2014

Engineering Behavior and Characterization of Biomass Ashes using Geotechnical Measurement Techniques

Francisco Javier Grau Sacoto
Louisiana State University and Agricultural and Mechanical College, fjgrau@hotmail.com

Follow this and additional works at: https://digitalcommons.lsu.edu/gradschool_theses
Part of the Civil and Environmental Engineering Commons

Recommended Citation
https://digitalcommons.lsu.edu/gradschool_theses/1024

This Thesis is brought to you for free and open access by the Graduate School at LSU Digital Commons. It has been accepted for inclusion in LSU Master’s Theses by an authorized graduate school editor of LSU Digital Commons. For more information, please contact gradetd@lsu.edu.
ENGINEERING BEHAVIOR AND CHARACTERIZATION OF BIOMASS ASHES USING GEOTECHNICAL MEASUREMENT TECHNIQUES

A Thesis
Submitted to the Graduate Faculty of the Louisiana State University and Agricultural and Mechanical College in partial fulfillment of the requirements for the degree of Master of Science in Civil Engineering

in

The Department of Civil and Environmental Engineering

by
Francisco Grau Sacoto
B.S.C.E., Universidad Catolica de Santiago de Guayaquil, 2011
May 2014
Dedicated to my parents, siblings and my whole family,

who have been my support throughout these years.
ACKNOWLEDGEMENTS

First of all, I thank to God for His love, guidance and all the opportunities He has given me in my life. I would like to express my sincere thanks to my advisor, Dr. Jong-Won Jung, who gave me the opportunity to work and research under his constant guidance and patiently taught and supported me during these years at Louisiana State University. I would also like to thank the members of my advisory committee: Dr. Murad Abu-Farsakh, Dr. Maria Teresa Gutierrez-Wing and Dr. Jin-Woo Choi, for their help and advice in this research.

I would like to express my gratitude to my parents: Francisco and Sandra, for their advice and unconditional support that helped me to achieve my goals; to my brother Andres, my sister Mariuxi, and all my family members who have supported me all my life. A special thanks to my fiancée Diana Carvajal, who has become my family here in Baton Rouge, for all the love and help along these years.

I really appreciate the help, support and advice of my classmates, labmates and friends. Finally, my sincere thanks go to the Government of Ecuador and its institutions that provided me financial support for my studies; I would be glad to contribute and serve my country after this learning period.
TABLE OF CONTENTS

ACKNOWLEDGEMENTS ........................................................................................................ iii

LIST OF TABLES .................................................................................................................. vi

LIST OF FIGURES .............................................................................................................. vii

ABSTRACT ........................................................................................................................ xi

CHAPTER 1. INTRODUCTION ............................................................................................ 1
  1.1 General Information ........................................................................................................ 1
  1.2 Objectives ........................................................................................................................ 1
  1.3 Thesis Organization ........................................................................................................ 2

CHAPTER 2. LITERATURE REVIEW .................................................................................. 3
  2.1 Biomass classification ...................................................................................................... 3
    2.1.1 Agricultural biomass and waste resources ............................................................ 4
    2.1.2 Forest biomass and wood waste resources ............................................................ 5
    2.1.3 Energy crops .............................................................................................................. 7
    2.1.4 Municipal solid wastes ........................................................................................... 8
  2.2 Most Common Biomass Materials ................................................................................. 8
  2.3 Physical Properties of the Biomass Materials ............................................................... 9
    2.3.1 Wood ........................................................................................................................ 9
    2.3.2 Sugarcane (Bagasse) ............................................................................................... 9
  2.4 Chemical Properties of the Biomass Derived Materials ............................................. 9
  2.5 Maximum Shear Modulus ............................................................................................ 11
  2.6 Thermal Properties ..................................................................................................... 16

CHAPTER 3. CHARACTERIZATION OF WOOD AND SUGARCANE BAGASSE
  ASHES ............................................................................................................................. 21
  3.1 Samples ......................................................................................................................... 21
  3.2 Particle Size Distribution ............................................................................................. 23
  3.3 Specific Gravity ............................................................................................................. 24
  3.4 SEM Imaging .................................................................................................................. 25
  3.5 Chemical Composition ................................................................................................. 29
  3.6 pH and Atterberg limits ............................................................................................... 30

CHAPTER 4. ENGINEERING BEHAVIOR ....................................................................... 33
  4.1 Hydraulic Conductivity ................................................................................................. 33
  4.2 Consolidation ............................................................................................................... 38
  4.3 Shear Wave Velocity ................................................................................................... 43
  4.4 Thermal Conductivity Tests ....................................................................................... 52
CHAPTER 5. ANALYSES AND DISCUSSION .................................................................56
  5.1 Hydraulic Conductivity ..................................................................................56
  5.2 One-dimensional Consolidation .....................................................................59
  5.3 Shear Wave Velocity .......................................................................................60
  5.4 Thermal Conductivity .....................................................................................62

CHAPTER 6. CONCLUSIONS AND RECOMMENDATIONS ........................................65

CHAPTER 7. FUTURE WORK ....................................................................................67

REFERENCES ..........................................................................................................68

VITA .........................................................................................................................72
LIST OF TABLES


Table 2.2 Distribution of Agricultural Residues materials (Milbrandt 2005). ........................................4

Table 2.3 Distribution of Forest and wood residues (Milbrandt 2005).................................6

Table 2.4 Distribution of Energy crops (Milbrandt 2005). .........................................................8

Table 2.5 Elementary composition of biomass materials, tested in dry conditions (Zanzi 2001). ........................................................................................................10

Table 2.6 Ash chemical compositions of materials used (Abdullahi 2006, Teixeira, De Souza et al. 2008), American Coal Ash Association 1995) .................................10

Table 2.7 Average thermal properties of soils constituents (Farouki 1981). ...............................17
LIST OF FIGURES

Figure 2.1 Sugarcane plantation and bagasse (Grobe 2006) ................................................................. 5

Figure 2.2 Forest biomass waste. (Toso 2011) ......................................................................................... 6

Figure 2.3 Switchgrass plantation (Turco 2010) ..................................................................................... 7

Figure 2.4 Bender elements: (a) schematic representation of bender elements, (b) series type, and (c) parallel type. (Lee and Santamarina 2005) ........................................................................ 12

Figure 2.5 Peak-peak method for the determination of the wave travel time with bender elements (Santamarina, Klein et al. 2001) .................................................................................................. 13

Figure 2.6 Typical shear wave signal within near field: (A) first deflection, (B) first bump maximum, (C) zero after first bump, (D) major first peak. (Lee and Santamarina 2005) ........................................................................ 14

Figure 2.7 Bender element response for different input signals: Tip-to-tip distance D=90mm. Resonant frequency of the bender element f=4kHz (Lee 2003) .......... 14

Figure 2.8 Detail of bender element connection to soil or ash sample. (Dyvik and Madshus 1985) ................................................................................................................................. 15

Figure 2.9 Schematic set-up of shear wave test equipment (Leong, Cahyadi et al. 2009) ............. 16

Figure 2.10 Summary of heat transfer paths in particulate materials (Yun and Santamarina 2008) ................................................................................................................................. 18

Figure 2.11 Typical thermal needle probe and peripheral electronics. (Cortes, Martin et al. 2009) ................................................................................................................................. 20

Figure 2.12 Schematic set-up of the transient head method. (Yun and Santamarina 2008) ........ 20

Figure 3.1 Testing samples materials: (a) Ottawa 20-30 sand, (b) wood ash, and (c) sugarcane bagasse ash ....................................................................................................................... 22

Figure 3.2 Particle size distribution of the materials used. .................................................................... 23

Figure 3.4 Sputter Coater device EMS550X. .................................................................26

Figure 3.5 Jeol JSM 6610LV Scanning Electron Microscope ........................................26

Figure 3.6 Wood ash micrograph................................................................................27

Figure 3.7 Sugarcane bagasse ash micrograph............................................................28

Figure 3.8 Coal fly ash Class F micrograph.................................................................29

Figure 3.9 EDS analysis of wood ashes. .......................................................................29

Figure 3.10 EDS analysis of sugarcane bagasse ashes. ...............................................30

Figure 3.11 a) Benchtop pH meter, (b) Centrifuge device, and (c) centrifuge tube with sample..................................................................................................................31

Figure 3.12 Acidity analysis with pH values of Ottawa 20-30 sand and biomass ashes. Result values are filled in black and reference values in white. (Etiégni & Campbell, 1991; Jamil, Qasim, Umar, & Subhan, 2004; Naik et al., 2002; Rajamma, 2011; Vallero, Farnsworth, & Peirce, 2001) .........................................................32

Figure 4.1 Constant head permeameter used with Ottawa 20-30 sand..........................34

Figure 4.2 Falling head permeameter used with (a) wood ash, and (b) sugarcane bagasse ash. .................................................................................................................................35

Figure 4.3 Variation of hydraulic conductivity (k) with void ratio. ...............................35

Figure 4.4 Equivalent hydraulic conductivity of mixtures between .............................36

Figure 4.5 Equivalent hydraulic conductivity of mixtures between .............................37

Figure 4.6 GeoJac setup with the software Sigma I-CON, and sample chamber, on right..39
Figure 4.7 Biomass ashes’ consolidation curve in saturate condition. ........................................41

Figure 4.8 Consolidation curves for sand and sand-wood ash mixtures.................................42

Figure 4.9 Consolidation curves for sand and sand- sugarcane bagasse ash mixtures. ..........42

Figure 4.10 Agilent Waveform Generator 33210A. ..................................................................43

Figure 4.11 Krohn-Hite model 3944 Multi-channel filter............................................................44

Figure 4.12 Agilent Technologies Digital Oscilloscope model DSO6014A. ...........................45

Figure 4.13 Materials used to assemble bender elements.........................................................46

Figure 4.14 Assembly of bender elements (BE): .................................................................47

Figure 4.15 Shear wave velocity with consolidation stress of sand-wood ash mixtures. .......49

Figure 4.16 Shear wave velocity with consolidation stress of sand- sugarcane bagasse ash mixtures......................................................................................................................50

Figure 4.17 Maximum shear modulus with consolidation stress of sand-wood ash mixtures. .....51

Figure 4.18 Maximum shear modulus with consolidation stress of sand- sugarcane bagasse ash mixtures.............................................................51

Figure 4.19 Thermal Properties Analyzer QuickLine 30. .......................................................52

Figure 4.20 Thermal conductivity (λ) with consolidation stress of sand-wood ash mixtures......54

Figure 4.21 Thermal conductivity (λ) with consolidation stress of sand- sugarcane bagasse ash mixtures................................................................................................................55

Figure 5.1 Equivalent hydraulic conductivity of sand – wood ash mixtures. ........................57

Figure 5.2 Loose and dense packing of mixtures.................................................................58

Figure 5.3 Equivalent hydraulic conductivity of sand – wood ash mixtures. ........................58

Figure 5.4 Equivalent hydraulic conductivity of sand – sugarcane bagasse ash mixtures........59
Figure 5.5 Variation of Compressibility Index (Cc) with content of biomass ash. ..........................60

Figure 5.6 Typical values for $\alpha$-factor and $\beta$-coefficient. ..........................................................62

Figure 5.7 Thermal conductivity and ash content variations with void ratio of Ottawa sand - wood ash mixtures. .................................................................64

Figure 5.8 Thermal conductivity and ash content variations with void ratio of Ottawa sand - sugarcane bagasse ash mixtures. .........................................................64
ABSTRACT

Biomass, the organic material derived from plants or animals in a biological process, has rapidly become a topic of worldwide interest. The need to find new types of renewable energy sources has led to the use of natural materials as an economic, sustainable and environmental alternative. The combustion of biomass matter becomes biomass ash, which contains macronutrients and micronutrients. Currently, the recycling potential is wasted and most of the biomass ash is dumped without control or just disposed in landfills.

