr>
<th>Statistical Parameters</th>
<th>Nest Weight (g)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Mean</td>
<td>60.29</td>
</tr>
<tr>
<td>Standard Deviation</td>
<td>39.84</td>
</tr>
<tr>
<td>Mode</td>
<td>-</td>
</tr>
<tr>
<td>Variance</td>
<td>1587</td>
</tr>
<tr>
<td>Range</td>
<td>174.99</td>
</tr>
<tr>
<td>Minimum Value</td>
<td>9.27</td>
</tr>
<tr>
<td>First Quartile Q1</td>
<td>27</td>
</tr>
<tr>
<td>Median</td>
<td>53.22</td>
</tr>
<tr>
<td>Third Quartile Q3</td>
<td>79.05</td>
</tr>
<tr>
<td>Maximum Value</td>
<td>184.26</td>
</tr>
</tbody>
</table>
4.3. Organic Fraction Content inside the Nest

The organic fraction contents (larva, pupa, and spiders) inside the nests were weighted before preserved in the 95% ethanol solution (5% deionized water). The nests' content consists of mud dauber larva and some spiders as food for the mud dauber larva. Using the SAS program, Figure 4.3 shows a histogram of the organic fraction weight distribution of the collected nests. The most frequent values of the organic fraction weight are between 0.2-1 g. The mean of their weight is 1.12 g with a standard deviation of 1.09 as shown in Table 4.2, which means that the organic fraction weights are widely distributed. The maximum weight of the organic fraction is 4.47 g and the minimum is zero because some samples were empty during collection.

![Figure 4.3. Distribution of the organic fraction contents of the nest samples](image-url)
Table 4.2. Statistical analysis of the organic fraction content (larva, pupa, and spiders) in the nest samples

<table>
<thead>
<tr>
<th>Statistical Parameters</th>
<th>Organic fraction inside the nest (g)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Mean</td>
<td>1.12</td>
</tr>
<tr>
<td>Standard Deviation</td>
<td>1.1</td>
</tr>
<tr>
<td>Mode</td>
<td>0.09</td>
</tr>
<tr>
<td>Variance</td>
<td>1.2</td>
</tr>
<tr>
<td>Range</td>
<td>4.47</td>
</tr>
<tr>
<td>Minimum Value</td>
<td>0</td>
</tr>
<tr>
<td>First Quartile Q1</td>
<td>0.37</td>
</tr>
<tr>
<td>Median</td>
<td>0.71</td>
</tr>
<tr>
<td>Third Quartile Q3</td>
<td>1.47</td>
</tr>
<tr>
<td>Maximum Value</td>
<td>4.47</td>
</tr>
</tbody>
</table>

4.4. Nest Moisture Content

One soil specimen (5-15 g) was collected from every nest for drying in the oven (110°C). The soil specimens were weighed before and after drying to calculate the moisture content of every nest. The moisture content of all nest soils range from 1.17% to 4.06% as shown in Table 4.3. The mean of the nests' moisture contents is 2.14% with a standard deviation of 0.65% as shown in Table 4.3. Figure 4.4 shows a histogram of the moisture contents of all soil samples. The most frequent value of the moisture content is about 2%.

The comparison of moisture contents between different collection locations (from A to I) is shown in Figure 4.5. The moisture contents of the soil nests range from 1.2% to 3%. Furthermore, the moisture contents of the nests at location A could reach about 4%. 
Figure 4.4. Distribution of the moisture contents of the nest samples

Table 4.3. Statistical analysis of the moisture contents of nest samples

<table>
<thead>
<tr>
<th>Statistical Parameters</th>
<th>Moisture Content (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Mean</td>
<td>2.14</td>
</tr>
<tr>
<td>Standard Deviation</td>
<td>0.65</td>
</tr>
<tr>
<td>Mode</td>
<td>1.39</td>
</tr>
<tr>
<td>Variance</td>
<td>0.42</td>
</tr>
<tr>
<td>Range</td>
<td>2.89</td>
</tr>
<tr>
<td>Minimum Value</td>
<td>1.17</td>
</tr>
<tr>
<td>First Quartile Q1</td>
<td>1.64</td>
</tr>
<tr>
<td>Median</td>
<td>2.11</td>
</tr>
<tr>
<td>Third Quartile Q3</td>
<td>2.45</td>
</tr>
<tr>
<td>Maximum Value</td>
<td>4.06</td>
</tr>
</tbody>
</table>
4.5. Organic Content of Nest Soil

