

1-13-2017

The Properties of Particleboard Using Bagasse, Sisal and Waste Carpet

Hanchi Zhu

hanchi.zhu@uconn.edu

Recommended Citation

Zhu, Hanchi, "The Properties of Particleboard Using Bagasse, Sisal and Waste Carpet" (2017). *Master's Theses*. 1040.
https://opencommons.uconn.edu/gs_theses/1040

This work is brought to you for free and open access by the University of Connecticut Graduate School at OpenCommons@UConn. It has been accepted for inclusion in Master's Theses by an authorized administrator of OpenCommons@UConn. For more information, please contact opencommons@uconn.edu.

The Properties of Particleboard Using Bagasse, Sisal and Waste Carpet

Hanchi Zhu

B. E., Donghua University, 2014

A Thesis

Submitted in Partial Fulfillment of the

Requirements for the Degree of

Master of Science

At the

University of Connecticut

2017

Copyright by

Hanchi Zhu

2017

APPROVAL PAGE

Master of Science Thesis

The Properties of Particleboard Using Bagasse, Sisal and Waste Carpet

Presented by

Hanchi Zhu, B.E.

Major Advisor_____

Dr. Richard Parnas

Associate Advisor_____

Dr. Luyi Sun

Associate Advisor_____

Dr. Douglas Adamson

University of Connecticut

2017

Acknowledgements

First and foremost, I would like to express my sincere appreciation to my major advisor Dr. Richard Parnas. I really appreciate for giving me the opportunity to pursue my Master degree in his group and thank for his support, help, patience and guidance throughout my Master degree's study. Moreover, I really appreciate his help that teach me how to process science research and show what the conference looks like in America. He also provided many suggestions for my career and personal life to give me enormous help.

I also want to thank Dr. Luyi Sun and Dr. Douglas Adamson for being my committee members and thank for their valuable time and suggestions. Moreover, I am thankful to my current labmates, Elizabeth Brown and Jennifer Caffyn, for their help in my study and research.

I thank all the staff in the IMS who helped me a lot for my research and wish they will have a happy life every day. I really cherish all the time in the IMS.

At last, I want to thank the most important people in my life. Thank my parents, my younger sister and my girlfriend for unconditioned love and support. They encourage me at any time whatever problem I confront with. Thank my best friends in UConn for their friendship. With them, I will never feel alone during my study abroad. Love you all forever.

Table of Contents

Chapter 1. Introduction	1
1-1. particleboard overview	1
1-2. Materials used for Particleboard.....	2
1-2-1 Sisal Introduction	2
1-2-2 Bagasse Introduction.....	3
1-2-3. Waste carpet Introduction	4
1-3. Particleboard Properties.....	5
1-3-1. Modulus of Rupture and Modulus of Elasticity	5
1-3-2. Sound dampening introduction	6
1-3-3. Flame retardant material introduction.....	7
1-4. Reference	8
Chapter 2. Sisal Based Particleboard	11
2-1. Introduction	11
2-2. Materials and method	13
2-2-1. Materials.....	13
2-2-2. Compression molding equipment	14
2-2-2. Compression method	15
2-2-3. Mechanical properties test	16
2-3. Results	17
2-3-1. Content of pMDI.....	17
2-3-2. Commercial sisal and waste sisal fibers	18
2-3-2. Content of carpet.....	19
2-3-4. Water Swell test	21
2-4. Discussion.....	22
2-5. Conclusion.....	26
2-6. Reference	27
Chapter 3. Bagasse Based Particleboard.....	28

3-1. Introduction	28
3-2. Materials and method	32
3-2-1. Materials.....	32
3-2-2. Compression method	33
3-2-3. Compression Molding Process	35
3-3. Results and Discussions	37
3-3-1. Density and Pressure.....	37
3-3-2. The size of the bagasse piece	38
3-3-3. The comparison between sheared face fiber, carpet backing, and unseparated carpet	39
3-3-4. Commercial Prototype Boards.....	41
3-4. Conclusions	47
3-5. Reference	47
Chapter 4. Appendix for Bagasse Compression Particleboard.....	49
4-1. Instruction.....	49
4-2. Materials and Method.....	49
4-2-1. Fresh Bagasse.....	49
4-2-2. Wet Bagasse from Louisiana	50
4-2-2. Thermal gravimetric analysis (TGA).....	50
4-3. Results and Discussions	51
4-3-1. Freshness of Bagasse Fibers	51
4-3-2. the moisture content of the bagasse	53
4-4. Conclusion	58
Chapter 5. Flame Retardant improvement to the particleboard.....	59
5-1. Introduction	59
5-2. Materials and method	61
5-2-1. Coating bagasse and carpet fiber	61
5-2-2. Compression method	62
5-3. Results	62

5-3-1. TGA of coated bagasse fiber.....	62
5-3-2. MOR & MOE of coated particle board	64
5-3-3. Flame retardant property	66
5-4. Discussion and Conclusion	67
5-5. Acknowledgements	68
5-6. Reference	68
Chapter 6. Sound dampening of particle board	69
6-1. Introduction	69
6-2. Sound dampening test equipment.....	70
6-3. Sound dampening test.....	72
6-4. Results	72
6-4-1. Sound dampening test for ¾ inch thick panels	72
6-4-2. Sound dampening tests for lab particleboard.....	73
6-5. Discussion and Conclusion	76
6-5-1. three quarters inch particle board.....	76
6-5-2. lab particle board.....	76
6-5-3. Sound dampening compared between bagasse and carpet	77
Chapter 7. Future Work	79
7-1. The recipe of flame retardant board	79
7-2. Sound dampening	79
7-3. Eco-friendly binder.....	80

Table of Figures

Figure 2-1. The Process of Sale Sisal Fibers	12
Figure 2-2. Photos of sisal fibers without vacuum drying.....	14
Figure 2-3. a. The Photo of Compression molding equipment, b. The mold prior to compression, c. The mold after compression.	15
Figure 2-4. a.45% and 47.5% sisal particle board in medium density, b. 95% and 90% sisal particleboard in high density	23
Figure 2-5. The mechanical properties of commercial sisal and waste sisal boards	24
Figure 2-6. Water swell in width and weight test.....	25
Figure 3-1. a. The UConn mold, b. Schematic of the UConn mold before and after compression.	34
Figure 3-2. Rectangular wood frame mold at UMaine.....	35
Figure 3-3. a. Tumbling resin blender, b. Coil spinning disc atomizer	36
Figure 3-4. Relationship between compression pressure and particleboard density.	37
Figure 3-5. The effect of bagasse particle size on the MOR and MOE of bagasse particleboard.....	38

Figure 3-6. The MOR and MOE of particleboard made with 20% Face Fiber or 20% Backing Material or 20% Unseparated Carpet.....	40
Figure 3-7. a. The MOE and MOR from boards 3-7, divided by M-2 standard value, b. The MOE and MOR from Boards 8 and 9, divided by M-2 standard value.	43
Figure 3-8. Trend lines for MOE (a) and MOR (b) for boards 3-9. The requirements for M-2, M-3, H-2, and H-3 particleboards are denoted in the figures by the horizontal dashed lines.....	45
Figure 4-1. TGA graphs of various bagasse fibers	55
Figure 5-1. a. Moisture content of the coated bagasse fibers with 12% add-on weight before adding water b. moisture content of bagasse fibers before use	64
Figure. 5-2. Photos of the coated and control samples after vertical flame test.....	67
Figure 6-1. Photo of sound dampening test equipment in Uconn lab	70
Figure 6-2. Model of sound dampening test equipment	71
Figure 6-3. Sound dampening property for commercial board and 3 quarters inch particle boards manufactured in UMaine.....	73
Figure 6-4. Sound dampening data for 75% bagasse-20% face carpet-5% pMDI in different compression force	75
Figure 6-5. Sound dampening data for 47.5% bagasse-47.5% face carpet-5% pMDI in different compression force	75

Figure 6-6. Sound dampening property of the boards with 47.5% bagasse-47.5%
face carpet-5% pMDI and 75% bagasse-20% face carpet-5% pMDI under 8000lb
force.....78

Index of Tables

Table 2-1. 5% and 10% pMDI particleboard test data using commercial sisal fiber	17
Table 2-2. Test data for boards using commercial waste sisal, with 5% pMDI binder.....	19
Table 2-3. Various sisal content particle board test data (Avg: average, St.Dev: standard deviation).....	20
Table 2-4. Water swell test of sisal and carpet fiber particleboards.....	21
Table 3-1. The recipe, density and moisture content of the panels made in UMaine	41
Table 3-2. Individual flexure test results for prototype board 2.....	42
Table 3-3. Flexure test data from 3 layer boards 8 and 9.	44
Table 3-4. Required board densities to reach required MOR and MOE for each level.....	46
Table 4-1. Results of fresh and common bagasse particle board	52
Table 4-2. Mechanical properties of Louisiana wet and dried bagasse particleboard	57
Table 5-1. Mechanical properties of coated and uncoated particle boards	65
Table 6-1. Density and thickness of particle board in different compression force	74

Abstract

The demand for manufactured panels for construction, furniture and other applications place strains on the forestry industry leading to deforestation. Similarly, one component of the very large waste stream from construction and renovation is post consumer carpet. The post consumer carpet waste and widely available waste biomass streams can be used to produce panels sustainably. Laboratory scale panels were produced with several ratios of bagasse and carpet to deduce a reasonable formulation to produce M-2 grade particleboard. The selected formulation was used to produce several industrial prototype panels of 18mm thickness for independent testing. Statistical analysis was performed to assess the reliability of attaining required properties of several grades of particleboard. M-2 grade particleboard can be produced with greater than 95% reliability using 75% bagasse, 20% post consumer carpet, and 5% pMDI binder.