The main objective of this research is to provide an environmental solution recycling the biomass ash and reducing the waste. Thus, biomass ashes from two kinds of materials were selected and tested in the laboratory. Wood ash is used in this study since wood is currently one of the largest biomass energy sources that has been applied in engineering in construction of roads, landfills and concrete mixtures. Also, sugarcane bagasse ash was used in this study because sugarcane is the most abundant crop in Louisiana. Bagasse is the residue matter, mostly consisting of the dry fibrous mass remaining after the juice is extracted.

Therefore, wood and sugarcane bagasse ashes’ physical and chemical properties were investigated for their characterization such as particle size distribution –sieve and hydrometer, specific gravity, pH, microscope examination using SEM and elemental analysis using EDS. Also, geotechnical tests were conducted such as hydraulic conductivity, one-dimensional consolidation, shear wave velocity using bender elements and thermal conductivity.

Samples containing 100% of Ottawa 20-30 sand, wood ash and sugarcane bagasse ash were tested first. Later, mixtures of sand with 2~10% ash were tested in order to compare and evaluate the behavior of those biomass ashes when mixing them with a non-cohesive soil.
CHAPTER 1
INTRODUCTION

1.1 General Information

The need to implement new kinds of energy resources lead to the use of natural materials as an economic and environmental alternative. Biomass is considered any organic material, either animal or plants, derived from any living or recent living structure. Through photosynthesis, plants absorb energy from the sun. A short amount of biomass is converted to biofuel by thermal, chemical and biochemical methods. Thus, biomass has expanded fast and has become the source of energy of the future. Nowadays, most biomass is considered as waste from agriculture and it is typically discarded or disposed without control. For this reason, new applications can be addressed and it could be considered as an economic and environmental alternative in geotechnical engineering.

Physical and chemical treatment methods have been applied to soils in order to improve their engineering behavior. For example, soil densification is one of the physical methods that modify the soil structure such as compaction and the decrease of void ratio. Chemical methods consider mixing the soil with any material that alters inner properties of soils.

1.2 Objectives

The objective of this study is to evaluate the benefits of the biomass ash when mixing with dry Ottawa 20-30 sand using the most abundant biomass materials in the state of Louisiana and the United States. Various tests, including characterization of ashes and geotechnical properties test, with different soil-ash compositions, were performed and the results were analyzed.
The particular objectives of this research are:

- Provide an environmental solution for the uncontrolled disposal of agricultural and wood residues converted to ashes, recycling the biomass ash and reducing the waste.
- Since biomass ash is obtained for free, propose a new alternative, in a cheap and natural way to replace soils with a certain amount of biomass ash in geotechnical engineering projects.
- Measure the geotechnical properties of biomass ash such as hydraulic conductivity, thermal conductivity, consolidation, and maximum shear modulus.
- Study the geotechnical engineering behavior of soils and biomass ashes mixtures with different concentrations.

1.3 Thesis Organization

The central themes of this research are the behavior of soil including biomass ashes. The manuscript is organized as follows.

Chapter 2 documents the critical points of this research, presenting the concepts applied for this thesis and addressing previous studies as references.

Chapter 3 introduces the materials, sampling, and characterization tests performed for this research.

Chapter 4 presents the equipment, methods and results of the laboratory tests performed to obtain the geotechnical parameters studied in this thesis.

Chapter 5 explains the results, analyzes the behavior and causes of the main tests performed.

Chapter 6 summarizes the salient conclusions and recommendation for further studies.
2.1 Biomass classification

Many authors and researchers have given their own classification of biomass materials, citing the many resources available in the United States. The four main categories of biomass materials can be divided are:

- Agricultural biomass and waste resources
- Forest biomass and wood waste resources
- Biomass energy crops
- Municipal solid wastes

In this section, the categories listed above are reviewed and explained in order to know the characteristics of each class of biomass, the categories they are subdivided, availability, and important information about them.

It is very important to know the amount and availability of each type of biomass, as well as the most common materials of each type so they can be selected for using in the experiments.

Table 2.1 shows the percentage of dry tons for each class of biomass available in the United States. Four different studies were taken for the calculation of these values and the average values gotten from these sources are shown in this table.

<table>
<thead>
<tr>
<th>TYPE OF BIOMASS SOURCES</th>
<th>AVAILABILITY (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Agricultural and waste resources</td>
<td>42 ± 4</td>
</tr>
<tr>
<td>Forest and wood waste resources</td>
<td>40 ± 2</td>
</tr>
<tr>
<td>Energy crops</td>
<td>17 ± 2</td>
</tr>
<tr>
<td>Municipal solid wastes</td>
<td>1 ± 1</td>
</tr>
</tbody>
</table>
2.1.1 Agricultural biomass and waste resources

Agricultural residues include plant and animal based residual materials. It is all the matter left after harvest crops and methane emissions from manure management, which together reach a potential source of up to 155 million tons of biomass for production (Union of Concerned Scientists 2012). They can be roots, leaves, fruits, stems and other parts of plants that are not used after the plant’s main use is achieved. These residues are neither consumable nor marketable and, due to the large volume amount, residues are incinerated producing ashes that are just dumped without control or used as soil fertilizers. Additionally, oil can be extracted from the seeds and residues of several crops for use as a biofuel.

The most abundant primary agriculture residues are shown in Table 2.2. The most common crops in the country used for biomass of this class are: corn stover, soybeans, wheat, sugarcane, cotton, grain sorghum and rice. Different papers were analyzed in order to determine their proportions, which are shown in the Table 2.2.

In animal manure systems, residues can be collected from animal activities and wastes, becoming a secondary agricultural residue. Methane is produced by the anaerobic decomposition of organic matter.

Table 2.2 Distribution of Agricultural Residues materials (Milbrandt, 2005).

<table>
<thead>
<tr>
<th>AGRICULTURAL AND WASTE RESIDUES</th>
<th>AVAILABILITY (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Corn stover</td>
<td>43 %</td>
</tr>
<tr>
<td>Soybeans</td>
<td>30 %</td>
</tr>
<tr>
<td>Wheat</td>
<td>11 %</td>
</tr>
<tr>
<td>Sugarcane</td>
<td>4 %</td>
</tr>
<tr>
<td>Cotton</td>
<td>3 %</td>
</tr>
<tr>
<td>Sorghum (grain)</td>
<td>2.5 %</td>
</tr>
<tr>
<td>Rice</td>
<td>2.4 %</td>
</tr>
<tr>
<td>Others</td>
<td>4.1 %</td>
</tr>
</tbody>
</table>

The most abundant feedstock in Louisiana is sugarcane. Figure 2.1 shows a sugarcane plantation and a stack of sugarcane bagasse on the right, which is the remaining of the plant after the juice is extracted.

Figure 2.1 Sugarcane plantation and bagasse (Grobe 2006).

2.1.2 Forest biomass and wood waste resources

Approximately one third of the United States total area is considered forestland (Perlack et al., 2005). This type of biomass, together with the agricultural residues, is one of the biggest sources of biomass in the country, and it is “the largest source of biomass used for heat and power generation” (Biomass Research and Development Board, 2008). The residues of harvested wood leave timber on the ground, as well as branches and leaves - which are about one third of the trees- that appeared as waste at first. These residues must be removed from the ground because they can cause forest fires.

This type of biomass is divided into four categories, according to the way of collect them: forest residues, primary and secondary mill residues, and urban wood residues. Forest residues are mainly a product of logging residues. Mill residues are wood materials and sawdust
generated at plants and furniture factories. Urban wood residues include the less common way to get woody biomass, by collecting wood waste such as in construction and demolition (Milbrandt, 2005).

In the wood and forest category, which covers the 40% of the total biomass, the most available tree species for woody biomass are aspen, oaks, pines, maples, tulip-wood and hickory (Milbrandt, 2005). Unfortunately, there is no information about the availability of each class of trees. The distribution of each category of this biomass class is shown in Table 2.3.

<table>
<thead>
<tr>
<th>FOREST AND WOOD RESIDUES</th>
<th>AVAILABILITY (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Forest residues</td>
<td>33 %</td>
</tr>
<tr>
<td>Primary mill residues</td>
<td>46 %</td>
</tr>
<tr>
<td>Secondary mill residues</td>
<td>3 %</td>
</tr>
<tr>
<td>Urban wood residues</td>
<td>18 %</td>
</tr>
</tbody>
</table>

Southern yellow pines are very popular in the southern United States because they are grown in the red clay soil of the South (Spartanburg Forest Products 2013). Figure 2.2 shows a stack of wood wastes, which is the remaining of a forest logging.

Figure 2.2 Forest biomass waste. (Toso 2011)
2.1.3 Energy crops

Energy crops are dedicated plants grown with low economic cost and used merely as biomass for getting energy. They are useful because of their resistance to plagues, drought, earliness of growth and adaptation to almost every land. The best weather for these crops is the tropical regions because the photosynthesis assimilation is greater than the template regions. However, this option is not truly cost-effective because the profits are not enough, and they can use large areas of fertile soil useful for other crops, which can produce more benefit. These dedicated crop plants grow fast and can get very tall, around 4 meters tall. They are mainly produced in the east of the United States. Their moisture can widely vary through the type and age of the plant, having higher water content when they are young (Milbrandt, 2005).