Oven-dried specimen (5-15 g) from every nest were weighed and then placed into the muffle furnace for heating at 550°C. After 3 hours of heating in the muffle furnace, samples were transferred to a dissector to cool the samples down without gaining any extra weight from humidity as shown in Figure 4.6. The samples were weighed, then the organic contents of the nest soil were calculated. SAS program was used for the statistical analysis of the organic contents. The mean of the organic contents is 4.68% with a standard deviation of 2% as shown in Table 4.4. The organic contents of the mud dauber specimens as shown in Table 4.4 range from 1.86 to 9.86%. The organic contents between nine different locations (from A to I) were compared using a boxplot as

Figure 4.5. Comparison of moisture contents of the nest samples among different locations.
shown in Figure 4.8. The results show similar organic content range between different locations except for locations A and G.

![Image of Muffle Furnace and Desiccator]

Figure 4.6. Measuring the organic content of the nest specimens using a muffle furnace and a desiccator

![Histogram of Organic Content]

Figure 4.7. Distribution of the organic contents of the nest samples
Table 4.4. Statistical analysis of the organic contents of nest samples

<table>
<thead>
<tr>
<th>Statistical Parameters</th>
<th>Organic Content (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Mean</td>
<td>4.68</td>
</tr>
<tr>
<td>Standard Deviation</td>
<td>2</td>
</tr>
<tr>
<td>Mode</td>
<td>2.43</td>
</tr>
<tr>
<td>Variance</td>
<td>4.18</td>
</tr>
<tr>
<td>Range</td>
<td>8</td>
</tr>
<tr>
<td>Minimum Value</td>
<td>1.86</td>
</tr>
<tr>
<td>First Quartile Q1</td>
<td>2.92</td>
</tr>
<tr>
<td>Median</td>
<td>4</td>
</tr>
<tr>
<td>Third Quartile Q3</td>
<td>6.6</td>
</tr>
<tr>
<td>Maximum Value</td>
<td>9.86</td>
</tr>
</tbody>
</table>

Figure 4.8. Comparison of organic contents of the nest samples among different locations.
4.6. Density of the Nest

Intact nest samples were used for measuring the total density of the nests. Based on the recommended procedure of ASTM standard D7263 (ASTM, 2009). Paraffin wax was used to coat the specimens’ surface as shown in Figure 4.9 (a). Mass of moist soil specimen, the mass of wax-coated specimen, and the mass of the submerged paraffin coated specimen were measured using the digital density meter as shown in Figure 4.9 (b). Then, the total density of the nests was calculated using the equation below:

\[
\rho_m = \frac{M_t}{\frac{M_c - M_{sub}}{\rho_w} - \frac{M_c - M_t}{\rho_p}}
\]

Where:

- \( M_t \) = mass of moist soil specimen
- \( M_c \) = mass of wax coated specimen
- \( M_{sub} \) = mass of submerged paraffin coated specimen
- \( \rho_p \) = density of paraffin (0.92 g/cm\(^3\))
- \( \rho_w \) = density of water (1 g/cm\(^3\))
- \( \rho_m \) = density of moist soil specimen.

The dry unit weights were then calculated using the calculated total density and the measured moisture contents. SAS program was used to analyze the measured dry unit weights of all nests. The average nest dry unit weight is 101.98 pcf (lb/ft\(^3\)) with a standard deviation of 10.73 pcf as shown in Table 4.5. The most frequent value of dry unit weight of the mud dauber nests is 105 pcf as shown in Figure 4.10.

The comparisons of the dry unit weights between different locations (from A to I) were compared using a boxplot as shown in Figure 4.11. The same figure also shows that the dry unit
weights of the nests are similar between those nine locations. Typical dry unit weight of nests from
different locations range from 92 to 112 pcf, which might prove the possibility that mud daubers
target a specific range of dry unit weights.