Chapter 1. Introduction

1-1. particleboard overview

Particleboard, known as chipboard, is wood product manufactured from wood or non-wood materials and a synthetic resin or other suitable binder. The particleboard is made by mixing the raw materials and binder together and forming the mixture into a sheet or a panel. The binder is mist-sprayed even into the raw material mixture through fine nozzles. There are some types of binders that are commonly used. Amino-formaldehyde based binders are the best performing when considering both cost and ease of use. Urea Melamine binders are used to offer water resistance with increased melamine offering enhanced resistance. Because that could improve the property of water resistance, urea melamine binders are commonly used for the panel set for external products.^[1] The particleboard product could be used as construction panels and furniture and the particleboard currently has a steadily growing market. Particleboard is cheaper, denser and more uniform than conventional wood and plywood and show better mechanical characteristics. The application of the particleboard is large, such as packing, building and furniture. Considerable amount of research focus on the use of non-wood materials in the particleboard producing, such as reed^[2], bamboo^[3], rice husks^[4], tea leaves^[5], sunflower stalks^[6], bagasse^[7]. The demand for the particleboard representing 57% of the total volume of wood-based panels has recently increased dramatically throughout the world, especially for housing construction and furniture manufacturing. Worldwide demand for particleboard has been steadily growing since then at a rate between 2 and 5% per annum. In recent years, wood-based industries all over the world are facing difficulty in obtaining wood raw material. Deforestation, forest

degradation, and increasing wood demand for wood-based panels has led to a shortage of raw materials in the wood industrial sector for a long time. As a result the use of renewable resources such as agricultural residues is now gaining increased interest in the production of composite panels. ^{[8][9]} Wallboard product sales for construction in the US were 22 billion square feet in 2015. In 2015, reconstituted wood panel products in the US had a market value of \$5.7 billion of which particleboard was estimated to be 27% (Medium density fiberboard 15%, Waferboard and Oriented strand board 35% and others such as Hardboard, Cellulose fiberboard 23%) of the total revenue, or approximately \$1.52 billion. ^[10] The industry is projected to have an annual growth of 2.7% through 2018. The data from Statista website shows that in 2015, operating revenue of particle board manufacture in China has been up to almost 6.64 billion US dollar, increased 4.17% from 2014. And in Japan operating revenue is 42.4 million US dollar in 2015, increased 2.42% from 2014. ^[11] According to a life cycle assessment (LCA) case, bagasse (the waste of sugarcane) is one of eco-friendly and healthy raw materials to manufacture particleboards. ^[12]

1-2. Materials used for Particleboard

1-2-1 Sisal Introduction

Sisal, the botanical name as Agave Sisalana, is one of the species of Agave which are widely cultivated and used in many different countries. In 2013, the top five countries produced sisal are Brazil, United republic of Tanzania, Kenya, Madagascar and China. ^[13] Because of its good stiffness property, the sisal could be used in many products. Apart from the traditional use for rope and agriculture twine, it could be used in low-cost and specialty paper, dartboards, buffing cloth, filters, geotextiles, mattresses, carpets, handicrafts and so on. ^[14]

1-2-2 Bagasse Introduction

Bagasse, is a kind of fibrous matter that remains after sugarcane are crushed and milled for sugarcane juice. It is dry residue left after the extraction of juice from the stalks and is a by-product of sugarcane juice. ^[15]The chemical content of the bagasse is reported as cellulose (45-55%), hemicellulose (20-25%), lignin (18-24%), ash (1-4%) and waxes (lower than 1%). ^[16]For each ten tons of sugarcane milled, they would remain three tons of wet bagasse left as by-product, which the moisture content of that by-product ranges between 40% and 50%. And the fresh bagasse would be stored in different conditions for different productions. The bagasse would be stored under the moist environment for electricity and they would be stored wet to remove remaining sugar and short pith fibers for paper and pulp production.

Bagasse explored as a renewable power source is used in many fields. The primary use of bagasse is fuel source, burned for heat energy. Although the current experiment improves that the carbon dioxide emissions are less than the amount of carbon dioxide absorbed from the atmosphere during the time of sugarcane plant, carbon dioxide is a kind of greenhouse gas which should be eliminated as common. Instead, the second product for fuel is produced ethanol. Because of the rich content of cellulose, ethanol would be produced directly from the bagasse. In other fields, the bagasse is used typically as a substitute for wood materials for making pulp, paper and board and fed animals as forage.

1-2-3. Waste carpet Introduction

The carpet is a textile floor covering usually decorated with beautiful pattern and view. The average life expectancy of commercial carpet is between eight and eleven years, with huge amount of annual demand, the carpet waste becomes one of the serious problems that people have to face. ^[17] The carpet waste generated over two millions tons each year and most of them could be simply handled by landfilling, which is a polluted method. The carpet waste could be classified by their origin: pre-consumer and post-consumer carpet waste. Pre-consumer carpet waste includes scrap generated through the process of producing. As an example, in the case of special shape of carpet, such as automobiles, plenty of carpet scrap is cut and wasted during the trimming and fitting process. Because the carpet left has an irregular shape and no further use. Post-consumer carpet waste includes used carpet depended on its lifetime. It is reported that the total amount of post-consumer carpet could reach up to 3.4 billion pounds annually in the United States. ^{[18][19]}

Generally, carpet consists of primary and secondary backings (polypropylene or polyester), face fibers (nylon 6, 31%; nylon 66, 21%; Polyethylene terephthalate, 34%; Polypropylene, 8%; other 6%)^[20], filler materials (CaCO₃-filled) and adhesive (styrene-butadiene latex rubber is a thermoset material which cannot be re-melted or reshaped). In addition, some of carpet waste from special sources, such as aircrafts, may contain chemical additives such as flame retardants and stain resistant chemicals. Because of various chemical additives, they make carpet waste recycling and classify much more difficult and complex, that means there will be an additional cost for classifying during the recycling process. Currently, the cost of carpet waste in landfills is up to 100 million dollars per year in the United States. Without classify and process cost, the direct cost for landfills is equal to \$0.025/lb ^[21]. And also, even though the cost of landfills is

low, the considerable amount of carpet waste will lead to a huge amount of expense for waste carpet landfills. Therefore, balance the value of environment and economy, plenty of research work should focus on carpet waste recycling.

1-3. Particleboard Properties

1-3-1. Modulus of Rupture and Modulus of Elasticity

Modulus of rupture (MOR), also known as flexural strength is a mechanical property, defined as the stress in a material just before it yields in a flexure test. By using a three point flexural test technique, a specimen having either a circular or rectangular cross-section is bent until fracture or yielding for modulus of rupture test. The modulus of rupture represents the highest stress experienced within the material at its moment of failure or breaking. ^[22]

Modulus of elasticity (MOE), also known as tensile modulus, is a number that measures an object or substance's resistance to being deformed elastically when a force is applied to it. The modulus of elasticity of an object is defined as the slope of its stress-strain curve in the elastic deformation region. ^{[23][24]} The higher modulus of elasticity the material has, the stiffer it is.

For the particleboard manufactured in this project, the standards of MOR and MOE are set by American National Standards Institute. The ANSI is a private non-profit organization that oversees the development of voluntary consensus standards for products, services, processes, systems, and personnel in the United States. They also coordinates American standards with international standards so that American products can be used worldwide. ^[25] The standard in this project is the ANSI-particleboard standard. This standard provides a common basis for

understanding throughout the particleboard industry and among and between those specifying and using industry products. ^[26]The MOR and MOE of various grades are provided in this standard, and they are classified by the density of boards and grade of boards. A typical grade is M2, which means grade 2 in the medium density.

1-3-2. Sound dampening introduction

Sound could be easily and simply generated by the vibrating. At present, the sound pollution have been listed into one of the most harmful polluted source against human beings. The noise control or noise mitigation become the important factor of design in public and private constructions. Noise control is a set of strategies to reduce noise pollution or to reduce the impact of that noise, whether outdoors or indoors. ^[27] Everyone sometimes need a relative quiet and peaceful environment to study, rest or some other special activities. Some additional sound generated from other would be distracted and interrupted the activities and make people uncomfortable and awful. From the field of noise, the sound dampening or sound absorbing methods should be taken action in the commercial and constructional materials. Basically, there are four common technologies for noise control. They are sound insulation, sound adsorption, vibration damping and vibration isolation.

- Sound insulation is preventing the transmission of noise by the introduction of a mass barrier, such as glass and concrete.
- Sound absorption is that some special materials like sponge could convert the transmission sound into heat within the materials, such as cell foams.