The most popular of these energy crops are switchgrass, hybrid poplar, prairie, willow, alfalfa, cottonwood pines and eucalyptus. An example of an aquatic plant is the water hyacinth, which has one of the highest biomass productivities (Milbrandt, 2005). Figure 2.3 shows a switchgrass plantation and its relative height.

Figure 2.3 Switchgrass plantation (Turco 2010).
Table 2.4 shows the availability of the most common designated energy crops in the United States.

<table>
<thead>
<tr>
<th>ENERGY CROPS</th>
<th>AVAILABILITY (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Switchgrass</td>
<td>58%</td>
</tr>
<tr>
<td>Hybrid Poplar</td>
<td>37%</td>
</tr>
<tr>
<td>Prairie and others</td>
<td>5%</td>
</tr>
</tbody>
</table>

2.1.4 Municipal solid wastes

The smallest amount of biomass available is collected from municipal solid wastes originated from newspaper, food and other wastes. They are combusted into energy as mixed wastes and methane is obtained from domestic wastewater treatment. Another example of wastes biomass is household garbage (food wastes, textiles and leather), vegetative waste (lawn clippings and tree trimmings), paper, cardboard, wood, etc.

2.2 Most Common Biomass Materials

According to the tables above, the three most available biomass materials harvested in the United States are corn, wood (forest residues) and switchgrass. In the state of Louisiana, sugarcane is the most important and leading farm product, putting Louisiana as the nation’s second largest sugar producer and home of one of the world’s biggest sugar refineries. Only these four crops resources cover the 69.6% of the total biomass available in the United States.

The crops that were used in this research are sugarcane and wood, and they were chosen for their importance and availability in the state of Louisiana and the country, respectively. It is relevant to know the physical and chemical properties of these materials before mixing and using them with the soil samples. In the next sections, a brief overview of these properties is shown.
2.3 Physical Properties of the Biomass Materials

2.3.1 Wood

Wood has become the main source of biomass available, having 40% of the total biomass in the country. The most available class of wood biomass is the residues of wood generated at manufacturing plants when products are processed such as slabs, ending, trimming, sawdust, etc.

Wood is an anisotropic material; thus it doesn’t behave the same way on all the directions of the fiber. However, it is a very resistant material and one of the most suitable for working in tension due to its structure. Hardness is another property of wood. The core or the central part of the trunk has the largest hardness due to its compaction. Its moisture can vary depending on the type of wood, season, weather and zone. However, most of the primary mill wood residues tend to have low moisture content, less than 20% (Perlack et al., 2005).

2.3.2 Sugarcane (Bagasse)

Sugarcane can be considered as the major crop in the state of Louisiana and one of the world’s largest crops. Since the main use is to extract the juice from the cane, the fibrous material that remains after that process, which is called bagasse, was only a waste matter. The bagasse moisture is typically high, around 40%-50%, and this makes it helpful for various uses.

2.4 Chemical Properties of the Biomass Derived Materials

The materials that were used contain many chemical components that provide similar characteristics in those plants. Most of them are carbohydrates in the form of monosaccharide and polysaccharide sugars, acid, proteins, and other compounds. An interesting chemical compound for this study is lignin. It is a polymer found in the cell walls of plants. The main function is to support the plants’ structure and provide stiffness in plants, give shape and form the plant, giving strength to the cell wall and the whole plant (Arms & Camp, 1995). The more
lignin a plant has, the more strength it has. Lignin constitutes 25.2% in sugarcane bagasse and 29.5% in wood pines (Singh & Harvey, 2009). Additionally, it is important to know the chemical elementary compositions of the materials that are going to be used in the experiments, as shown in Table 2.5.

Table 2.5 Elementary composition of biomass materials, tested in dry conditions (Zanzi, 2001).

<table>
<thead>
<tr>
<th>ELEMENTS</th>
<th>WOOD (%)</th>
<th>SUGARCANE (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Carbon (C)</td>
<td>49.3</td>
<td>49.5</td>
</tr>
<tr>
<td>Oxygen (O)</td>
<td>44.2</td>
<td>43.8</td>
</tr>
<tr>
<td>Hydrogen (H)</td>
<td>6.0</td>
<td>6.2</td>
</tr>
<tr>
<td>Nitrogen (N)</td>
<td>0.5</td>
<td>0.5</td>
</tr>
<tr>
<td>Sulfur (S)</td>
<td>0.01</td>
<td>-</td>
</tr>
<tr>
<td>Ash Content</td>
<td>0.5</td>
<td>3.7</td>
</tr>
</tbody>
</table>

Chemical and mineral compositions of ash mainly depend on the components of the biomass material (plants). The chemical ash composition can also vary in each material because the combustion temperature is a relevant variable and can affect the ash composition (Misra, Ragland, & Baker, 1993). Table 2.6 shows the chemical composition of biomass ashes, including wood and sugarcane bagasse ash. Additionally, coal fly ash class C and F compositions are provided in order to compare these materials.

Table 2.6 Ash chemical compositions of materials used (Abdullahi, 2006; Teixeira, De Souza, de Almeida Santos, Vilche Peña, & Miguel, 2008, American Coal Ash Association 1995).

<table>
<thead>
<tr>
<th>CONSTITUENTS</th>
<th>WOOD ASH</th>
<th>SUGARCANE BAGASSE ASH</th>
<th>COAL FLY ASH CLASS C</th>
<th>COAL FLY ASH CLASS F</th>
</tr>
</thead>
<tbody>
<tr>
<td>SiO₂</td>
<td>31.8</td>
<td>85.5</td>
<td>40</td>
<td>55</td>
</tr>
<tr>
<td>Al₂O₃</td>
<td>28</td>
<td>5.3</td>
<td>17</td>
<td>26</td>
</tr>
<tr>
<td>Fe₂O₃</td>
<td>2.34</td>
<td>1.3</td>
<td>6</td>
<td>7</td>
</tr>
<tr>
<td>CaO</td>
<td>10.53</td>
<td>2.1</td>
<td>24</td>
<td>9</td>
</tr>
<tr>
<td>MgO</td>
<td>9.32</td>
<td>1.1</td>
<td>5</td>
<td>2</td>
</tr>
<tr>
<td>SO₃</td>
<td>-</td>
<td>-</td>
<td>3</td>
<td>1</td>
</tr>
<tr>
<td>Na₂O</td>
<td>6.5</td>
<td>-</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>K₂O</td>
<td>10.38</td>
<td>3.5</td>
<td>-</td>
<td>-</td>
</tr>
</tbody>
</table>
2.5 Maximum Shear Modulus

The Maximum Shear Modulus (Gmax) is a relevant parameter to estimate the dynamic response of soils. It is very useful for many engineering applications, such as the design of foundations under dynamic loads, liquefaction evaluation, and soil stability analyses. The Shear Modulus is defined as the ratio of the shear stress to the shear strain in a material. This parameter varies depending on the type of soil, void ratio and fines content, since the mechanical behavior of clean sands is different from the sand with fines.

This Maximum Shear Modulus value can be determined from the elastic wave theory with the following formula:

\[ G_{\text{max}} = \rho \cdot V_s^2 \]  \hspace{1cm} (2.1)

where \( \rho \) is the density of the soil specimen, and \( V_s \) is the Shear Wave Velocity.

There is a wide range of methods to estimate Shear Wave Velocity (Vs) in the field including impulsive seismic methods using explosives, hammers or any other mechanical mean, and sustained source methods using a mechanical or electromagnetic vibrator, and in laboratories using bender elements (Duke, 1969). S-wave velocity depends on the void ratio, effective confining stress and inherent properties of the soil such as grain size distribution, grain shape, angularity, roughness and mineralogical composition (Robertson, Sasitharan, Cunning, & Sego, 1995). It has been previously reported that Vs increases with the increment of confining stress (Nakagawa, Soga, & Mitchell, 1996). However, this relationship varies depending on the material tested. Likewise, Vs increases as void ratio decreases due to the compaction and reduction of specimen’s length. In this research, S-wave velocity was measured with bender elements, which can be calculated dividing the travel length of the shear wave over the travel time, using the following equation:
where $L =$ the travel length of the shear wave, and

$\Delta t =$ travel time

Bender elements are two-layered transducers which, due to their piezoelectric properties, convert a mechanical energy into a signal of electrical energy and vice versa. When a mechanical load is applied to the bender element, it generates voltage and a shear wave is propagated through the specimen. Then, the receiver bender element at the other end of the specimen bends when the signal arrives and it creates an electrical signal displayed in an oscilloscope as a waveform (J. Lee & Santamarina, 2005). A typical bender element consists of two conductive outer electrodes bonded to two sheets of piezoceramic plates, and a conductive metal shim at the center (J. Lee & Santamarina, 2005), as shown in Figure 2.4a.

\[
V_s = \frac{L}{\Delta t}
\]  

(2.2)

Figure 2.4 Bender elements: (a) schematic representation of bender elements, (b) series type, and (c) parallel type. (J. Lee & Santamarina, 2005)
There are two types of bender elements: the series type and the parallel type. The series bender element has two piezoelectric layers that act in the opposite poling direction. In the parallel type, the two piezoelectric layers act in the same poling direction. Figure 2.4 describes the above mentioned. Since the parallel type has two times larger displacement than the series type for the same applied voltage, for geotechnical analysis parallel bender elements are typically used as a source and the series type as a receiver.

In the Equation 2.2 shown above, used for the calculation of the shear wave velocity (Vs), the travel length of the wave (L) through the specimen can be easily determined in the laboratory by measuring the distance between the two bender elements. One bender element acts as a sender or source and the other as a receiver, and they should be placed at the top and bottom of the specimen in the chamber. On the other hand, the accuracy of the wave travel time is sometimes discussed to determine. There are many methods to determine the travel time, and the two most known are the peak-peak method and the start-start method (Lohani, Imai, & Shibuya, 1999). The first one consists in calculating the differences of time between the first peak on the departing sine wave and the equal point on the arriving sine wave. Figure 2.5 illustrates the peak-peak method in a sine waveform. The travel time is denoted by Δt.

Figure 2.5 Peak-peak method for the determination of the wave travel time with bender elements (Santamarina, Klein, & Fam, 2001)
The second method, start-start, involves the difference of time between the start of the first sine wave and the start of the following sine wave. The red arrow in Figure 2.6 shows the start of the first wave at point C and a typical shear wave signal with its parts.

Figure 2.6 Typical shear wave signal within near field: (A) first deflection, (B) first bump maximum, (C) zero after first bump, (D) major first peak. (J. Lee & Santamarina, 2005).