![Paraffin coated mud dauber nest specimen](image1.png)

![Densitometer equipment](image2.png)

(a) paraffin coated mud dauber nest specimen       (b) Densitometer equipment

Figure 4.9. Dry density measurement process for mud dauber nest samples (ASTM, 2009)

![Histogram of dry unit weights](image3.png)

Figure 4.10. Distribution of the dry densities of the nest samples
Table 4.5. Statistical analysis of the dry densities of nest samples

<table>
<thead>
<tr>
<th>Statistical Parameters</th>
<th>Dry unit weight (pcf)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Mean</td>
<td>101.98</td>
</tr>
<tr>
<td>Standard Deviation</td>
<td>10.73</td>
</tr>
<tr>
<td>Mode</td>
<td>87.78</td>
</tr>
<tr>
<td>Variance</td>
<td>115.11</td>
</tr>
<tr>
<td>Range</td>
<td>67.54</td>
</tr>
<tr>
<td>Minimum Value</td>
<td>74.4</td>
</tr>
<tr>
<td>First Quartile Q1</td>
<td>95.04</td>
</tr>
<tr>
<td>Median</td>
<td>101.88</td>
</tr>
<tr>
<td>Third Quartile Q3</td>
<td>107.94</td>
</tr>
<tr>
<td>Maximum Value</td>
<td>141.94</td>
</tr>
</tbody>
</table>

Figure 4.11. Comparison of dry unit weights of the nest samples among different locations.
4.7. Specific Gravity of the Nest Soil

The specific gravity tests were conducted for five different nest samples from different places, according to ASTM standard D854 (ASTM, 2014). One sample was organ pipe mud dauber nest, and the others are steel blue and black and yellow mud dauber nests. As shown in Table 4.6, the specific gravities between five specimens are similar with an average value of 2.57. The mean specific gravity of the nests is slightly lower than the soil specific gravity that often ranges between 2.6 and 2.9.

Table 4.6. Specific gravities of nest samples

<table>
<thead>
<tr>
<th>Nest Number</th>
<th>Nest type</th>
<th>Specific Gravity</th>
</tr>
</thead>
<tbody>
<tr>
<td>A7 II</td>
<td>Black and yellow or steel blue mud dauber nest</td>
<td>2.44</td>
</tr>
<tr>
<td>A25 I</td>
<td>Organ pipe mud dauber nest</td>
<td>2.6</td>
</tr>
<tr>
<td>D3 II</td>
<td>Black and yellow or steel blue mud dauber nest</td>
<td>2.59</td>
</tr>
<tr>
<td>E1 II</td>
<td>Black and yellow or steel blue mud dauber nest</td>
<td>2.62</td>
</tr>
<tr>
<td>F3 II</td>
<td>Black and yellow or steel blue mud dauber nest</td>
<td>2.6</td>
</tr>
<tr>
<td>Average</td>
<td></td>
<td>2.57</td>
</tr>
</tbody>
</table>
4.8. Discussion

The general nest shape of the organ pipe mud dauber nests is different from the black and yellow mud dauber nests. The organ pipe mud dauber nests consist of several sausage shape cells connected side by side, which is different from the amorphous shape of the black and yellow mud dauber nests. The reason is that the organ pipe mud daubers do not construct extra layers of soil on the surface of the nests.

The nests of the mud dauber species do not have specific volume and weight. The weight of the collected mud dauber nests ranges from 9.27 to 184.26 g, which depends on the numbers of cells in each nest.

The organic contents of the nest specimens range from 1.86 to 9.86% with a mean of 4.86%. The range of organic contents between different locations is very similar except for locations A and G.

Mud dauber nests have low moisture content. The range of the moisture contents is between 1.17% and 4.06%. Mud daubers prefer to construct their nest under shade for preventing direct exposure to the rainwater. Because rainwater may erode the nest soil and causes the soil structure failure. The range of moisture contents of the nests between different locations is similar except for locations A and G. This is probably attributed to the higher organic contents existing in the nests of locations A and G.

The dry unit weights of the nests range from 74 to 141 pcf with mean of 101.93 pcf. The measured dry unit weights are consistent with the reported range of low plastic sandy silt, which ranges from 80 (minimum dry unit weight) to 135 pcf (maximum dry unit weight).
The mean of the nests' specific gravity is 2.57, which is slightly lower than the specific gravity of typical soils (2.6-2.9). This probably due to the higher organic contents within the nest soil.
CHAPTER 5. MECHANICAL PROPERTY OF THE NEST SOIL

5.1. Testing Method

Soil mechanical properties include shear strength, cohesion, and friction angle. Several lab tests can be used to measure those mechanical properties, including the unconfined compression test, direct shear test, and triaxial shear test. Since the mud dauber nests have an amorphous shape and open cells existing inside the nests, it is difficult to measure the nests' mechanical properties using those traditional lab testing methods. Hence, an electrical penetrometer device was used to measure the nests' unconfined compression strength (i.e., penetrometer resistance).