- Vibration damping is extracting the vibration energy from the thin sheet and dissipating it as heat.
- Vibration isolation means preventing transmission of vibration energy from a source to a receiver by introducing a flexible element or a physical break, such as rubber.

Some sound dampening or sound absorbing materials usually adopt not only one fundamentals, they commonly combine some of the technologies together. Whatever the basic technologies will use, the public have explored and attempted to solve this perplexing problem by sound.

1-3-3. Flame retardant material introduction

Flame retardants are inhibit or delay the spread of fire by suppressing the chemical reactions in the flame or by the formation of a protective layer on the surface of a material.^[28] The flame retardant materials are highly used in many different fields such as aircraft and construction. It is reported that there are totally 1345500 fires in the United States during 2015, which increased 3.7% from 2014. The fires during 2015 results in 3280 civilian fire deaths and 15700 civilian fire injures and 14.3 billion dollars for property damage. And 501500 fires were classified as structure fires, that is to say, there would be one fire reported in every 63 second.^[29] In order to eliminate the expense from the fires, apart from avoidless damage, the flame retardant materials could widely been used indoor and outdoor.

The mechanisms of the flame retardant vary depending on the different function and position. Additive and reactive flame retardant chemicals can function in the gaseous and solid phase. Some basic mechanisms are following:

Endothermic degradation, some compounds break down for absorbing the heat and cooling the materials.

Thermal shielding, creating a thermal insulation barrier between the burning and unburned parts.

Dilution of gas phase, inert gases (often carbon dioxide) produced by the thermal degradation of some chemicals dilute the content of combustible gases.

Gas phase radical quenching, released hydrogen chloride or hydrogen bromide from some special materials could reduce the potential for some reactive radicals to avoid burning.

Flame retardants are typically added to industrial and consumer products to meet flammability standards for furniture, textiles, electronics, and building products like insulation. ^[30] In 2013, the world consumption of flame retardants was more than 2 million tons. The most important application area is the construction field. ^[31] Therefore, increasingly number of projects focus on the flame retardants.

1-4. Reference

[1] https://en.wikipedia.org/wiki/Particle_board

[2] Nahla, A. E.; Ragab, E. A.; Yehia, F.; Mohamed, A. Y., *Journey of Applied Polymer Science*, 2007, Vol. 106, 3592-3599.

[3] Rowell, R. M.; Norimoto, M., *Mokuzai Gakkaishi*, 1988, 34, 627.

[4] Vasisth, R. C.; Chandramouli, P., *FAO Background Paper*, 1975. FO/WCWP/75.

[5] Nemli, G.; Kalayciohlu, H., In *Proceedings of the XI World Forestry Congress*, 1997, Vol. 4, 47.

[6] Khristova, P.; Yussifou, N.; Gabir, S.; Glavche, I.; Osman, Z., *Cellul Chem Technol*, 1988, 32, 327.

- [7] Sho Nonaka; Kenji Umemura; Shuichi Kawai, Characterization of bagasse binderless particleboard manufactured in high-temperature range, *Journal of Wood Science*, February 2013, Volume 59, Issue 1, pp 50–56
- [8] Effect of resin type and content on properties of composite particleboard made of a mixture of wood and rice husk, Nadir Ayrilmis, Jin Heon Kwon, Tae Hyung Han. *International Journal of Adhesion & Adhesives*, 38(2012)79-83
- [9] Properties of hardwood saw mill residue-based particleboard as affected by processing parameters, Nirdisha Gamage et al. *Industrial Crops and products*, 2009(29) 248-254
- [10] Reconstituted Wood Product Manufacturing. Rep. N.p.: n.p., n.d. IBISWorld Industry Report. Web.
- [11] www.statista.com/forecasts
- [12] Khristova, P.; Yussifou, N.; Gabir, S.; Glavche, I.; Osman, Z., *Cellul Chem Technol*, 1988, 32, 327.
- [13] http://faostat3.fao.org/browse/rankings/countries_by_commodity/E
- [14] <https://en.wikipedia.org/wiki/Sisal>
- [15] <https://en.wikipedia.org/wiki/Bagasse>
- [16] A study into the permeability and compressibility of Australian bagasse pulp, Rainey T.J., PhD thesis (2009) in Queensland University of Technology
- [17] Mihut, C.; Captain, K. D.; Gadala-Maria, F., *Polym Eng Sci*, 2001, 41, 1457-1470.
- [18] Y. Wang, *Polym-Plast Technol Eng*, 1991, 38(3), 553-546.
- [19] Jain, A.; Pandey, G.; Singh, A. K.; Rajagopalan, V.; Vaidyanathan, R.; Singh, R. P., *Advances in Polymer Technology*, 2012, Vol.31, No.4, 380-389.
- [20] Clair, D., *Floor Trends*, 2014, Vol.16, 10, 25-27.
- [21] Braum, M.; Levy, A. B.; Sifniades, S., *Polym-Plast Technol Eng*, 1999, 38, 471.
- [22] https://en.wikipedia.org/wiki/Flexural_strength
- [23] https://en.wikipedia.org/wiki/Elastic_modulus
- [24] Askeland, Donald R., Phulé, Pradeep P., *The science and engineering of materials* (5th edition), 2006, p189, ISBN 978-0-534-55396-8.
- [25] https://en.wikipedia.org/wiki/American_National_Standards_Institute
- [26] American National Standard Institute, A208.1-2009 Particleboard
- [27] https://en.wikipedia.org/wiki/Noise_control
- [28] https://en.wikipedia.org/wiki/Flame_retardant
- [29] Hylton J.G. Haynes, NFPA's "Fire Loss in the United States during 2015", Sep 2016

[30] Shaw, S.; Blum, A.; Weber, R.; Kannan, K.; Rich, D.; Lucas, D.; Koshland, C.; Dobraca, D.; Hanson, S.; Birnbaum, L. (2010), Halogenated flame retardants: do the fire safety benefits justify the risks, *Reviews on Environmental Health*. 25 (4): 261–305.
doi:10.1515/REVEH.2010.25.4.261

[31] Market Study: Flame Retardants 3rd edition, Feb 2015

Chapter 2. Sisal Based Particleboard

2-1. Introduction

Sisal fibers are commonly used in various products and obtained from the plant called Agave Sisalana. It is one of the major hard fibers produced throughout the world. ^[1] Barreto et al found that the content of sisal is cellulose (65.8%), hemicellulose (12%), lignin (9.9%), pectin (0.8%), wax (0.3%) and water soluble compounds. ^{[2][3]} The usual sisal plant lives for 7-10 years and produces 200-250 commercial leaves each year, which are 1.5 -2 meters long and have around 1000 sisal fibers in each leaf. In the United States of America, sisal cultivation occurs in Hawaii and Florida. Brazil is the largest producer and exporter in the world. ^[4] Sisal is one of the most widely used natural fibers because of its outstanding characteristics related to its low cost and density, nice mechanical properties and non-toxicity. ^{[5][6]}

Sisal fibers are exported in the form of bales. Before the sisal bales are ready for sale, the sisal fibers are classified based on type, length, color and other factors. The classified fibers are then brushed and pressed as shown in fig 2-1. ^[7]



a. classifying the sisal fibers



b. brushing the sisal fibers



c. sisal fibers being pressed into bales



d. ready for sale

Figure 2-1. The Process of Sale Sisal Fibers ^[7]

Generally, sisal fibers are used in ropes and twines for their strength, durability and resistance to deterioration in saltwater. Mansfield Richard documented that sisal cordage dominated the rope and cordage industry for many years, and even now has a good market. ^[8] In fact, the sisal fibers are classified into different grades. The lower grade sisal fibers are used in the paper industry for their high content of cellulose and hemicellulose. The medium grade sisal fibers are used for manufacturing ropes, twines and cordages. The high grade sisal fibers are surface treated and twisted into yarns for carpets. However, since sisal fibers absorb and release moisture from the air, leading to expansion and contraction, sisal carpets are best used in limited areas. Sisal has also been used for animal feed, tequila liquor and extraction of pharmaceutical materials. Waste sisal can be also utilized for biogas.

In this chapter, the sisal classified into commercial and waste fibers was compressed into particleboard mixed with waste carpet face fibers composed of PET. The MOR and MOE was compared for particleboards made with equal amounts of waste and commercial grades of sisal fiber. The difference in the quality between commercial and waste sisal fibers was found to significantly affect the mechanical properties of the produced particleboards. The best recipe of

the particleboard consisted of sisal and PET carpet fibers was established by optimizing the content of the sisal fibers and PET carpet fibers. And also, the optimal dosage of the binder was determined by considering the ANSI standard and the cost of the particleboard.