Different input waveform signals can be used for measuring Vs with bender elements in the laboratory. On the left side of Figure 2.7, a few of the most common input waveform and frequencies are shown. The output wave signal is shown on the right of the same figure.

<table>
<thead>
<tr>
<th>Input Wave</th>
<th>Output Wave</th>
</tr>
</thead>
<tbody>
<tr>
<td>Square wave</td>
<td></td>
</tr>
<tr>
<td>Impulse wave</td>
<td></td>
</tr>
<tr>
<td>Sine: f = 40kHz</td>
<td></td>
</tr>
<tr>
<td>Sine: f = 12kHz</td>
<td></td>
</tr>
<tr>
<td>Sine: f = 4kHz</td>
<td></td>
</tr>
<tr>
<td>Sine: f = 1kHz</td>
<td></td>
</tr>
<tr>
<td>Sine: f = 0.5kHz</td>
<td></td>
</tr>
</tbody>
</table>

Figure 2.7 Bender element response for different input signals: Tip-to-tip distance D=90mm. Resonant frequency of the bender element f=4kHz (J.-S. Lee, 2003)
According to Lee and Santamarina, some difficulties can be obtained when using bender elements such as electrical crosstalk caused by electromagnetic coupling through the soil, mixed radiation of both P and S waves, near field effects, and uncertain detection of first arrivals (J. Lee & Santamarina, 2005). For reducing these electromagnetic coupling effects, electric shielding and grounding should be used in bender elements. In the next chapter, a method to assembly bender elements is explained. A detail of an assembled bender element is shown in Figure 2.8. At least two bender elements should be used to measure shear wave velocity in an experiment. One acts as a source or transmitter, and the other works as a receiver bender element.

For the assembly of bender elements, a process should be followed carefully in order to prevent the difficulties addressed above. They should be correctly soldered, coating should be applied and let it dry at least two times, crosstalk should be prevented by shielding it, and bender elements should be placed inside a screw with epoxy, which fills the voids and prevent from water. After this process, bender elements should be placed in a chamber facing each other in the direction of the shear wave propagation. A more detailed explanation is provided in the next chapter.

![Figure 2.8 Detail of bender element connection to soil or ash sample. (Dyvik & Madshus, 1985)](image)
A special instrumentation is required to perform this test. A waveform/signal generator is needed to send the first signal to the transmitter bender element. A filter/amplifier is useful for increasing the voltage then the signal is not strong enough and for minimizing the noise of high frequency signals. A digital oscilloscope is necessary to display in waveforms the electrical signal received. After the source bender element receives the voltage, it sends those waves to the to the bender element acting as a receiver, which converts the motion of the waves into electrical signals. A schematic set-up of the equipment needed for this experiment is shown in Figure 2.9.

![Figure 2.9 Schematic set-up of shear wave test equipment (Leong, Cahyadi, & Rahardjo, 2009)](image)

### 2.6 Thermal Properties

Conduction and diffusion phenomena control the transfer of heat through soils or any particulate material. Thermal conductivity is a property of any material to regulate the transmission of heat due to a temperature gradient. The differential equations for steady-state conduction assume isotropic conditions, linear material response and mass conservation. Fourier’s Law controls the heat transfer by conduction. In one-dimensional case, the equation for thermal conduction is:

\[ H = -\lambda A \frac{\partial \tau}{\partial x} \]  

(2.3)

where, \( H \) = the amount of heat flowing per second,
\[ \lambda = \text{Thermal conductivity of material} \]

\[ A = \text{area of object} \]

\[ \frac{\partial T}{\partial x} = \text{Temperature gradient} \]

The rate of heat flow depends on the thermal gradient and the thermal conductivity of the mass. Conductive heat flow travels primarily through the solid phase of a solid mass. Since the thermal conductivity values of soil minerals are higher than those for air and water, the heat flow is predominantly through the solids. Heat capacity (Cp) can be defined as the ability of a given volume of a material to keep internal energy while undergoing a given temperature change, without a phase change (Kodide, 2010). Thermal diffusivity (α) is a way to measure how fast a body can change its temperature. Table 2.7 presents average values of volume heat capacity, thermal conductivity and thermal diffusivity for soils components.

Table 2.7 Average thermal properties of soils constituents (Farouki, 1981).

<table>
<thead>
<tr>
<th>MATERIAL</th>
<th>VOL. HEAT CAPACITY, VHC cal/cm³ °C</th>
<th>THERMAL CONDUCTIVITY, ( \lambda ) cal/cm³ °C</th>
<th>THERMAL DIFFUSIVITY, ( \alpha ) ( 10^{-3} \text{cm}^2 / \text{s} )</th>
</tr>
</thead>
<tbody>
<tr>
<td>Quartz</td>
<td>0.46</td>
<td>8.4</td>
<td>43</td>
</tr>
<tr>
<td>Many soil minerals (average)</td>
<td>0.46</td>
<td>2.9</td>
<td>15</td>
</tr>
<tr>
<td>Dry Soil w/organic matter</td>
<td>0.6</td>
<td>0.25</td>
<td>1.00</td>
</tr>
<tr>
<td>Water</td>
<td>1</td>
<td>0.6</td>
<td>1.42</td>
</tr>
<tr>
<td>Air</td>
<td>0.00029</td>
<td>0.026</td>
<td>0.21</td>
</tr>
</tbody>
</table>

Thermal conductivity of soils can be affected by many factors such as mineralogy, particle size, applied pressure, density, water content and pore fluid. For example, thermal conductivity values increase with larger particle size, increment of contact pressure, decrease of porosity, water content of soils and higher saturating pore fluid (Yun & Santamarina, 2008). Another important factor that affects thermal conductivity in soils is contact area. After the
application of a load, particles deform and contact area increases, thus thermal conductivity increases too.

According to Yun and Santamarina, primary particle-level head conduction action in granular materials can be in different ways. Figure 2.10 shows the diverse paths for heat transfer in particles.

1. Particle conduction is developed when the heat flow travels through the mineral that constitutes the particle. Mineralogy plays an important role in this path.

2. Contact conduction occurs directly through the contact area. This transfer path is very important because thermal conductivity increase when stress is applied and the contact area increases.

3. For particle-fluid-particle conduction, the flow goes from particles, passing across the interstitial fluid in pores.

4. Particle-particle radiation occurs due to two neighboring particles interaction that produces heat propagation by radiation across the gap between them.
5. Particle-fluid conduction develops when the heat transfer starts from the particle and follows with the fluid through the porous.

6. Pore fluid conduction results when the path of heat transfer is merely through the porous network.

7. Pore fluid convection takes place when the fluid near particles warms up and initiates natural convection currents. This is mostly important when D50 ≥ 6 mm (Yun & Santamarina, 2008).

8. Radiation occurs when this phenomenon occurs in the particle surface into the surrounding medium.

All methods for determining thermal conductivities relate the measurement of heat flux and temperature gradient. The most difficult part is the measurement of the heat flux, which can be obtained from different ways. Methods of measuring the heat flux are mainly divided in two classes: absolute or directly, when it is measured by the electrical power going into the heater, and comparative, when its measurement is done indirectly.

One of the most common methods for measuring the thermal conductivity of materials is the transient heat method. This technique consists in applying a source of heat to produce a temperature gradient using a needle probe that has a very large length to diameter ratio to stimulate conditions for an infinitely long specimen, in accordance with ASTM D5334. The needle probe contains a heating wire to produce the heat and a thermocouple to measure the temperature (Figure 2.11).
The process consists in applying a known current and voltage to the needle probe that results in a heat wave which propagates radially into the specimen to rise the temperature over a period of time. The temperature measured increases creating an approximately linear portion of the quasi-steady-state with the logarithm of time in the x-axis, which is used to calculate the thermal conductivity of the specimen. The thermal needle probe should be placed at the center of the tested specimen (Figure 2.12).
CHAPTER 3
CHARACTERIZATION OF WOOD AND SUGARCANE BAGASSE ASHES

This chapter shows a description of the sand and biomass ashes tested and the experimental plan and results covered in this research. The materials used in the experiments are wood ashes and sugarcane bagasse ashes that were used as biomass ashes in order to analyze their properties and how they perform as a mixture with cohesionless soils in this study. These ashes can be obtained after incineration of the leaves, branches, stems, and other residual parts, following the directions with the American Standards of Testing and Materials (ASTM E1755).

Wood ash was provided by RoyOMartin, a wood manufacturing company founded in Louisiana. The samples were obtained from the wood plant in Oakdale, Louisiana. The ashes were product of the incineration of wood residues such as barks, chips and knots from Southern Yellow Pines, a group of trees species native to the Southern United States. This kind of trees grows easily in red clayey soils, common in humid tropical regions. After burning the wood residues in a big furnace, water was sprinkled on the ashes to cool them down. When the sample arrived to the laboratory, they were dried at 110 °C in order to perform the tests properly.

Sugarcane bagasse ashes were obtained from the company Alma Plantation, a sugarcane mill in Lakeland, Louisiana. The sugarcane variety provided is LCP 85-384 and its bagasse was burned in boilers in plant and then transported in dry condition to the laboratory.

3.1 Samples

For this research, it was important to choose a cohesionless standardized soil such as a poor graded sand (SP) or silty sand (SM), according to the Unified Soil Classification System (USCS). Ottawa 20-30 Sand, standardized by ASTM C778, was chosen for its properties and since previous tests were already done. The main physical properties and parameters of these
soils should be obtained from the group of tests that is explained in the next section. Moreover, the ashes of the biomass materials described in the previous chapter were tested and their properties were obtained as well. Later on, the results were analyzed and compared between the Ottawa 20-30 sand itself, the biomass ash, and soil-ash mixtures. There were different mixture ratios, varying the ash content in order to get the trial with the soil optimum condition. The ash content intervals were 2% at first place, and 1% when approaching to the optimum condition for the hydraulic conductivity tests. These percentage rates are based on dry weight of the ashes. A picture of testing samples in dry condition can be observed in Figure 3.1.

![Testing samples materials: (a) Ottawa 20-30 sand, (b) wood ash, and (c) sugarcane bagasse ash.](image)

In order to define the characterization of the ashes and sand, main physical properties and parameters were determined with a set of tests in accordance with the ASTM standards. Tests for defining these parameters were run, such as grain size distribution with a sieve analysis in wet and dry conditions (ASTM C117 and ASTM C136) for particles with a diameter larger than...
0.075 mm. and by sedimentation with a hydrometer (ASTM D422) for the finer particles, Atterberg limits (ASTM D4318), specific gravity (ASTM D854), determination of pH (ASTM D4972), microscope examination using Scanning Electron Microscope (SEM), and Energy-dispersive X-ray spectroscopy (EDS).