A penetrometer (diameter of 3.5 mm, Figure 5.1) was slowly pushed into the nest with a penetration depth of 6 mm. The penetrometer reading shows the maximum penetration resistance, which was converted to the soil penetrometer resistance based on the in-house calibration as shown in Figure 5.2.

Figure 5.1. Equipment for measuring the penetrometer resistances of the nest samples
Figure 5.2. Calibration relationships for the penetrometer device

(a) y = 0.2028x + 1.9603
R² = 0.9843

(b) y = 3.6722x - 0.7605
R² = 0.9967
5.1.1. Penetrometer Test

To conduct the penetrometer tests, the nest was placed on a glass plate under the penetrometer. The penetrometer was slowly moved towards the nest sample using the penetrometer handle. The penetrometer was pushed into the nests by 6 mm (Figure 5.1). The boundary (i.e., a glass plate) did not interfere with the penetrometer test as the penetration depth is only 6 mm.

A total of 1055 penetrometer tests were performed on the nest samples from collected locations. The measured penetrometer resistance ranges from 0.87 to 17.53 tsf. The wide range of penetration resistances might be due to several factors, such as the location on the nest surface where we apply the penetration, the thickness of the nests, the geometric shape, and the structure of the nests. It was also observed that the penetrometer resistances of the intact nests are higher than those of the broken nests. It means that the geometric structure of the nests contributes to the nest strength.

To achieve consistent readings, we performed the penetrometer tests in stages assigned with a specific name. The first stage was to apply the penetrometer tests on the intact nests until the intact nests were fractured (Figure 5.3). The second stage was to perform the penetrometer tests on solid pieces until failure. After the tests on these solid pieces, the broken and smaller pieces were divided into three groups. The first group of the small pieces was subjected to penetration perpendicular to the horizontal section (Figure 5.3). The second group was subjected to penetration on the area between the mud dauber nest chambers (Figure 5.3). There were thick and thin areas between chambers, which was also considered in the tests. The third group was for testing on the small broken pieces as shown in Figure 5.3.
The penetrometer resistances were processed through the SAS program to perform statistical analysis. Figure 5.4 shows a histogram of the penetrometer resistances of all collected nests regardless of the location, the test category, and the mud dauber nest types. The data seemed to be normally distributed. The most frequent penetrometer resistance value is between 2 and 3 tsf. The average penetrometer resistance is 3.95 tsf with a standard deviation of 2.5 tsf, as shown in Table 5.1. The standard deviation is high due to some outlier values. Table 5.1 shows that the range of the penetrometer resistance is between 0.87 and 17.53 tsf. This wide range of the penetrometer resistance is attributed to the size, structure, thickness of the nest samples. Figure 5.5 shows a boxplot comparison of the penetrometer tests between different test categories. The intact nest has the highest penetration resistance, followed by the nests as a solid piece. The nests tested perpendicular to the horizontal section ranked the third, followed by the small broken pieces and the thick section samples. The thin section sample experienced the lowest penetration resistance. Figure 5.6 shows a boxplot comparison of the penetrometer resistance between different locations (from A to I). The typical penetrometer resistances are similar between different locations except for some outliers. The typical penetrometer resistance ranges from 1.7 to 5 tsf, indicating the nests are stiff to hard soils based on the soil consistency classification. It is also important to note the black and yellow and the steel blue mud dauber nests show higher penetration resistances than those of the organ pipe nests as shown in Figure 5.7.
Figure 5.3. Nest testing stages during the penetrometer tests
Figure 5.4. Distribution of the penetration values of the nest samples

Table 5.1. Statistical analysis of the penetration resistance of nest samples

<table>
<thead>
<tr>
<th>Statistical Parameters</th>
<th>Penetration Resistance (tsf)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Mean</td>
<td>3.95</td>
</tr>
<tr>
<td>Standard Deviation</td>
<td>2.5</td>
</tr>
<tr>
<td>Mode</td>
<td>3.01</td>
</tr>
<tr>
<td>Variance</td>
<td>6.13</td>
</tr>
<tr>
<td>Range</td>
<td>16.66</td>
</tr>
<tr>
<td>Minimum Value</td>
<td>0.87</td>
</tr>
<tr>
<td>First Quartile Q1</td>
<td>2.22</td>
</tr>
<tr>
<td>Median</td>
<td>3.26</td>
</tr>
<tr>
<td>Third Quartile Q3</td>
<td>5.03</td>
</tr>
<tr>
<td>Maximum Value</td>
<td>17.53</td>
</tr>
</tbody>
</table>
Figure 5.5. Comparison of penetration values of the nest samples among different sample categories.