2-2. Materials and method

2-2-1. Materials

The commercial and waste sisal fibers were obtained from a sisal producer in Haiti. The commercial fibers are smooth, straight and reflective light yellow fibers (Fig 2-2a). The waste sisal fibers were picked from the sisal plants after the high quality commercial fiber was removed (Fig 2-2b). The waste sisal fibers are darker yellow, twisted and thinner than the commercial sisal fibers. The waste sisal fibers are mixed with sisal pulp and other impurities. The commercial sisal and waste sisal fibers were cut into pieces, 4-5 centimeters long, and vacuum dried overnight before use. PET face fiber from post consumer carpet was provided by CARE. The binder, polymeric methylene diphenylene isocyanate (pMDI) was purchased from Huntsman Corporation. Release agent was purchased from Sprayon. Acetone was purchased from Sigma Aldrich.



a. Commercial sisal fibers

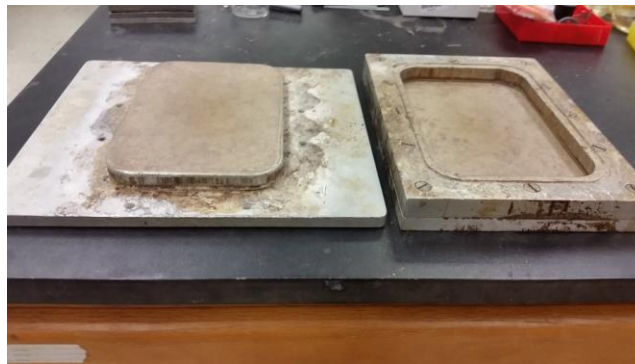


b. Waste sisal fibers

Figure 2-2. Photos of sisal fibers without vacuum drying

2-2-2. Compression molding equipment

The compression mold comprises two parts. The top part is the cover of the compression mold and the bottom part has a rectangular cavity with rounded corners, into which the compression charge was placed. (See Fig. 2-3) The area of the rounded rectangle is approximately 300 cm² (46.5 inch²).



a.

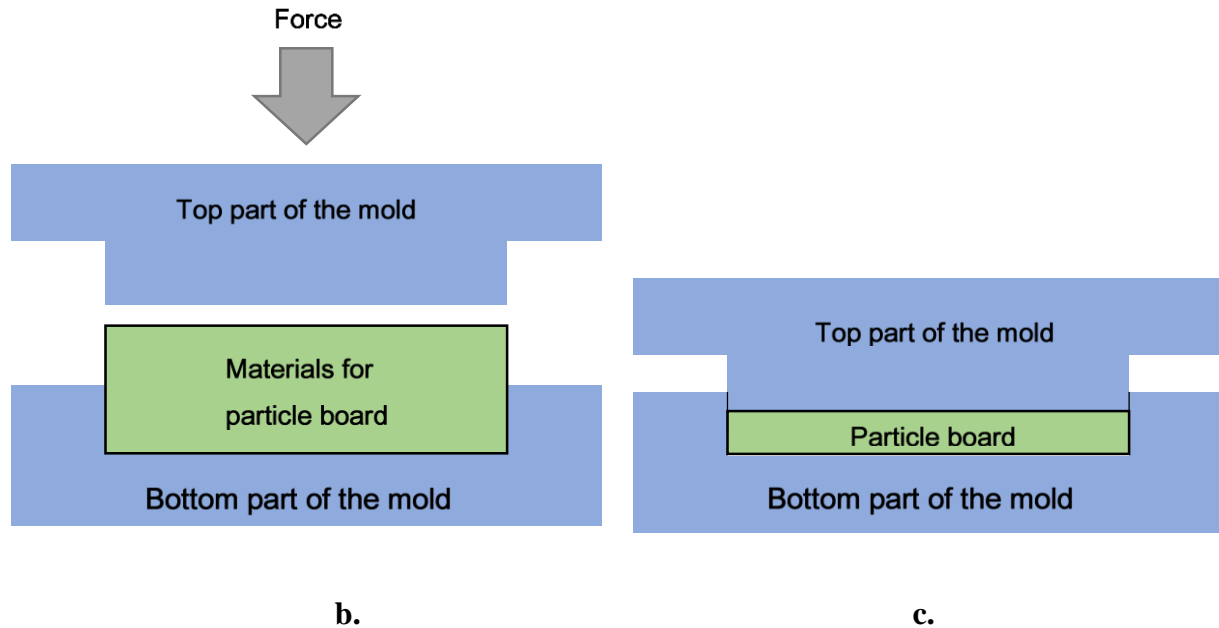


Figure 2-3. a. The Photo of Compression molding equipment, b. The mold prior to compression, c. The mold after compression.

2-2-2. Compression method

The cut sisal fibers were vacuum dried overnight before use to adjust their moisture content to an appropriate level for use with the pMDI binder. A typical formulation is 75% commercial sisal fibers, 20% facing carpet and 5% pMDI binder. The total mass of the boards is 110 grams. If the total mass of one particleboard is 110 grams, the mass of each component material is easily calculated. The mass of commercial sisal fibers is $110 * 75\% = 82.5$ grams. The mass of facing carpet fibers required is $110 * 20\% = 22$ grams. The mass of binder is $110 * 5\% = 5.5$ grams. The sisal and carpet fibers were mixed together in a plastic container. The binder was dissolved in 100 ml acetone. The binder solution was then sprayed onto the mixture of Sisal and carpet fibers to obtain an even dispersion, and the materials left in the hood for 20 minutes to allow

acetone to evaporate. The mold release agent was sprayed onto the mold surfaces 2 minutes before use to prevent the particleboard from sticking to the mold surface. The materials were evenly layered into the compression mold and compressed at 2.08MPa and 160°C for 20 minutes. After 20 minutes, the mold was removed from the hot press and allowed to cool to room temperature. Then the mold was opened and the particleboard removed.

2-2-3. Mechanical properties test

The produced particleboards were tested for Modulus of Rupture (MOR) and Modus of Elasticity (MOE) by a standard 3-point flexure test. Each board was cut into two rectangular samples, with width of 50 millimeters and length equal to 24 times the average thickness plus 50mm (if the thickness of a particleboard is 5.66 mm, the length of each sample is 185.84 mm). Although two samples are cut from the same particleboard, the average thickness of each board may be slightly different, leading to different sample lengths. After cutting each sample, the volume was calculated from the length, width and average thickness. Each sample was also weighed, and the density of each sample could then be calculated easily.

The 3-point flexure test was conducted with an Instron model 1011. The span between the two sample support points is determined by the thickness of each sample, and is equal to 24 times the average thickness. So if the thickness of a sample is 5 mm, the span of this sample is 120 mm. The applied force is recorded 10 times per second and converted into the MOR and MOE with the following functions ^[9].

$$E = \frac{F_{max}L^3}{4wd^3D}, \quad \sigma = \frac{3F_{max}L}{2wd^2}, \quad D = t * s$$

E: MOE (GPa), σ : MOR (MPa), F: Force applied to the sample (Newton), L: span between two supporting points (mm), w: width of the testing sample (mm), d: thickness of the testing sample (mm), D: deflection (mm), t: time (s), s: downward displacement speed (mm/sec).

2-3. Results

2-3-1. Content of pMDI

The content of pMDI recommended by the Huntsman Corporation is the range between 5% and 10% of the total mass of the particleboard. Because of the high expense of pMDI compared to other materials, the target content must allow the particleboard reaching the standard of ANSI with the least content of pMDI. Therefore, particleboards using commercial grade sisal fiber with 5% and 10% pMDI content were tested and the results shown in table 2-1. 95% sisal and 90% sisal boards were pressed under 30000lb force at the temperature of 160 C for 20 minutes. 47.5% sisal and 45% sisal boards were pressed under 10000lb force at the temperature of 160 C for 20 minutes.

Table 2-1. 5% and 10% pMDI particleboard test data using commercial sisal fiber

	95% Sisal – 5% pMDI		90% Sisal – 10% pMDI	
Sample #	MOR (MPa)	MOE (GPa)	MOR (MPa)	MOE (GPa)
1	45.6	3.63	53.7	3.84
2	46.8	3.68	52.1	3.96

3	37.6	3.75	50.4	3.86
4	39.8	3.54	51.2	3.92
Average	42.45	3.65	51.85	3.90
	47.5% Sisal – 47.5% Face Carpet – 5% pMDI		45% Sisal – 45% Face carpet – 10% pMDI	
Sample #	MOR (MPa)	MOE (GPa)	MOR (MPa)	MOE (GPa)
1	25.94	2.50	39	2.80
2	28.65	2.58	35.2	2.50
3	27.92	2.61	36.5	2.65
4	26.84	2.53	38.7	2.55
5	19.99	1.93		
6	18.66	1.57		
7	22.82	2.56		
8	21.74	2.76		
Average	24.07	2.38	37.35	2.63

2-3-2. Commercial sisal and waste sisal fibers

In section 2-2-1, the sisal materials were classified into commercial sisal fibers and waste sisal fibers because of their properties. When they were manufactured into particleboards, the measured MOR and MOE values were significantly different between commercial sisal and

waste sisal fibers. We used 95% sisal and 5% pMDI in 110g materials as recipe for both classes of fibers. The sisal fibers were pressed under 30000lb force at 160 C for 20 minutes. And then each board was cut into two samples to test the mechanical properties, size and density. Table 2-2, below, shows the results with two different fibers.

Table 2-2. Test data for boards using commercial waste sisal, with 5% pMDI binder.