### 3.2 Particle Size Distribution

For the Particle Size Distribution, a complete graph was drawn after the sieve analysis and hydrometer tests. These values were compared with the particle size distribution of coal fly ash. Results for sieve method for particles with a diameter larger than 75-μm and hydrometer method by sedimentation process for the finer particles are shown in Figure 3.2.

![Figure 3.2 Particle size distribution of the materials used.](image)

Ottawa 20-30 Sand is classified as poor graded sand (SP) by the USCS, having values of 1.38 for uniformity coefficient (Cu) and 1.01 for coefficient of gradation (Cc). The effective size
parameters are: D10=0.66, D30=0.78 and D60=0.91. This is the coarser material of all used, as shown in Figure 3.2.

Particle size distribution by sieve analysis of wood ashes was performed first, and 25.4% were finer than the 75-μm (No. 200) sieve. The wood ash samples contained residues particles including barks and chips from wood trees. Later, an analysis by hydrometer test indicated the distribution of the finer particles. The same testing method was applied for the sugarcane bagasse ashes: sieve analysis followed by the hydrometer test. This test showed that 78% of the sample weight was finer than 75-μm. Each test was performed two times and then average values were calculated to present them in the following figure. Coal fly ash class F was included in this figure to compare with the materials used in this study. Since this distribution depends on many factors such as type of coal, type and time of incineration, and storage, a constant value may not be obtained in same coal fly ash class F. ASTM C618 determines that the maximum amount of retained on 45-μm sieve is 34%. Reference values were taken from (Chindaprasirt, Jaturapitakkul, & Sinsiri, 2005).

3.3 Specific Gravity

Specific gravity (Gs) tests for sand and ashes were performed using a 500 mL water picnometer and a vacuum pump was used to ensure that there are no air bubbles in the water and between the solid particles.

Results of the specific gravities of Ottawa sand and biomass ashes were obtained and expressed in Figure 3.3, which shows the specific gravity values of the materials used and its range. Reference values from previous studies were found and added to this figure. Specific gravity values obtained from laboratory tests are filled in black, and reference values are represented with white dots.
Figure 3.3 Specific gravity of Ottawa 20-30 sand and biomass ashes. Result values are filled in black and reference values in white. (Abdullahi, 2006; Amin, 2010; Chusilp, Jaturapitakkul, & Kiattikomol, 2009; Naik, Kraus, & Siddique, 2002; Osinubi, Bafyau, & Eberemu, 2009; Santamarina & Cho, 2001; Sua-iam & Makul, 2013)

The average specific gravity value of wood ash was 2.41 and for sugarcane bagasse ash 2.34, while Ottawa sand held 2.65. The specific gravity of the solid materials by water picnometer depends on their chemical composition and particle structure (Kim, Yoon, Balunaini, & Salgado, 2006). Chemical composition and the arrangement of atoms affect the specific gravity of materials (Rafferty, 2011). For example, materials that have a higher content of heavy chemical elements such as iron and magnesium have higher specific gravity than materials containing carbon. In the same way, a denser particle structure with fewer voids can also have higher specific gravity.

3.4 SEM Imaging

Micrograph imaging of ashes using a Scanning Electron Microscope (SEM) is necessary to study the microstructure of their particles. The Jeol JSM 6610LV SEM that was used for this
research is located in the Socolofky Microscopy Center from the Department of Biological Sciences at Louisiana State University. Samples were fixed with a two-layered adhesive carbon and aluminum pin studs in order to be placed in the SEM adapter. Since biomass ashes are not conductive materials, the samples need to be coated with a gold alloy to prevent charging of the specimen. A Sputter Coater device, model EMS550X (Figure 3.4), was used for this task. After the coating, the SEM pin studs were inserted in the specimen stage so the image processing could be taken with the Scanning Electron Microscope (Figure 3.5).

![Sputter Coater device EMS550X](image)

**Figure 3.4 Sputter Coater device EMS550X.**

![Jeol JSM 6610LV Scanning Electron Microscope](image)

**Figure 3.5 Jeol JSM 6610LV Scanning Electron Microscope**

SEM images were obtained to examine the surface characteristics and study the microstructure of the biomass ashes. Images of three types of ashes were taken including wood
ash, sugarcane bagasse ash, and coal fly ash class F. For each material, one main image with 200x of magnification was captured, then three interesting spots were focused to get three pictures with a magnification of 800x, and finally 2500x of magnification was used to get three more pictures of those relevant spots.

SEM photomicrographs of wood ashes were obtained to know their particle organization. The mixture is heterogeneous with different sizes and different shapes. The size of the particles showed in the image varies from 10-μm to 200-μm and their shape is generally sub-angular. Porous structures can also be found. These particles are the result of the incineration of wood waste as bark, chips, sawdust and knots. Figure 3.6 shows the images obtained by the SEM from a wood ash sample.

Sugarcane bagasse ashes samples were also analyzed by SEM and images were obtained to know the microstructure of their particles. These images show a heterogeneous mixture of
particles with different sizes and different shapes. Their shape is mainly sub-angular and they have low sphericity; however, they have a scattered particle shape and size to generalize a common shape. A lot of voids are observed indicating a small contact between particles. The size of the particles showed in the main image varies from 10-µm to 300-µm. The images obtained by the SEM are shown in Figure 3.7.

Figure 3.7 Sugarcane bagasse ash micrograph.

In order to compare the structure of biomass ash samples with a similar material used in engineering, coal fly ash was analyzed. First, three coal fly ash class F micrograph images were taken with the same magnification than the other ashes. Generally, the shape of these particles is very spherical and their sizes in these images vary from 1-µm to 22-µm, as shown in Figure 3.8, showing a homogenous particle shape mixture.
3.5 Chemical Composition

In order to determine the chemical composition of the biomass ashes, Energy-dispersive X-ray spectroscopy (EDS) tests were performed to obtain the chemical composition using this elemental analysis. Figure 3.9 shows the results of the EDS analysis of wood ashes.

![Figure 3.9 EDS analysis of wood ashes.](image)
Wood ash EDS analysis shows the largest peaks for Calcium, Oxygen, Silicon and Potassium, and lower peaks for Sodium, Magnesium and Aluminum.

Figure 3.10 shows the results of the EDS analysis of sugarcane bagasse ashes, where the most predominant chemical elements are Oxygen and Silicon. Lower peaks were observed for Aluminum and Potassium.

EDS analysis of both wood and sugarcane bagasse ash are consistent with the chemical composition analysis compared as a reference and shown in Table 2.6.

3.6 pH and Atterberg limits

For the acidity determination, a benchtop pH meter model Thermo Scientific Orion 2 star was used to measure pH of materials. Approximately 10 grams of each material should be used and mixed with approximately 10 mL of water in a centrifuge tube. Then, the tubes should be placed in the centrifuge and spin those samples to extract the water from the pores of the materials to measure the pH correctly. A calibration of the pH meter must be taken before measuring, using two of three buffers (pH 4, pH 7 or pH 10). The pH meter must be calibrated
before every measurement. For the calibration, two of the three buffer solutions should be used. It is recommended to use the two solutions to provide a range in which the pH of the sample is going to be measured in order to provide an accurate reading. Figure 3.11 shows the equipment used for this test.

![Image](image-url)

Figure 3.11 a) Benchtop pH meter, (b) Centrifuge device, and (c) centrifuge tube with sample.

Three samples of Ottawa sand, wood and sugarcane bagasse ashes were prepared, and measurements were taken after introducing them in the centrifuge. Wood ashes exhibit a value of 12.57, while sugarcane bagasse ashes had 8.65. These results indicate that both biomass ashes displayed high alkalinity, with values above seven, the neutral value. In the other hand, Ottawa 20-30 sand showed a value of 4.01, which is considered as acid. These measured values and referenced ranges are shown in Figure 3.12. In Figure 3.12, pH values obtained from laboratory test are represented with dots filled in black, while reference values are represented with white dots.
Figure 3.12 Acidity analysis with pH values of Ottawa 20-30 sand and biomass ashes. Result values are filled in black and reference values in white. (Étiégni & Campbell, 1991; Jamil, Qasim, Umar, & Subhan, 2004; Naik et al., 2002; Rajamma, 2011; Vallero, Farnsworth, & Peirce, 2001)

Atterberg liquid and plastic limits tests were conducted with wood and sugarcane bagasse ashes in accordance with the ASTM because Ottawa Sands do not have any plasticity. Wood and sugarcane bagasse ashes materials did not show the plasticity, while coal fly ash had a liquid limit (LL) value of 22.5 and 16.33 of plasticity index (PI) (Geliga & Ismail, 2010).
CHAPTER 4
ENGINEERING BEHAVIOR

For obtaining the geotechnical parameters proposed in this study, the following soil tests were run, in accordance with their standards: Hydraulic Conductivity: Constant Head method (ASTM D2434) and Falling Head method (ASTM D5084), one-dimensional consolidation (ASTM D2435), determination of shear wave velocity using bender elements and determination of the thermal conductivity of solids (ASTM D5334).

4.1 Hydraulic Conductivity

Hydraulic conductivity tests were performed with different void ratios for Ottawa 20-30 sand, wood and sugarcane bagasse ashes. Due to the average particle diameter, constant head method was run when determining the hydraulic conductivity of the Ottawa 20-30 sand, and falling head method was used for both wood and sugarcane bagasse ashes, since they performed as finer soils.

Constant head method is used in accordance with ASTM D2434 to determine the coefficient of permeability of materials for laminar flow of water, and it is chosen for granular soils. This permeability cell has a diameter of 4 in. and its length is 4.57 in. This device has also two mesh screens, one on top and the other at the bottom of the soil sample in order to prevent migration of particles during the test. Figure 4.1 shows the setup of the constant head method used with the Ottawa 20-30 sand samples and with sand-biomass ash mixtures. The image on the right shows a close-up of the permeability cell for this experiment.
Falling head method is commonly used to determine the coefficient of permeability of materials for one-dimension, laminar water flow through soils with finer particles. This test is run in accordance with ASTM D 5084. This permeability cell is made of acrylic, it has a diameter of 3 in. and its length is 5.75 in. For this test’s setup, two porous stones are placed in both ends of the sample using a filter paper of the same diameter between them to distribute the deaired water across the entire porous area of the sample. This is also required to impede the migration or washing out of the fine ash particles of the sample during the test. The setup of the falling head permeameter cell is shown in Figure 4.2. Samples are remolded in the laboratory to reach a specific density and void ratio before starting the tests.
Results of the hydraulic conductivity (k) tests for Ottawa 20-30 sand, wood ashes and sugarcane bagasse ashes are shown in Figure 4.3.