Figure 5.6. Comparison of penetration values of the nest samples among different locations
5.2. Compaction Test of Nest Soils

A compaction test was performed to measure the maximum and minimum dry unit weights of the nest soil. These measurements were compared to the dry unit weights of the mud dauber nests. The nest soil, including organ pipe and black and yellow mud dauber nests, at location A, was selected due to the availability of nest soil for compaction tests. All nest samples from place A were broken into soil particles and mixed with water for compaction tests. The compaction test was performed following ASTM standard D698 (ASTM, 1998).

Figure 5.8 shows the standard proctor compaction curve of the nest soil from location A. The maximum dry unit weight is 105.6 pcf, corresponding to an optimum moisture content of 15.5%. The maximum, average, and minimum dry unit weights of mud dauber nests are also shown.
in Figure 5.8. (142, 102, and 87 pcf). Compared to the compaction test curve, the dry unit weights of the nests show a wider distribution as shown in Figure 5.8. However, 80% of the dry unit weights of the nests range from 90 to 114 pcf, which matches the dry unit weight range of the compaction test. High soil density in the nests can be possibly illustrated by that the mud daubers use a unique compaction technique to compact soil. Some literature studies show that the mud daubers could generate high frequency buzzing vibration to compact soil (Camillo, 2002), which can significantly increase the dry unit weights (our research conclusion).

Figure 5.8. Compaction curve of the nest soils compared to the dry unit weights of the mud dauber nest
5.3. Discussion

The penetrometer tests were used to measure the penetrometer resistance (i.e., unconfined compression strength) of the mud dauber nests.

The penetrometer resistance of the mud dauber nests range from 0.87 to 17.53 tsf with the mean value of 3.95 tsf and standard deviation of 2.5 tsf, indicating the nest specimens are stiff to hard soil based on the consistency classification of the cohesive soil. The penetrometer resistance decreased with the sample size. The intact nests showed the highest penetration resistances, demonstrating that the structure of the nests may enhance the nest strength.

Also, there were no clear differences in the penetrometer resistances between mud dauber nests from different locations. It is also important to note that the black and yellow nests have a little higher penetrometer resistance than those of organ pipe nests, which may attribute to the extra soil layer covering the nests. The organ pipe nests do not have the extra layers of soil covering the nests. However, black and yellow and steel blue mud daubers construct extra layers of soil covering the nests.

From the standard compaction test, the maximum dry unit weight of the mud dauber nest soil is 105.6 pcf, corresponding to 15.5% optimum moisture content. The measured dry unit weights of the nests match the range of the dry unit weights achieved from the compaction tests. Based on our observation and Camillo study (2002), the mud daubers use a unique construction technique (i.e., high frequency buzzing vibration) to compact their soil for building nests.
CHAPTER 6. NEST SOIL CLASSIFICATION USING THE REVISED SOIL CLASSIFICATION SYSTEM

6.1 Particle Size Distribution of the Nest Soil

The particle size analysis was conducted for soil samples from four different places (A, D, E, and F). One particle size distribution analysis was performed for each of those locations except location A. Two tests were conducted for location A. One test is for organ pipe nests, and the other is for black and yellow nests at location A. Furthermore, one test was conducted for a soil collected near the nest location F, which was used to assess the difference of the particle size distributions between the nest soil and the surrounding soil.