	Commercial Sisal Fibers			Waste Sisal Fibers		
Sample #	MOR (MPa)	MOE (GPa)	Density(lb/ft ³)	MOR (MPa)	MOE (GPa)	Density(lb/ft ³)
1	45.6	3.63	55.66	39.7	2.97	61.20
2	46.8	3.68	59.98	34.9	2.65	60.08
3	37.6	3.75	57.72	36.8	2.68	58.23
4	39.8	3.54	58.43	34.2	2.78	59.42
Average	42.25	3.65	57.95	36.4	2.77	59.73

2-3-2. Content of carpet

One goal of this project is recycling waste carpet into particleboard. To maximize the content of waste carpet, particleboards were produced with varying fractions of sisal and carpet to evaluate the effects of composition. Although sisal is used to produce particleboard [10], the combination

of sisal with waste carpet has not been reported. From the density and their mechanical properties, the best fitted recipe could be found based on the ANSI standard. Table 2-3 shows data collected for boards pressed at 10000lb force at 160 C for 20 minutes, using a total mass of 110g with 5% pMDI in each board. Each recipe had made 2 boards and cut into four samples for test.

Table 2-3. Various sisal content particle board test data (Avg: average, St.Dev: standard deviation).

	MOR (MPa)		MOE (GPa)		Density(lb/ft3)	
Sisal %	Avg \pm St.Dev	Avg $- 1^{\text{st}}$ St.Dev	Avg \pm St.Dev	Avg $- 1^{\text{st}}$ St.Dev	Avg \pm St.Dev	Avg $+ 1^{\text{st}}$ St.Dev
80	33.93 \pm 1.82	32.11	2.81 \pm 0.14	2.67	47.76 \pm 0.92	48.68
75	32.22 \pm 1.26	30.96	2.75 \pm 0.14	2.61	46.24 \pm 1.5	47.74
70	26.1 \pm 2.38	23.72	2.64 \pm 0.23	2.41	45.31 \pm 3.43	48.74
47.5	24.07 \pm 3.77	20.3	2.38 \pm 0.41	1.97	46.46 \pm 2.32	48.78
40	18.02 \pm 1.66	16.36	2.16 \pm 0.32	1.84	47.80 \pm 1.09	48.89

2-3-4. Water Swell test

In the water swell test, samples of particleboard were placed into water and the water mass uptake and increase in board thickness measured as functions of time. The thickness and mass data are shown in Table 2-4.

Table 2-4. Water swell test of sisal and carpet fiber particleboards.

	Thickness (mm)				Mass (g)			
	Carpet 95%/pMDI 5%		Sisal 47.5%/Carpet 47.5%/pMDI 5%		Carpet 95%/pMDI 5%		Sisal 47.5%/Carpet 47.5%/pMDI 5%	
Time (hr)	Thick ness (mm)	Thickne ss swell (%)	Thick ness (mm)	Thicknes s swell (%)	Mass (g)	Mass swell (%)	Mass (g)	Mass swell (%)
0	4.46	0	4.72	0	34.535	0	31.72 22	0
1	4.53	1.56950 7	5.35	13.3474 6	39.382 1	14.035 33	40.04 05	26.222 33

2		1.56950		19.9152	39.986	15.785	42.76	34.800
	4.53	7	5.66	5	4	15	16	23
4		2.01793		29.6610	40.400	16.983	44.84	41.370
	4.55	7	6.12	2	4	93	57	08
5		2.24215		33.0508	40.206	16.422	45.48	43.392
	4.56	2	6.28	5	4	18	72	32
6		3.36322		34.9576	40.540	17.389	46.45	46.436
	4.61	9	6.37	3	6	89	28	25
7		3.58744		39.8305		16.820	47.82	50.773
	4.62	4	6.6	1	40.344	62	86	28
8		6.72645			41.640	20.573	52.15	64.403
	4.76	7	7.08	50	1	62	24	48

2-4. Discussion

To obtain the best fitted content of pMDI, the amount of other materials must be kept the same, such as sisal and facing carpet fibers. From Figure 2-4a, the particleboards were all made in the medium density (density: 46.25 ± 2.02 lb/ft³) and the particleboard made with 10% pMDI have the higher properties than the board made with 5% pMDI in both MOR and MOE. From Figure

2-4b, the particleboards in high density present the similar distribution with the level of ANSI-H2 and ANSI-H3 compared to Figure 2-4a. But even though the particleboard made with 5% pMDI showed a lower mechanical data, they still pass the levels of ANSI-M3 and ANSI-M2. Standing for the view of manufacturing cost, the pMDI has a much higher price per unit than other materials. Therefore, the best fitted content of pMDI should be 5% of the total mass of the particleboard.

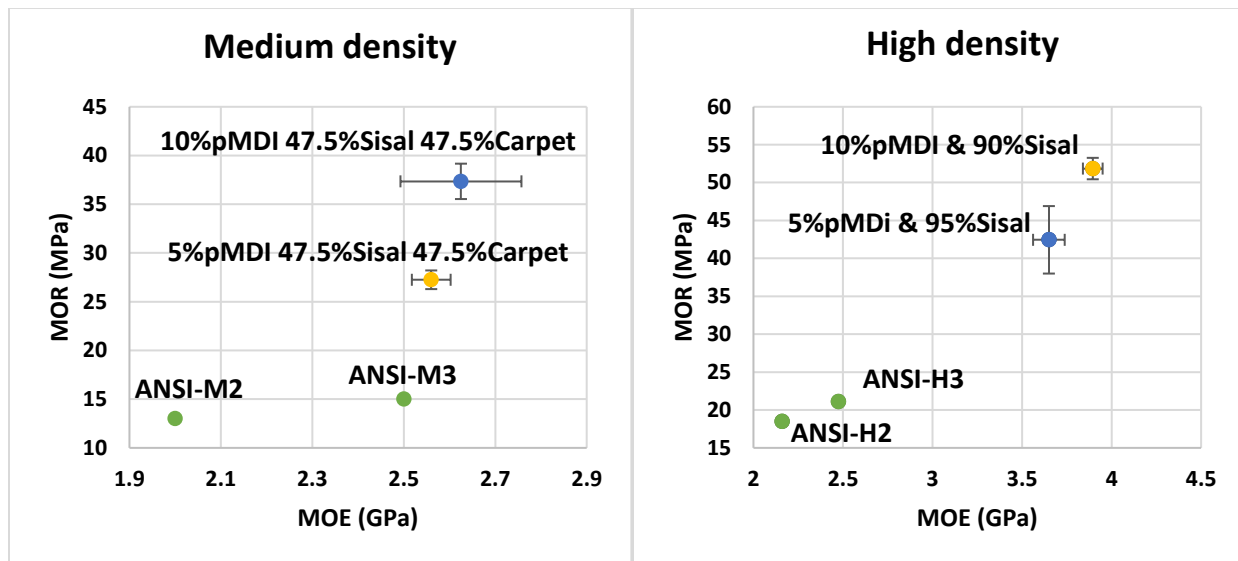


Figure 2-4. a. 45% and 47.5% sisal particle board in medium density, b. 95% and 90% sisal particleboard in high density

The commercial and waste sisal fibers may determine the mechanical properties of the particleboard are good or not, so the quality of sisal fibers should be investigated with experiment. We used commercial sisal fibers and waste sisal fibers to make two particleboard and cut into 4 samples for testing. Because they are pressed under 30000lb force, they are all in high density (average density of commercial sisal board is 57.95lb/ft³, average density of waste sisal board is 59.73lb/ft³). Maintaining all condition in the same state, that is the only difference

is the quality of the sisal fibers. From Figure 2-5, compared to the waste sisal fibers, average MOR of commercial sisal board increased 16.62% and average MOE of commercial sisal board increased 31.77%. The commercial sisal fibers indeed have a better mechanical properties than the waste sisal fibers in the field of manufacturing the particle board.