![Figure 4.3 Variation of hydraulic conductivity (k) with void ratio.](image)
Different void ratios and densities were established for every type of material in order to get a trendline presenting the variation of the hydraulic conductivity with different void ratios. Similar void ratio intervals were tried to reach for the materials. However, wood and sugarcane bagasse ashes could not be taken to such low void ratio due to their low specific gravity.

After obtaining the hydraulic conductivity ($k$) of the materials used for this research, mixtures of sand with biomass ashes were prepared in dry conditions replacing mass percentage of sand with wood or sugarcane bagasse ash. Hydraulic conductivities of mixtures of sand and a fraction of ash were determined with the constant head method due to the larger amount of sand.

Mixtures of 0.5, 1, 1.5 and 4% of wood ash with Ottawa 20-30 sand were tested. In Figure 4.4, the equivalent hydraulic conductivity of mixtures is shown with the percentage of mass fraction of ashes.

![Figure 4.4 Equivalent hydraulic conductivity of mixtures between Ottawa 20-30 sand and wood ash.](image)
The same experiment was tried with sand and sugarcane bagasse ash mixtures. The results rapidly show that with a very small fraction of ash, a very low hydraulic conductivity can be reached. Mixtures of 1, 2 and 10% of sugarcane bagasse ash with Ottawa 20-30 sand were tested this time. Figure 4.5 illustrates the variation of hydraulic conductivity depending on the fraction of the mixture of sugarcane bagasse ash with sand.

![Figure 4.5](image)

**Figure 4.5** Equivalent hydraulic conductivity of mixtures between Ottawa 20-30 sand and sugarcane bagasse ash.

Due to the similar particle size distribution of wood and sugarcane bagasse ashes, previous graphs of both materials used in mixtures with Ottawa 20-30 sand show a very much alike behavior.
4.2 Consolidation

It is relevant to study the compressibility characteristics of soils or any construction material. Starting from the concept that consolidation is any process where the volume of the sample is reduced by the expulsion of water after the application of an external load, in this test samples are restrained laterally and loaded axially with total stress increments until excess of pore water pressures depletes. One-dimensional deformation for each loading step was recorded since the load is applied axially and void ratio calculations were performed as well. After the first loading period, an unloading set was applied and then another loading period was performed in order to obtain a virgin consolidation curve, a rebound curve and then a recompression curve.

For these one-dimensional consolidation tests, an automated loading system called GeoJac was used. It has a 2000 load-pound capacity with a load sensor at the bottom of the frame with controlled speed. There is also a direct current displacement transducer (DCDT) on top to measure deformation as load is applied. This loading system works together with the software Sigma-1 ICON for Windows, that is a software that shows the real time display of the results, such as the deformation curve against time for each loading step and the consolidation curve versus void ratio even when the test is in progress.

The soil and ash samples were setup in a stainless steel chamber made exclusively for this test along with the one for determining the shear-wave velocity. This chamber consists of a double base plate, where a hose is connected for the correct drainage of the system. A plate with smaller diameter and small holes for drainage as well, is placed on top of the sample. Two filter papers are placed between the plates and the sample to prevent the intrusion of very fine ash particles into the pores and maintain the correct flow of water. The top plate and one upper
bottom plate have an aperture for bender elements that are explained later. Final set up is shown in Figure 4.6.

![Figure 4.6 GeoJac setup with the software Sigma I-CON, and sample chamber, on right.](image)

Consolidation tests were performed for each material itself and different sand-ash compositions to study their inner compressibility characteristics and their behavior when mixed. While these tests were run, shear wave velocity data was obtained for every loading step. Samples were setup in the chamber, where the specimen had a diameter of 2.50 inches and a height of 2.0 inches approximately. Lateral deformation of the chamber was restrained in order to achieve a one-dimensional consolidation due to an axial load applied. The loading schedule was divided in three periods: initial loading, unloading, and reloading. The initial loading consisted in applying a consolidating pressure of 12, 24, 48, 96 and 192 kPa; then, for the unloading phase the specimen received 96, 48 and 24 kPa; and lately, the reloading stage used 48, 96, 192, 384, 768 and 1536 kPa as consolidating pressure. The same process was followed in all experiments with all the specimens to make a final comparison of the materials.
First, each material including Ottawa 20-30 sand, wood ash and sugarcane bagasse ash were tested in dry conditions. The results and compressibility of samples were analyzed. Afterwards, those materials were tested in saturated conditions. Sand specimens were prepared using the regular saturation process. The chamber was filled with a certain amount of sand, previously weighted to reach a desired void ratio, and then water was poured inside the chamber. The granular microstructure of sand helped to a fast saturation process and let water flow through the bottom drain of the chamber.

For the biomass ash specimens, an inverse saturation process was applied. In this process, first a certain amount of water was poured inside the chamber and then the solids were filled inside. It was important to keep the water level above the solids level to reach a better saturation. The bottom drain was checked to assure a good drainage during consolidation. During the tests, due to the difficulty of adding water on top of the chamber to keep the specimen saturated, the saturation process was achieved adding water to the bottom drain hose which was held in upright position so water in both sides remains at an equal level.

At first, initial void ratio was tried to be constant for all the materials to make a better compressibility comparison. However, this was the most complicated part since sand and biomass ashes have different microstructure, hence different maximum and minimum void ratio. The results of the consolidation of the wood and sugarcane bagasse ashes in saturate conditions are shown in Figure 4.7., where sugarcane bagasse ash exhibits more compressibility than wood ash. The void ratio of wood ash at 12 kPa, the initial axial pressure, is 1.53; while sugarcane bagasse ash had e=2.73. At 192 kPa, wood ash had e=1.21 and sugarcane bagasse ash e=1.66. Finally, when 384 kPa was applied, wood ash had a void ratio of e=1.03 and sugarcane bagasse ash had e=1.13, almost the same even though the big difference of initial void ratios between
these two ashes. Sand compressibility was not plotted in the same graph because there was only a small volume change and could not be compared with the biomass ashes.

After these tests, new experiments were performed with mixtures of sand and each biomass ash type at different compositions. A percentage of the weight of the standardized sand was replaced with wood and sugarcane bagasse ash. The mixtures containing 2, 4, 6, 8 and 10% of ashes were tested with the same procedure than before and an inverse saturation process was selected again to try achieving the saturation of the specimen. The void ratio at the first loading step was $e=0.65$ and it was unified for all the compositions.

The results of these tests, compared with the consolidation curve of pure Ottawa sand, are shown in Figure 4.8 for sand and wood ash mixtures and in Figure 4.9 for sand and sugarcane bagasse ash mixtures. Both figures display results of tests in saturate conditions.
Figure 4.8 Consolidation curves for sand and sand-wood ash mixtures.

Figure 4.9 Consolidation curves for sand and sand- sugarcane bagasse ash mixtures.
4.3 Shear Wave Velocity

For the determination of the shear wave velocity of samples, the same GeoJac loading system, software and procedure were required. While the one-dimensional consolidation test was being performed, the shear wave velocity was measured for every load increment with this equipment: a signal generator, a filter/amplifier, a digital oscilloscope and bender elements.

A signal/waveform generator is the device that starts the circuit creating an electrical signal to the bender element in the chamber that acts as a sender. It is connected to the source bender element and to the oscilloscope. The device that was used is an Agilent Waveform Generator model 33210A as shown in Figure 4.10. The characteristics of the signals that can be considered are waveform, frequency and amplitude. This signal generator can provide different functions including sine, square, triangle, noise and pulse. In the experiments, square type of waveform was used because it is one of the most used ones. The maximum amplitude of the square signal was ± 5 V; thus, the peak-to-peak voltage was 10 V. This voltage had to be amplified to transmit higher energy to the bender elements. The frequency applied was 20 Hz, which is equivalent to 20 cycles per second.

![Figure 4.10 Agilent Waveform Generator 33210A.](image-url)
A filter or amplifier was necessary for this test. A Krohn-Hite model 3944 filter, as shown in Figure 4.11, was used for receiving the voltage of the waveform from the signal generator and amplifying this voltage in order to transfer it to the bender element acting as a sender or source. The voltage required to be amplified because of the loss of the output voltage received, so gain functions were used to amplify it when the amplitude of signal was not strong enough. This device also acts as a filter to define the highest and lowest frequencies of interest in the signal. In channel 1, a high-pass frequency of 200 Hz was selected, while a low-pass frequency of 100 Hz was used. Low-pass frequency is important because it minimizes the noise of high frequency signals.

A digital oscilloscope was used for displaying in waveforms the electrical signal that the second bender element, acting as a receiver, obtained from the waves along the sample. The Agilent digital oscilloscope model DSO6014A was used for the tests, providing a real time display of the received and converted signals and allowing saving the waveform in a flash drive to export it to a file compatible with Microsoft Excel. This digital oscilloscope can be used with the direction buttons, so the input and output signals can be placed on the screen modifying the
vertical and horizontal position and sensitivity. Channels displayed can be changed to focus on the most relevant segment. Those features are very important because only the signal displayed on the screen is recorded and then exported to MS Excel. Figure 4.12 shows the oscilloscope used and an example of the display with the signal received. Other important feature of this device is stacking; it is used to minimize the noise of the high frequency by getting just one averaged signal out of 1024 signals. It is also relevant to ground the circuit to prevent crosstalk so the reading of the signal could be clear.