PARIO Meter apparatus was used for particle size distribution analysis as shown in Figure 6.1. PARIO Meter apparatus can perform a full particle size analysis for soil passing through sieve #10 (2 mm). Since the particle size of all nest soils is less than 2 mm, the PARIO Meter device can be used. The nests were first broken into particles using a mortar and a rubber-tipped pestle. 50 g of soil was mixed with 30 ml of distilled water and 30 ml of H₂O₂ (30% volume concentration) for a retention period of 24 hours. Then, the sample was positioned on a heater (80°C) for five hours to remove the organic content. After heating, the soil was cleaned using a centrifuge and then dried in the oven for 24 hours. The weights of soil after removing the organic content were measured. The soil was mixed with 200 ml of distilled water and the dispersing agent (1 ml of 40% Na₄P₂O₇ per gram of soil sample) into the 500 ml flask. The mix was left overnight on a shaking table to let the soil particles disperse. All soil was then transferred to the PARIO cylinder and washed from the flask to ensure the whole sample flowed into the cylinder. The sample cylinder was filled with distilled water to bring the water level to the 1000-ml mark. PARIO device was connected to a computer and placed into the cylinder for 24 hours. After the 24 hours test, the
soil was dried and then sieved using three sieves #35 (opening size of 0.5 mm), #60 (opening size of 0.25 mm), #270 (opening size of 0.053 mm). The retained weights on those sieves were recorded, which was used to calculate the percentage of fine, medium, and coarse sands by weight.

Figure 6.2 shows the particle size distributions of the nest samples from different locations (A15 II, A27 I, D4 II, E2 II, and F6 II). The particle size distribution curves between different nest locations are similar. The fractions of sand, silt, and clay are 20% to 50%, 50 to 70%, and 0% to 10%. Figure 6.3 compares the particle size distribution curves between the nest soil at location F and soil from the surrounding area of location F. The comparison in Figure 6.3 shows that the surrounding soil has a higher percentage of fine-grained soil, which indicates that the mud daubers can select soil particles to build their nests. Thus, the nest soil classification is independent of the surrounding soil.

Figure 6.1. Particle size analysis of the nest samples using PARIO hydrometer
Figure 6.2. Particle size distribution of nest samples at different locations

Figure 6.3. Particle size distribution of nest samples and surrounding soil from location F.
6.2. Fall Cone Test

Fall cone tests were conducted for nest soils at two locations (A and F) following the British standard 1377-2 (British standard, 1990). Regardless of the nest types (both organ pipe and black and yellow), all nests of location A were smashed into soil particles. According to the BS 1377-2, the soil that is used for the fall cone test should be passed through sieve #40 (0.425 mm). However, we used the nest soil passing through sieve #200 (0.075 mm) according to the revised soil classification system (Park et al., 2018). Figure 6.4 shows the liquid limit of the nest soil passing through sieve #200 (0.075 mm) at location A. The liquid limit for the nest soil at location A is 46 %. The same analysis was conducted for location F. The liquid limit is 34 % as shown in Figure 6.5.

Figure 6.4. Liquid limit of the nest sample at location A.
6.3. Roundness of Nest Soil Particles

The particle shape of soil is an essential parameter for use in the revised soil classification system (Park et al., 2018). Sphericity, roundness, and smoothness define different particle shape (Cho et al., 2006). Particle size and shape can affect the mechanical and physical properties of soils. Lower sphericity and roundness mean lower regularity. Lower regularity increases the void ratio, the compressibility, the friction angle, and decreases small-strain stiffness (Cho et al., 2006). Natural sands have roundness (R) ranging from 0.3 to 0.9 and sphericity (S) ranging from 0.5 to 0.9 as shown in Figure 6.7.

Nest soils were passed through sieve #60 (0.25 mm). The retained sands were observed under an optical microscope. Figure 6.6 shows the sand particle shape under the optical microscope.

Figure 6.5. Liquid limit of the nest sample at location F.
for mud dauber soils at locations A and F. The images of the particle shape were then compared to Figure 6.7 to characterize the roundness of the sand particles. It seems that both locations have a roundness of 0.7, according to Figure 6.7. The roundness of the particles was then used for classifying the nest soil using the revised soil classification system (Park et al., 2018).

Figure 6.6. Optical microscopy imaging of the nest sands: (a, and b) for location A, (c, and d) for location F.
6.4. Revised Soil Classification System

Unified Soil Classification System (USCS) reflects the soil's intrinsic physical properties and captures the soil behavior by classifying it into groups. Every group has its properties and behavior. There are some important limitations related to these soil groups, such as the failure of capturing the role of fines on the mechanical and hydraulic properties of soil, according to Park et al. (2017). USCS classification system considers the coarse-fine established boundary, despite the fine soils have a great range of plasticity. The USCS classification system also does not consider the effect of the particle shape on packing density. Finally, USCS does not show the role of pore-fluid chemistry in fine behavior despite its significant importance.
Revised Soil Classification System (RSCS) adopts the maximum and minimum void ratios for gravels and sands, which can be estimated from index properties (i.e., particle shape, liquid limit, and coefficient of uniformity). RSCS also considers three distinguished void ratio values for fines, including soft $e_F^{10\text{ KPa}}$, stiff $e_F^{1\text{ MPa}}$ for the mechanical response, and $\lambda e_F^{\text{LL}}$ for fluid flow control (Park et al., 2017).