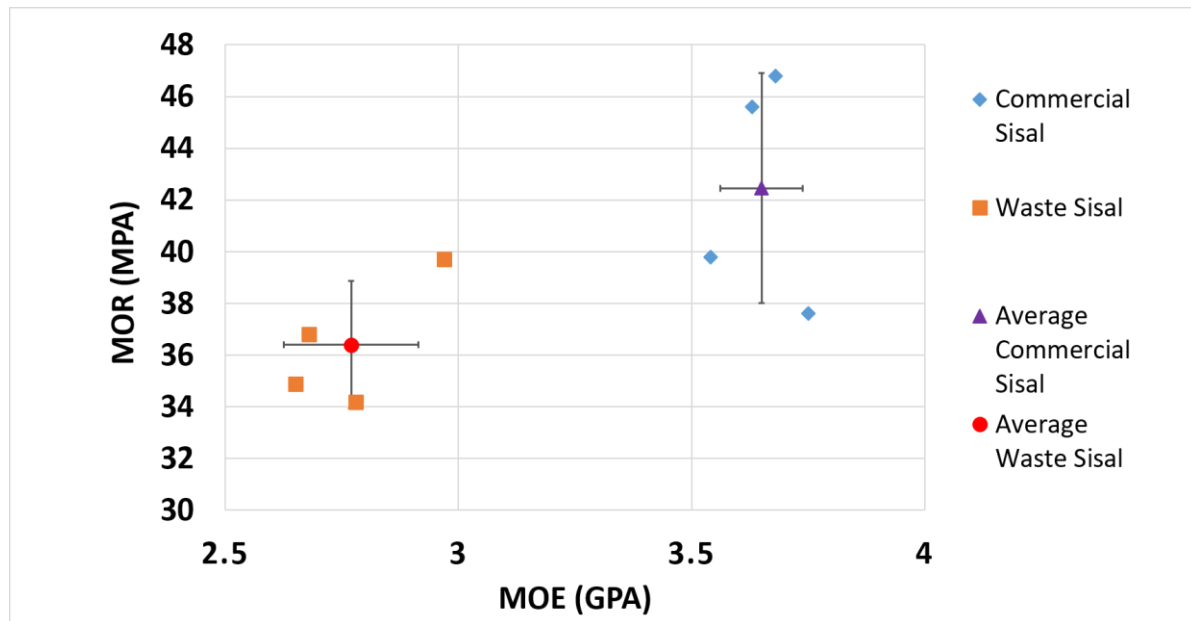


Figure 2-5. The mechanical properties of commercial sisal and waste sisal boards

Moreover, we must establish the best fitted recipe for our later experiments especially bagasse fiber. Keeping the best fitted content of pMDI and under 10000lb force for particleboards in medium density, we discussed the MOR, MOE and density. For making the test data more valuable and accurate for the future experiments, we used first standard deviation to fix the average, because we want to see the possible lowest mechanical properties and highest density, the average of MOR and MOE should be subtracted their first deviations and the density should be added their first deviations as shown in Table 2-3. The fixed average densities are all below

50lb/ft³ and the sisal fibers are the hard natural fibers. We use ANSI-M3 (MOR: 15MPa, MOE: 2.5GPa) as the level to establish the recipe. From the MOR in Table 2-3, the recipe that has 40% sisal should be ignored. The fixed average is subtracted by first standard deviation, but if they are subtracted by second standard deviation, the fixed average would be lower than ANSI-M3. From the MOE in Table 2-3, the best fitted recipe should be 75% sisal fibers. When the content of sisal fibers is lower than 75%, take 70% as an example, the fixed average would lower than the ANSI-M3. And for our future research, we need recycling as much carpet as we can. In another word, we need use sisal fibers as less as possible. Therefore, the best fitted recipe is 75% of sisal fiber, 20% carpet fiber and 5% pMDI.

In the water swell test, half of carpet fibers were replaced by the commercial sisal fibers. The particleboard sample with sisal fibers appears much larger swell rate than the one without sisal fibers in Figure 2-6. The sisal fibers are poor at waterproof compared with the carpet fibers.

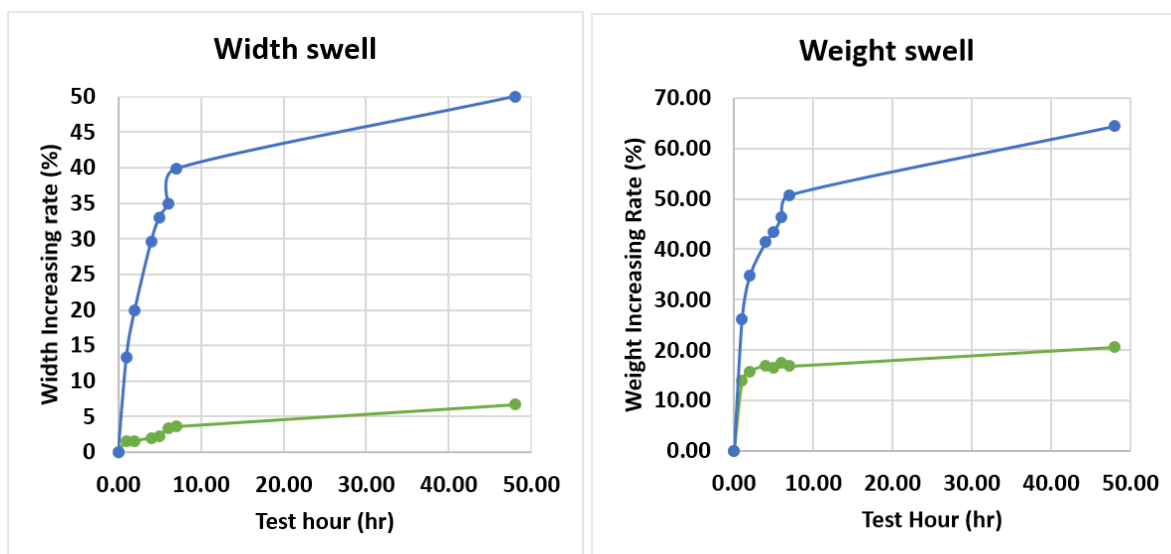


Figure 2-6. Water swell in width and weight test

2-5. Conclusion

For reducing the cost of manufacturing the particleboard, the content of pMDI should be 5% of the total mass of materials. And the best fitted recipe, based on its mechanical properties and density, should be 75% sisal fibers, 20% carpet fiber and 5% pMDI binder. The commercial sisal fibers have better mechanical properties than the waste sisal fibers. But the sisal fibers have a drawback in the field of waterproof.

2-6. Reference

- [1] Rachel Passos O.S. et al, Processing and Thermal Properties of Composites based on Recycled PET, Sisal Fibers, and Renewable Plasticizers, *Journal of Applied Polymer Science*, 2014, DOI: 10.1002/APP.40386
- [2] <https://en.wikipedia.org/wiki/Sisal>
- [3] Barreto A.C.H. et al, Properties of sisal fibers treated by alkali solution and their application into cardanol-based biocomposites, *Composites, Part A* 42 (2011) 492–500
- [4] Food and agriculture organization of the United Nations statistics division, 2013
- [5] Y. Li, Y.W. Mai, L. Ye, Sisal fiber and its composites: a review of recent developments, *Compos. Sci. Technol.* 60 (2000) 2037–2055
- [6] Marta Andrade et al, Characterization of the different fractions obtained from the pyrolysis of rope industry waste, *Journal of Analytical and Applied Pyrolysis*, 95 (2012) 31–37
- [7] <http://www.sisal.ws>
- [8] Richard G. Mansfield, Performance Fibers in Ropes and Cordage, *Technical Textile*, Apr 2005, Vol. 155 (4), pp.25-28
- [9] Instru-Met Remanufactures Instron Model 1000 & 1011 Test Frames
- [10] S. I. Durowaye, G. I. Lawal, O. I. Olagbaju, Microstructure and Mechanical Properties of Sisal Particles Reinforced Polypropylene Composite, *International Journal of Composite Materials*, 2014, 4(4), 190-195

Chapter 3. Bagasse Based Particleboard

3-1. Introduction

Carpet is an important commodity in daily life. Since the average life expectancy of carpet is between eight and eleven years,^[1] carpet waste has become one of the large waste handling problems requiring attention. Currently, most carpet waste is disposed in landfills. Carpet waste is classified as pre-consumer or post-consumer. Pre-consumer carpet waste includes scrap generated during production. Post-consumer carpet waste is used carpet. The total amount of carpet waste is estimated at over 2 million tons per year in the United States. The total amount of post-consumer carpet waste in the United States is estimated at 3.4 Billion pounds per year. Because of the high cost of landfills, a more effective and eco-friendly approach is required.^{[2][3]}

Generally, carpet consists of primary and secondary backings (polypropylene or polyester), face fibers (nylon 6, 31%; nylon 66, 21%; Polyethylene terephthalate, 34%; Polypropylene, 8%; other 6%)^[4], filler materials (CaCO_3) and adhesive (styrene-butadiene rubber, a thermoset material which cannot be melted or reshaped). In addition, some of carpet waste from special sources such as aircraft, may contain chemical additives such as flame retardants and stain resistant chemicals. The chemical additives make carpet waste recycling and classification much more difficult and complex. Currently, the cost of carpet waste disposal in landfills is roughly 100 million dollars per year in the United States. Without classification and processing costs, the direct cost for landfill disposal is about \$0.025/lb.^[4] Therefore, developing value-added uses for carpet waste is economically beneficial.

The four types of processes for carpet waste recycling are primary (depolymerization), secondary (polyamide extraction), tertiary (melt blending), and quaternary (combustion) recycling. Wright et al. used phosphoric acid to depolymerize the carpet waste mixture. The monomer can be classified and recycled by extensive processing.^[5] Yi Zhang et al. used compression molding to make glass-mat-reinforced thermoplastic. The glass-mat –reinforced thermoplastic from carpet waste has comparable mechanical properties to material produced from virgin polypropylene.^[6] However, the methods above have the high cost of classifying the waste carpet, and may be limited in the level of acceptable impurities.