![Oscilloscope](image)

**Figure 4.12** Agilent Technologies Digital Oscilloscope model DSO6014A.

One pair of bender elements, two-layered transducers with piezoelectric properties that convert a mechanical energy into a signal of electrical energy, was used in this setup. The first one was inserted in the aperture of the top plate of the chamber and the second one was located in the bottom plate and both tips were making contact with the specimen tested. These bender elements had to be assembled in the laboratory. For this procedure, the materials needed were: bender elements, soldering iron and accessories, coaxial cable, epoxy, silver conductive paint, polyurethane and screws, as shown in Figure 4.13.
Bender elements were purchased from the company Piezo Systems Inc. The assembly of these transducers was one of the most difficult tasks of the research because it took a little more than one week and they had to work perfectly so they can be used in the experiments. Fortunately, there was a lot of information and tips on the reference papers to follow the instructions to get a correct assembly and reading. See Figure 4.14a. Since the type of bender element chosen for this research is the parallel type, the negative wire of the coaxial cable should be separated in two parts in order to sold each one on each face of the bender element and the positive wire must be soldered on the groove that connects the positive or internal plate of the bender element. After soldering correctly the coaxial cable to the bender element, the circuit should be checked with a multimeter and the resistance must be infinity (open circuit). Then, since the bender element was used in saturated conditions, it had to be water-proofed. For this requirement, it must be coated with low viscosity polyurethane, covering with a thin layer all the surfaces and edges. Excess of this polyurethane should be dripped out and the bender element should be placed in an upright position for 24 hours to let it dry. If possible, the coating process should be repeated two or three times to prevent these transducers from water contact.
Grounding is necessary to prevent crosstalk, so a conductive silver paint was applied to the coated surface of the bender elements to create an electric shield. It should be set in upright position as well to dry for 24 hours. Figure 4.14b shows a bender element after conductive paint is applied. A hole in the center of the nylon screw was made using a drill. This hole must be large enough so the bender element could fit almost completely, just leaving the tip a couple of millimeters out. Afterwards, bender elements were covered with epoxy and let it cure for 24 hours again. Finally, the cable of the bender element was inserted in the screw through the hole and the empty space inside the screw was covered with epoxy and let it cure one more day.

Figure 4.14 Assembly of bender elements (BE):
(a) parallel-type bender element, (b) BE after soldering, coating and shielding, (c) BE inserted in the screw and filled with epoxy, (d) final setting in top and bottom plates.
The final result is shown in Figure 4.14c. The resistance was checked again with the multimeter and it showed an open circuit (OL) again. The stainless steel chamber consisted of a double base plate, a cylindrical body and a top plate. The top plate and bottom plate have an aperture for introducing the bender elements for this test, as shown in Figure 4.14d. The cylindrical body has an internal diameter of 2.5 inches and its length is 2.25 inches.

Simultaneously with the consolidation test, the receiver signals acquired from the digital oscilloscope were saved for every loading or unloading step in order to determine the shear wave velocity later. A flash drive saved the data from the oscilloscope and it was transferred to MS Excel for signal processing and analysis. A frequency spectrum for every stress at consolidation test could be obtained after plotting the data gathered from the oscilloscope. The frequency spectrum can be retrieved by setting the output voltage in the y-axis and time in the x-axis.

The shear wave velocity (Vs) was calculated by dividing the distance that the wave travelled over the time invested for that action to happen. The distance of the travel of the wave was measured from the span between the tips of both source and receiver bender elements, which is known as tip-to-tip distance. This length varied along the consolidation tests because of the settlement occurred during the process with loading or unloading increments.

Travel time (Δt) was obtained from the frequency spectrum measuring the time difference between the start of the first wave and the start of the following wave, according to the start-to-start method as explained in the previous chapter and shown in Figure 2.5. With this simple calculation, shear wave velocities for different loading pressures were obtained and plotted in the following graphs. The same procedure and calculation was used for performing test with wood and sugarcane bagasse ashes in saturated condition. Multiple data and signals were
saved along the experiment. The results are shown in the next figures, which displays the variation of shear wave velocity (Vs) with the consolidation stress (σ).

For the mixtures, two concentrations -2% and 6% of biomass ash- were selected for the analysis. During the consolidation tests, the receiving signals were obtained for those concentrations and the shear wave velocity was calculated. In Figures 4.15 and 4.16, results are plotted for wood ash and sugarcane bagasse ash, both in saturated conditions.

![Figure 4.15 Shear wave velocity with consolidation stress of sand-wood ash mixtures.](image)

Results on both graphs show that Ottawa 20-30 sand has the highest shear wave velocity and pure biomass ashes the lowest. Mixtures of sand and biomass ashes indicate that the higher ash content in the mixture, the lower shear wave velocity is obtained.
Figure 4.16 Shear wave velocity with consolidation stress of sand- sugarcane bagasse ash mixtures.

The Maximum Shear Modulus ($G_{\text{max}}$) was calculated using the Equation 2.1 in this study. The density of the specimen was calculated from the variation of specimen height due to the deformation of every load increment and then the maximum shear modulus was calculated. Results of maximum shear modulus for sand – biomass ash mixture are shown in Figure 4.17 for sand and wood ash, and Figure 4.18 for sand and sugarcane bagasse ash.
Figure 4.17 Maximum shear modulus with consolidation stress of sand-wood ash mixtures.

Figure 4.18 Maximum shear modulus with consolidation stress of sand- sugarcane bagasse ash mixtures.
4.4 Thermal Conductivity Tests

Thermal conductivity of samples was tested with different types of materials and different stresses during a consolidation test. A dead-weight consolidation frame was used for the consolidation tests and a thermal properties analyzer (TPA) for the thermal conductivity determination.

QuickLine 30, first from Anter Corporation but later under the direction of TA Instruments in Delaware, is the type of thermal conductivity analyzer chosen for this research. It is a device for direct measurement of thermophysical properties by the transient heat method, measuring with a needle probe, mostly used for porous materials or a surface probe for hard materials. Figure 4.19 shows this device with its thermal needle probe inside the chamber. This device can measure the thermal properties including thermal conductivity, temperature, thermal diffusivity and volume heat capacity in accordance to ASTM D5334: Standard test method for determination of thermal conductivity of soil and soft rock by thermal needle probe procedure.

![Thermal Properties Analyzer QuickLine 30](image)

Figure 4.19 Thermal Properties Analyzer QuickLine 30.
Since this transient heat method is considered a non-steady-state method, measurements for the determination of the thermal conductivity were taken during the heating-up process using a needle probe with a large length to diameter ratio assuming an infinitely long specimen. When the probe was inserted, known current and voltage change the temperature to perform these tests. (ASTM)

The admissible range for thermal conductivity of QuickLine 30 is between 0.015 and 6.0 W/mK, where 4 different needle probes and 3 surface probes cover a specific range. The needle probe used for this research is model 210422, which recommended range goes from 0.015 to 0.20 W/mK. If a measurement is outside of this range, there is a 5% of error on the reading and volume heat capacity and thermal diffusivity are not calculated. This device implements a dynamic measurement method that allowed taking thermal conductivity measurements relatively fast, and those measurements were stored in the internal memory.

The dead-weight consolidation frame used for the consolidation tests provides 9:1, 10:1 and 11:1 beam ratios to minimize the loading weight demands. The beam ratio used for these tests was 10:1. For measuring the deformation of the samples, a direct current displacement transducer (DCDT) was controlled with the software Sigma-1 ICON, the same used for consolidation tests with GeoJac.

The consolidation cell consisted of a stainless steel bottom plate, followed by an acrylic cylindrical body and an aluminum top plate with an aperture to introduce the needle probe for the thermal properties measurements. The acrylic body had a diameter of 4 inches, and it was 8 inches long. The load schedule applied on these test was: 1, 2 5, 8, 16, 32, 64 and 128 Kg., reaching the following loading stresses: 12, 24, 48, 96, 192, 384, 768 and 1536 KPa., which are
equivalent to the stresses applied during consolidation with GeoJac while measuring the shear wave velocity.

Thermal conductivity measurements were taken in 23 minutes per reading approximately, due to the dynamic measurement method of this device. For this experiment, tests were carried out in dry conditions because water caused a chemical reaction and thermal conductivity values were too high above the needle probe limits, causing a statistical error in the readings.

Mixtures of Ottawa 20-30 sand and biomass ashes were tested. Two wood and sugarcane bagasse ash concentrations (2% and 6% of biomass ash) were selected for the analysis. The needle probe was inserted through the hole on the top plate of the chamber and measurements were taken for the increments of loading. Figure 4.20 shows the variation of thermal conductivity with the consolidation stress of sand and wood ash mixtures.

![Figure 4.20 Thermal conductivity (λ) with consolidation stress of sand-wood ash mixtures.](image-url)
To asset the variation of thermal conductivity ($\lambda$) with different void ratios, measurements took place as a consolidation stress was applied. Figure 4.21 shows the variation of thermal conductivity with the consolidation stress of sand and sugarcane bagasse ash mixtures, compared with each material itself.

Figure 4.21 Thermal conductivity ($\lambda$) with consolidation stress of sand- sugarcane bagasse ash mixtures.
CHAPTER 5
ANALYSES AND DISCUSSION

This chapter is focused on the study and evaluation of the results obtained from the laboratory tests concerning implications on soil stabilization, including hydraulic conductivity, one-dimensional consolidation, determination of shear wave velocity and thermal conductivity.

5.1 Hydraulic Conductivity

Biomass ashes are constituted of a high amount of finer particles that is less than 75-μm (i.e. 78% for sugarcane bagasse ash and 25% of wood ash, Figure 3.2), which are the product of the incineration of wastes of living materials. From Figure 4.3, wood ash had a hydraulic conductivity from $10^{-4}$ to $10^{-3}$ cm/s, having different void ratios going from 1.20 to 1.90. On the other hand, sugarcane bagasse ash’s hydraulic conductivity was in the range of $4.3 \times 10^{-4}$ to $5.9 \times 10^{-3}$ cm/s with void ratios from 2.06 to 3.47. Those values compared to a specific soil type, can be similar to silty sands or silty soils.

Biomass ashes had lower hydraulic conductivity than Ottawa 20-30 sand due to their smaller particle size with larger surface areas (~44.9 m2/g (Kastner, Das, Buquoi, & Melear, 2003)- and larger void ratio space, which are not well connected and form confining layers. Biomass ash particles absorb and hold a lot more water than sand, thus the hydraulic conductivity in these materials is lower.

The mixture of sand and ashes created a sample with mixed particle sizes where the ashes particles filled the voids of sand causing a decrease of hydraulic conductivity. Due to the low specific gravity of biomass fly ash, a very low hydraulic conductivity can be reached with a small fraction of ash. This behavior occurs because of mass ratio in the mixture. Figure 4.4 shows that hydraulic conductivity decrease dramatically when replacing only 0.5% of wood ash.
In the case of sugarcane bagasse ash, Figure 4.5 illustrates the variation of hydraulic conductivity with the ash content. In this figure, hydraulic conductivity also decreases greatly after replacing with 1% of sugarcane bagasse ash.

In this analysis, Figure 5.1 shows the phase diagram of the sand – biomass ash mixtures, followed by the equations used for the calculation of the void ratio.