To classify the nest soil using RSCS, particle size analysis, fall cone tests, and roundness assessments of different nest soil samples were performed. Figure 6.8 shows the RSCS for location (A), and Figure 6.9 shows the RSCS for location (F). The mud dauber nest soils at locations A and F were classified as fine-grained soil (sandy silt).

Figure 6.8. Soil classification using (RSCS) for location A
6.5. Discussion

Particle size analysis showed that the soil particle sizes of different nest locations are similar. The percentage of sand, silt, and clay are from 20 to 50%, 50 to 70%, and 0 to 10%, respectively.

Comparing the particle size distributions of the nest soils to the surrounding soil demonstrated that the surrounding soil has a higher percentage of fine-grained soil. This might indicate that the mud daubers are able to select soil particles to build their nests. Furthermore, they might select specific proportions of different soil sizes to enhance the durability of their nests.
To classify the nest soil nest using RSCS, hydrometer tests, full cone tests, and roundness assessments of different nest soil samples were performed. Based on RSCS, the mud dauber nest soils were classified as fine-grained soil (sandy silt).
CHAPTER 7. MICROSCALE ANALYSIS OF THE NEST SOIL

7.1. SEM Imaging and EDS Analysis

Scanning Electron Microscopy (SEM) and Energy Dispersive X-ray Spectroscopy (EDS) analysis were conducted for three types of mud dauber nests. SEM imaging of the three samples was produced first to analyze the microscopic morphology of the samples. EDS was then used to scan the element composition to discover any saliva in the nest samples. SEM images of the organ pipe, steel blue, and black and yellow mud dauber nests are shown in Figure 7.1. The SEM figures show the layout of the particle packing. Silt or sand particles are coated by clay particles and cemented with surrounding silt or sand particles by clay serving as a cementing agent. The unique soil structure may lead to the reduction of the void ratio, increase of the dry unit weight, and increase of the penetrometer resistances, as shown from the previous experimental results. Figure 7.2 shows the EDS analysis of the mud dauber nest samples. Silica, calcium, oxygen, and carbon have a high percentage within the mud dauber nests.

7.2. X-Ray Diffraction Analysis

The X-Ray Diffraction (XRD) spectrums were obtained using the Panalytical Empyrean X-Ray diffractometer (Cu Kα, λ=0.154056 nm, 45 kV, 40 mA). The scattered radiation was detected in the angular range 5-60° (2θ) with a scan rate of 4°.min⁻¹. Black and yellow mud dauber nest sample from location A was used for analysis using XRD. Figure 7.3 shows an XRD spectrum of the mud dauber specimen from location A. It appears that the predominant minerals in the nest soil elements are quartz (96%) and calcium carbonate (4%).
Figure 7.1. Scanning Electron Microscope (SEM) imaging of nest samples: (a, b) steel blue mud dauber nest (G1 II); (c, d) Pipe organ mud dauber nest (A29 I); black and yellow mud dauber (2G I)
Figure 7.2. Energy Dispersive X-ray Spectroscopy (EDS) analysis of the nest samples
7.3. Optical Microscope Imaging

Several optical microscopy images of the mud dauber specimens were collected. Figure 7.4 (a) shows a sand particle covered up with small particles of silt and clay. Figure 7.4 (b) shows that two sand particles are cemented together by clay or silt. Figures 7.4 (c, d) show similar particle packing with SEM images. Silt or sand particles are cemented by surrounding clay or silt particles.
7.4. Discussion

Scanning Electron Microscopy (SEM) and Energy Dispersive X-ray Spectroscopy (EDS) analysis were conducted for three types of mud dauber nests. Silt or sand particles are coated by clay particles and cemented with surrounding silt or sand particles by clay serving as a cementing agent. Hence, this unique soil structure may lead to the reduction of the void ratio, increase of the dry unit weight, and increase of the penetrometer resistance.

Figure 7.4. Optical microscopy imaging of the nest specimens.
EDS analysis of the mud dauber nest samples showed that silica, calcium, oxygen, and carbon have a high percentage within the mud dauber nests.