Mancosh et al. used chopped carpet waste to make a composite material with the help of binder.^[7] Matthew et al. used post-consumer carpet as an alternative fuel in a rotary kiln combustor and monitored the emission of the carpet burning. The effect of carpet burning on thermal NO emission for polypropylene carpet could be negligible, however, for the nylon carpet, the amount of NO emissions would be increased.^[8]

The work outlined below recycles unclassified waste carpet into particleboard by blending it with other waste streams to produce a feedstock capable of being processed with little or no modification to existing processes or equipment. The goal of this project is to produce recycled particleboard in medium density (Density <50 pound/feet³) which can reach the standards punished by the ANSI A208.1-2009. The work below presents an example blending waste carpet with sugarcane bagasse, and additional data indicate blending waste carpet with a variety of other waste streams to produce particleboard is expected to work well also.

Global sugarcane production is about 1.91 billion tons annually and is concentrated in tropical regions, particularly in the developing countries of Latin America and Asia. Currently, over 100 countries are producing sugarcane. The top five are Brazil, India, China, Thailand and Pakistan.

^[9] The total area of Sugar cane harvested in the US in 2015 was roughly 892 thousand acres.

Sugarcane production in the U.S. was 33.24 million tons in 2015, an increase of 9.26% from 2014, and the states of Florida, Louisiana, Hawaii, and Texas are the major producers.

Aigbodion et al stated that 1 ton of bagasse would be left as residue from processing 3600 kg of sugarcane, and due to such large quantities, enormous efforts have been directed towards bagasse waste issues. ^{[10][11]} Some bagasse is burned, some is used to produce other products such as paper, and much is just left in waste piles. To improve profitability and flexibility to meet market demands, the sugar industry is actively looking at coproduction of both sugar and ethanol. ^[12]

Kumar et al used a continuous process with cell recycle for ethanol production from bagasse hydrolysate. High temperature fermentation facilitated in-situ ethanol recovery by stripping with air or N₂. Recycling the cells mitigated the cell washout problems common in continuous processes. ^[13]

Long Wu et al pretreated sweet sorghum bagasse for improved enzymatic digestibility in low temperature alkali by disrupting the lignin-carbohydrate complex to liberate the cellulose fibrils.

This method offers an alternative way to the efficient conversion of lignocellulosic sugarcane to ethanol. ^{[14][15]}

Maria Carolina de Albuquerque Wanderley et al improved the ethanol production based on combined pretreatments and fed-batch enzymatic hydrolysis. With alkali pretreatment, the sugarcane surface area increases 8% and reduced the lignin content and the crystallinity index by 83% and 33%, respectively. Measurements at 12, 24 and 36 hours indicated increasing ethanol production in their fed-batch experiments. ^[16]

It is not a perfect way to recycle the waste bagasse especially the bagasse after sugar mill. Rafael Ramos de Andrade et al set a model to prove kinetics of ethanol production from sugarcane bagasse enzymatic hydrolysate concentrated with molasses under cell recycle. ^[17] Although it works well, but it must be operated in factories

to test it right or wrong. Therefore, in our project, directly using the waste bagasse without chemical pretreatment to make particleboard can be a healthy and eco-friendly way.

One effective way to handle both carpet waste and sugarcane waste is making particleboard.

Particleboard is a panel product manufactured by pressing wood or non-wood materials with a binder. Particleboard is widely used in packaging, building and furniture. ^[18] A considerable amount of research focuses on the use of non-wood materials in particleboard, such as reed, bamboo ^[19], rice husks ^[20], tea leaves ^[21], sunflower stalks ^[22], and bagasse. Wallboard product sales for construction in the US were 22 billion square feet in 2015. In 2015, reconstituted wood panel products in the US had a market value of \$5.7 billion of which particleboard was estimated to be 27% (Medium density fiberboard 15%, Waferboard and Oriented strand board 35% and others such as Hardboard, Cellulose fiberboard 23%) of the total revenue, or approximately \$1.52 billion. ^[23] The industry is projected to have an annual growth of 2.7% through 2018. The data from Statista website shows that in 2015, operating revenue of particle board manufacture in China has been up to almost 6.64 billion US dollar, increased 4.17% from 2014. And in Japan operating revenue is 42.4 million US dollar in 2015, increased 2.42% from 2014. ^[24] According to a life cycle assessment (LCA) case, bagasse (the waste of sugarcane) is one of eco-friendly and healthy raw materials to manufacture particleboards. ^[25] Target on waste carpet and waste bagasse recycle and a high demand of market in particleboard. Mixing the waste carpet and bagasse to make particleboard in our project could get benefit in both commercial and environmental field if success.

3-2. Materials and method

3-2-1. Materials

Waste Sugarcane (Bagasse) was obtained from sources in Haiti and Louisiana, and vacuum dried before use to obtain moisture content near 7%. Post consumer carpet (PCC) was used to provide sheared polyethylene terephthalate (PET) face fiber, backing material, and unseparated shredded carpet, all of which were provided by *Carpet America Recovery Effort* (CARE). The binder, Polymeric Methylenediphenylene Diisocyanate (pMDI) was purchased from Huntsman Corporation. Release agent was purchased from Sprayon. Acetone was purchased from Sigma Aldrich.

Dried sugar cane from Haiti and Louisiana was used in this study. The bagasse from Haiti typically contained less water than the bagasse from Louisiana. For a set of small panels made in the laboratory at the University of Connecticut (UConn), the bagasse from Haiti was vacuum dried for 16 hours at 50 °C and 0.05Atm. One batch of bagasse from Louisiana required 20 hours to vacuum dry and another batch of bagasse from Louisiana required over 24 hours to vacuum dry. In all cases, after vacuum drying, the moisture content was approximately 7%, and could be maintained for several days by storing the material in a closed oven at 50C. The bagasse from Louisiana appeared fresher than the bagasse from Haiti, and that is probably why the Louisiana bagasse had higher initial moisture content.

For a set of large panels made in the Forest Products Laboratory at the University of Maine (UMaine), the bagasse was shipped from Louisiana to UMaine in a large wooden box and covered in a plastic bag. The bagasse was dried in a Nyle dehumidification dry kiln for more than 48 hours before use, resulting in moisture content of approximately 4%. Before the

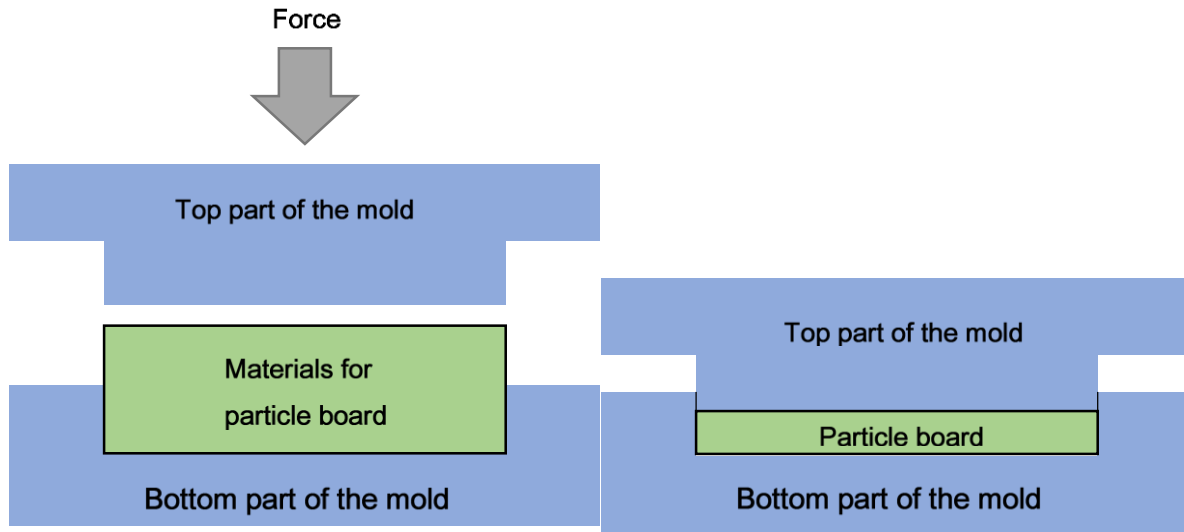
production of each panel, a calculated amount of water was added back to the bagasse in a tumbling blender to adjust the moisture content of the bagasse into the range of 6% to 8%.

3-2-2. Compression method

The compression mold in the UConn laboratory comprises two parts. The top part is the cover of the compression mold and the bottom part has a rectangular cavity with rounded corners, into which the compression charge was placed (Fig.3-1). The area of the rounded rectangle is approximately 300 cm² (46.5 inch²).



a.



b.

Figure 3-1. a. The UConn mold, b. Schematic of the UConn mold before and after compression.

The mold at the UMaine was a square wooden frame placed on top of a bottom panel. The inner area of the frame was roughly 7458 cm² (1156 inch²) (Fig.3-2). The compression charge was distributed evenly in the frame and the frame was then removed. An upper panel was then placed on top of the compression charge prior to insertion into the press. The texture of the top and bottom surfaces of the produced panels was imposed by the surface texture of the top and bottom panels.