![Figure 5.1 Equivalent hydraulic conductivity of sand – wood ash mixtures.](image)

\[
e = \frac{V_f}{V_s} \quad (5.1)
\]

\[
V_s = \frac{V}{1 + e} \quad (5.2)
\]

\[
V = V_f - V_s \quad (5.3)
\]

\[
V_{s_{ash}} = \frac{W_{ash}}{G_{s_{ash}}} \quad (5.4)
\]

\[
V_{f_{final}} = V_f - V_{ash} \quad (5.5)
\]

\[
e_{f_{final}} = \frac{V_{f_{final}}}{V_s + V_{s_{ash}}} \quad (5.6)
\]

Figure 5.2 shows the different ways of particle packing. The picture on the left expresses a loose packing with the highest void ratio. In this scenario, the finer particles are equal to 0.414 times the diameter of the coarser particles. The picture on the right shows the opposite scenario, where the densest packing exists and the finer particles are equal to 0.155 times the diameter of the coarser ones.
The variation of void ratio and equivalent hydraulic conductivity of the mixtures with the mass fraction of wood ash and sugarcane bagasse ash, are shown in Figures 5.3 and 5.4 respectively.

Figure 5.3 Equivalent hydraulic conductivity of sand – wood ash mixtures.
5.2 One-dimensional Consolidation

Figure 4.7 shows the consolidation curve of both wood and sugarcane bagasse ash in saturate condition for comparison. From this graph, it can be stated that sugarcane bagasse ash’s compressibility is larger than wood ash. Consolidations parameters were calculated to asset the compressibility of biomass ashes. The compressibility index (Cc) was equal to 1.105 for wood ash and 1.521 for sugarcane bagasse ash, having 50% more compressibility in the compression curve. The swell index (Cs), calculated from the unloading phase, was equal to 0.038 for wood ash and 0.100 for sugarcane bagasse ash, being almost three times higher in the recompression line. With these parameters, it can be estimated that consolidation and swelling is one half and three times higher, respectively, for sugarcane bagasse ash.

Mixtures of Ottawa 20-30 sand with fractions of biomass ashes showed a smaller amount of consolidation. Figures 4.8 and 4.9 show the consolidation curves in saturated condition of
sand itself and mixtures of 2, 4, 6, 8 and 10% of wood and sugarcane bagasse ash’s mass fraction, respectively, replaced in the mixture. It can be observed that the higher the fraction of ash is replaced, the higher volume change is expected. However, for the case of sand and wood ash mixtures, the deformation is not considerable. On the other hand, for the case of sand and sugarcane bagasse ash mixtures, the deformation is higher and so are the consolidation index parameters. The variation of the compressibility index with the percentage of biomass ash in both sand – wood ash and sand – sugarcane bagasse ash mixtures is shown in Figure 5.5.

![Figure 5.5 Variation of Compressibility Index (Cc) with content of biomass ash.](image)

### 5.3 Shear Wave Velocity

Results for the determination of shear wave velocity can be found in Figures 4.15, 4.16, 4.17 and 4.18. The first two of these figures show the variation of shear wave velocity with consolidation stress; where sand-biomass ash samples show a higher Vs value, followed by wood ash and sugarcane bagasse ash. It can be said that shear wave velocity increases when
deformation of specimens increase as well; and the more compressible a material is, the lower shear wave velocity values are obtained.

The recommended equation for calculating the shear wave velocity of wood ash in function of the consolidation pressure is:

\[ V_s = 102.18 \cdot \sigma^{0.118} \]  \hspace{1cm} (5.7)

where, \( V_s \) = shear wave velocity (m/s), and \( \sigma \) = consolidation stress (kPa),

And the recommended equation for sugarcane bagasse ash is:

\[ V_s = 46.587 \cdot \sigma^{0.1803} \]  \hspace{1cm} (5.8)

Ottawa 20-30 sand and biomass ashes mixtures are also shown in those figures, both in saturate condition. In both figures, shear wave velocity values decreased with the addition of biomass ashes because deformation was larger at the same consolidation stress intervals. In this case, sand and wood ash mixtures showed less deformation than sand and sugarcane bagasse ash mixtures.

Figure 5.6 shows the typical values for \( \alpha \)-factor and \( \beta \)-coefficient made after various materials. These coefficients can be used in the following stiffness-stress equation suggested by Santamarina (2001):

\[ V_s = \alpha \left( \frac{\sigma_o}{1 \text{ kPa}} \right)^\beta \]  \hspace{1cm} (5.9)

where \( V_s \) = Shear wave velocity of the medium subjected to 1 kPa confinement
\( \sigma_o \) = consolidation stress (kPa)
\( \alpha \) and \( \beta \) = factors determined after experiments.
Both parameters $\alpha$-factor and $\beta$-exponent are obtained from the equation after adjusting a trend line to the experiments performed with these materials. Dots filled in black were obtained after tests in this research and the ones in white after the precious reference.

![Graph showing typical values for $\alpha$-factor and $\beta$-coefficient.](image)

**Figure 5.6** Typical values for $\alpha$-factor and $\beta$-coefficient.

### 5.4 Thermal Conductivity

Determination of the thermal conductivity of the materials used in this research can be found in Figures 4.20 and 4.21, which shows the variation of values for thermal conductivity ($\lambda$) with the consolidation stress in dry condition. Ottawa 20-30 sand was the material with higher thermal conductivity, followed by wood ash and sugarcane bagasse ash.
Mixtures of Ottawa 20-30 sand with fractions of biomass ash showed higher thermal conductivity values than pure sand or pure biomass ash specimens, which variations of can be seen in figures above indicated.

From those graphs, thermal conductivity of mixtures increases with the replacement of biomass ash fractions. This occurs due to the small particles contained in biomass ashes, product of incineration of living organisms, which fill the voids of the sand structure, decreasing the void ratio of the specimen and creating a density change, which causes a higher thermal conductivity. The effect of void ratio in the mixtures and its calculation was previously explained in this chapter.

Additionally, after the analysis of the chemical composition of biomass ashes and the information of the thermal conductivity values of the oxides present in the research materials, it could be inferred that aluminum oxide (Al₂O₃) which is abundant in wood ash and has a thermal conductivity of 30 W/mK approximately, is the cause of a higher thermal conductivity than sugarcane bagasse ash.

The variation of thermal conductivity and ash content of the mixtures with void ratio of wood ash and sugarcane bagasse ash, are shown in Figures 5.7 and 5.8 respectively. In both graphs, the increment of ash content in the mixture causes a decrease in the void ratio and an increase in the thermal conductivity.
Figure 5.7 Thermal conductivity and ash content variations with void ratio of Ottawa sand - wood ash mixtures.

Figure 5.8 Thermal conductivity and ash content variations with void ratio of Ottawa sand - sugarcane bagasse ash mixtures.
CHAPTER 6
CONCLUSIONS AND RECOMMENDATIONS

The following conclusions can be made from this research work:

- After characterization of wood and sugarcane bagasse ashes, and with the geotechnical properties and parameters obtained in this thesis, these ashes can be applied to new engineering projects such as landfills or other works as a fraction replacement in a mixture with dry cohesionless sand as a cheap and natural alternative. The amount of ash replaced should be estimated considering the project requirements and limitations.

- **Hydraulic Conductivity (k)**
  For their particle structure and shape, hydraulic conductivity (k) of wood and sugarcane bagasse ash are lower than sand’s. Mixtures of sand with each of these ashes caused the filling of voids by the small ash particles decreasing Hydraulic conductivity (k) dramatically only with a small fraction –1%, due to the reduction of void ratio in the mixture.

- **Consolidation**
  Wood and sugarcane bagasse ash have higher compressibility than sand. It increases in saturate conditions due to the wash of very fine particles and readjustment of particles. In sand-ash mixtures, although biomass ash particles fill the voids, stiffness does not increase but compressibility does. It can be inferred that ash particles –which are smaller than sand– get between sand particles and the contact area between them decrease, reducing the total stress and stiffness itself.
• **Shear Wave Velocity (Vs)**

Shear wave velocity (Vs) and Maximum Shear Modulus (Gmax) are lower in wood and sugarcane bagasse ashes, compared with Ottawa 20-30 sand. The larger deformation in those specimens caused a decrement in the distance between the sender and receiver bender elements that resulted in a reduction of Vs and Gmax. However, this decrement is not serious, but it should be considered in designing and construction.

• **Thermal Conductivity (λ)**

Thermal conductivity (λ) of sand was larger than wood and sugarcane bagasse ash in dry condition. Increasing the ash content in the sand-ash mixtures causes a greater thermal conductivity because ash particles locate in the porous spaces reducing the void ratio and creating more contact areas between particles to transfer the heat.

• Wood ash and sugarcane bagasse ash cannot be used by themselves in engineering projects. Due to their lack of stiffness, they should be used with another material such as sand in small fractions in order to work successfully.
CHAPTER 7
FUTURE WORK

According to the results obtained in this thesis, the suggestions for future work may include:

1. Elaborate different mixtures with biomass ashes in order to study the geotechnical behavior with different materials. These mixtures include clayey soils and biomass ashes (wood and sugarcane bagasse ashes). Additionally, a fraction of lime or cementitious material can be added to the mixture.

2. Evaluate the potential cementation in mixtures of soils with wood or sugarcane bagasse ashes. This can be achieved by maintaining a constant stress for more than 24 hours to determine the increment of deformation after consolidation.

3. In addition to the geotechnical parameters already measured, determine the strength of the soils-biomass ashes mixtures by performing triaxial tests. Study the behavior of mixtures to evaluate new techniques on soil stabilization.

4. Propose a complete evaluation of the environmental impact of biomass ashes when mixed with soils.
REFERENCES


Fleshman, M. S. (2012). Laboratory modeling of critical hydraulic conditions for the initiation of piping.


Kodide, U. (2010). *Thermal conductivity and its effects on the performance of PCC pavements in MEPDG*. Faculty of the Louisiana State University and Agricultural and Mechanical College in partial fulfillment of the requirements for the degree of Master of Science in Civil Engineering in The Department of Civil and Environmental Engineering By Upender Kodide BE, Osmania University.


VITA

Francisco Grau Sacoto was born in 1988 in Guayaquil, Ecuador. He received his bachelor’s degree in Civil Engineering at Universidad Catolica de Santiago de Guayaquil in 2011. He worked as Geotechnical Engineering Assistant for a private consulting company in Ecuador before making the decision to pursue a Master’s degree with concentration in Geotechnical Engineering in the Department of Civil and Environmental Engineering at Louisiana State University in Baton Rouge. He worked as a graduate researcher for Dr. Jongwon Jung, Ph.D in LSU. He anticipates receiving his Master’s degree in May 2014 and plans to continue working in the industry.