X-Ray Diffraction (XRD) spectrum of mud dauber nests showed that the predominant minerals in the nest soil are quartz and calcium carbonate, which is similar to the minerals observed in the Hirundine and termites’ nests. This also confirms that mud dauber nests have low specific gravity.

Optical microscopy images showed similar particle packing with SEM images. Silt or sand particles are cemented together by clay serving as a cementing agent.
CHAPTER 8. CONCLUSIONS

To investigate the physical and mechanical properties of the nest soils, we collected the nests at several places around the Baton Rouge area. Geotechnical laboratory tests were conducted, including water content, organic content, specific gravity, dry unit weight, hydrometer, fall cone, compaction, and penetrometer tests. Statistical analysis was also performed for all laboratory data. Scanning Electron Microscope (SEM), Energy Dispersive Spectrum (EDS), and X-Ray Diffraction (XRD) were used to investigate the soil particle morphology and elemental composition. Based on the experimental results and analysis, we concluded that:

The organic contents of the mud dauber nest specimens range from 1.86 to 9.86% with a mean of 4.68%. These relatively high organic contents probably due to some organic matters (i.e., pollen grains, leaves fragments, spider webs) that were observed during nest investigation.

Mud dauber nests have low moisture content within the nest soil. The range of moisture content is between 1.17% and 4.06%. Mud daubers build their nests away from direct exposure to the sunlight to avoid rainwater erosion. The low moisture contents of the nest can sustain the matric suction induced cohesion in the nest soil.

The dry unit weights of the nests range from 74 to 142 pcf with a mean of 101.98 pcf. The measured dry unit weights are consistent with the reported range of low plastic sandy silt, ranging from 80 (minimum dry unit weight) to 135 pcf (maximum dry unit weight). According to RSCS, all the nest soils were classified as sandy silt soil, which is consistent with the findings of the dry unit weight measurements when performing the standard compaction tests, the maximum dry unit weight of the mud dauber nest soil is 105.6 pcf, corresponding to 15.5% optimum moisture content. The measured dry unit weights of the nests match the range of the dry unit weights achieved from
the compaction test. This might indicate that the high frequency buzzing vibration movement by
mud daubers (Camillo, 2002) used for compacting the soil during constructing their nests.

The mean of the specific gravity of the nest soils is 2.57, which is slightly lower than the
specific gravity of typical soils (2.6-2.9). This might due to the high percentage of organic contents
within the nest soil.

The penetrometer resistances of the mud dauber nests range from 0.87 to 17.53 tsf with the
mean value of 3.95 tsf and standard deviation of 2.5, indicating the nest specimens are stiff to hard
soil based on the consistency classification of the cohesive soil. Moreover, the intact nests showed
the highest penetrometer resistances. This might indicate that the structure of the nests may
contribute to the nest strength. It was also shown that the black and yellow nests have a little higher
penetrometer resistance than those of organ pipe nests, which may attribute to the nest thickness.
The organ pipe nests do not have extra layers of soil covering the nests. However, black and yellow
and steel blue mud dauber construct extra layers of soil covering the nests.

Particle size analysis showed that the soil particle sizes of nests from different locations
are similar. The percentage of sand, silt, and clay are from 20 to 50%, from 50 to 70%, and from
0 to 10%, respectively. The comparison of the particle sizes between nest soil and surrounding soil
indicated that the mud daubers nest soil has lower percentage of clay. They probably can select
specific proportions of different soil sizes to enhance the durability of their nests.

SEM imaging showed that silt or sand particles are coated by clay particles and cemented
with surrounding silt or sand particles by clay serving as a cementing agent. Hence, this unique
soil structure may lead to a reduction of the void ratio, increase of the dry unit weight, and increase
of the penetrometer resistance. The same findings were confirmed by the optical microscopy
imaging of the nest soil.
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VITA

Noura Sultan Saleh was born in Saudi Arabia in June 1991. She finished her bachelor’s degree in Civil Engineering – Faculty of Engineering – Mansoura University – Mansoura – Egypt (2008-2013). In January 2019, she joined Louisiana State University to pursue master’s degree. Since this time, she has worked as a graduate research assistant at the Department of Civil and Environmental Engineering. During this time, she worked on employing microorganisms to cement soil particles and mimicking organisms, insects, and plants to improve the engineering properties of soil. She plans to receive her Master’s this December 2020.