Figure 3-2. Rectangular wood frame mold at UMaine

3-2-3. Compression Molding Process

In the UConn laboratory, the Bagasse would be left in the vacuum oven at 50 C for a period sufficient to bring the moisture content to approximately 7%. For a panel consisting of 75% bagasse, 20% carpet and 5% binder, 82.5g of Bagasse was mixed with 22g of PET carpet. Then, 5.5g of binder were dissolved into 100ml of acetone. The binder solution was sprayed onto the mixture of Bagasse and PET carpet to obtain an even dispersion, and the materials left in the hood for 20 minutes to allow acetone to evaporate. The materials were evenly layered into the compression mold and compressed at 2.08MPa and 160 C for 20 minutes

At the UMaine, the bagasse was dried in the Nyle dehumidification dry kiln for 48 hours before use. The batch of bagasse selected for a panel was tested for average moisture content, and the mass of additional water required to achieve 7% moisture content calculated and added by tumbling the bagasse while the water was sprayed in the resin blender. The bagasse and the

waste carpet were then resinated in a 3' x 6' Coil Inc. tumbling resin blender (Fig. 3-3a) fed by a Masterflex peristaltic pump (Model 77200-52). The binder or the water was applied through a Coil spinning disc atomizer (model EL-4, Fig. 3-3b). The resinated material was placed into the wooden frame mold as noted above. A Dieffenbacher 34" x 34" hydraulic hot press was used to compress the material and produce the particleboard panel. Press data (position, mat pressure, core temperature and core gas pressure) were recorded at 1 s intervals using a PressMan data recording system. After the panel cooled to near room temperature it was trimmed to 32" x 32" prior to testing.



Figure 3-3. a. Tumbling resin blender, b. Coil spinning disc atomizer

3-3. Results and Discussions

3-3-1. Density and Pressure

The compression pressures used to produce the small panels in the UConn laboratory varied from 1.33 MPa to 4.45 MPa (193 psi to 645 psi), which led to densities ranging from 0.689 g/cm³ to 0.945 g/cm³ (43 lb/ft³ to 59 lb/ft³). When the pressure was below 2.97 MPa (430.1 psi), the density of bagasse board varied in a nearly linear relationship to the pressure. When the pressure was over 2.97 MPa, the density of bagasse board was nearly invariant with pressure (Fig.3-4). At roughly 3 MPa, the mold cover contacted the lower mold plate and did not transmit further compression pressure to the panel being produced in the mold.

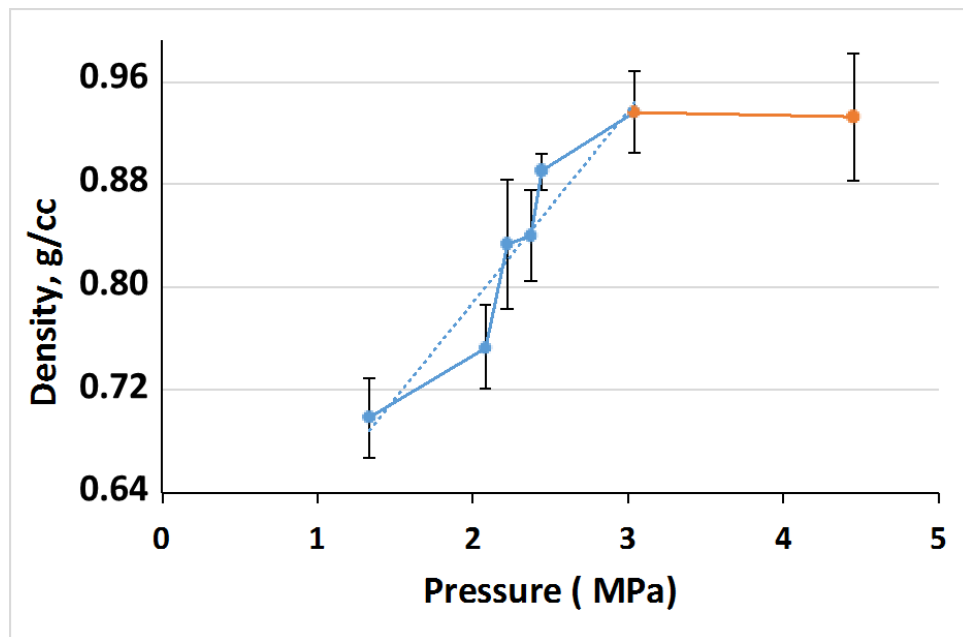


Figure 3-4. Relationship between compression pressure and particleboard density.

3-3-2. The size of the bagasse piece

In most of experiments in the UConn lab, the bagasse material was picked randomly with the size of the bagasse ranging from 5 cm to under 0.5 cm in length. The size of the bagasse may, however, be an important factor affecting the mechanical properties of the particleboard. A small set of experiments was conducted to illustrate the effect of bagasse particle size by dividing the bagasse into three sizes ranges. The first size class is over 4 cm, the second is between 0.5 cm and 4 cm, and the last is below 0.5 cm. The particleboard formulation was the same for all 3 size ranges, comprising 95% bagasse and 5% pMDI binder, compressed at 2.08MPa and 160°C for 20 minutes. Only one board was made with each particle size class, and each board provided two samples for measurement of flexural strength and stiffness. Figure 3-5 shows the average strength and stiffness of the two samples from particleboards made with each size class, indicating that the particleboard made with the longest bagasse, over 4cm, has the best MOR and MOE.

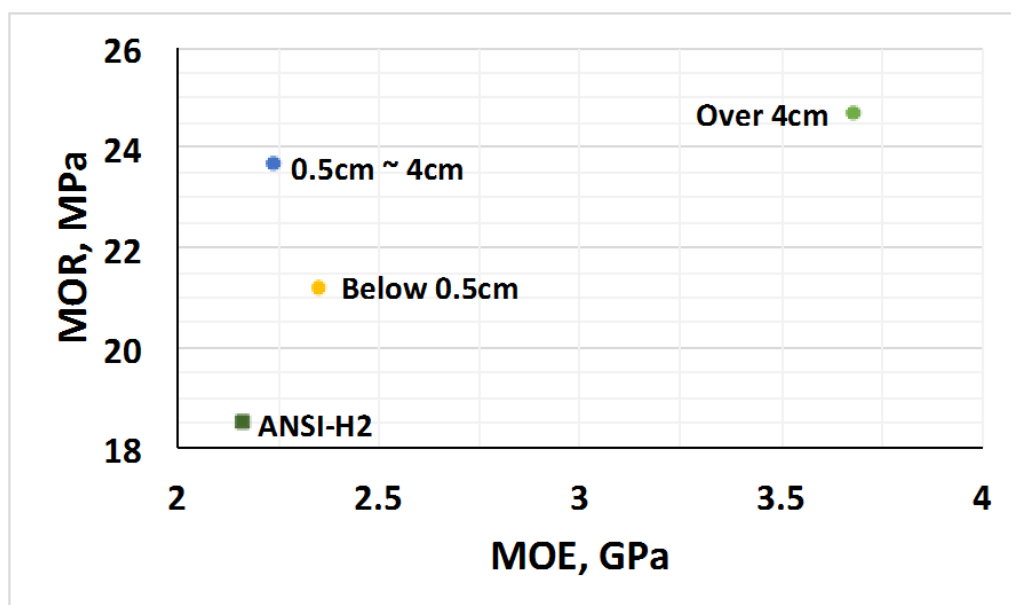


Figure 3-5. The effect of bagasse particle size on the MOR and MOE of bagasse particleboard

The experiments reported below in which post consumer carpet was mixed with the bagasse were conducted with randomly selected bagasse batches that were not size classified. Therefore, the results noted below may be improved by using size-classified bagasse.

3-3-3. The comparison between sheared face fiber, carpet backing, and unseparated carpet

Preliminary experiments indicated that a reasonable mixture of bagasse and post consumer carpet consisted of 75% bagasse, 20% post consumer carpet, and 5% pMDI binder. While many applications of post consumer carpet only use the face fiber, obtained by shearing it off the backing material, a goal in this study is to use the entire carpet material, unseparated and minimally processed. In order to understand the relative merits of face fiber, backing material and unseparated post consumer carpet on the mechanical properties of particleboard, several small boards were produced in the UConn laboratory using each type of material. In all cases the boards were produced with 75% bagasse, 20% carpet material, and 5% pMDI binder with compression pressure of 2.08 MPa (301 psi), temperature 160C, and molding time 20 minutes. The average MOR of the particleboard using face fiber was roughly 22 MPa (4 samples), and the average MOR using backing material is roughly 19 MPa (4 samples). Both are over the ANSI-H2 standard, which is 18.5 MPa. The average MOE of the particleboard using face fiber is 2.3 GPa, which is over 2.16 GPa of the ANSI-H2 standard. However, the average MOE using backing material is 1.87 GPa, which is lower than 2 GPa of the ANSI-M2 standard (Fig. 3-6). The average density of the particleboard using face fiber is 0.777 g/cm³ (48.50 lb/ft³), the

density of the particleboard using backing fiber is 0.8522 g/cm³ (53.20 lb/ft³). Therefore, the particleboard with 20% sheared face fiber is medium density but reaches the standard of ANSI – H2 and well exceeds the ANSI-M2 standard.

If unseparated waste carpet can be used, then the cost of particleboard feedstock can be minimized. The unseparated carpet includes PET from the face fiber, and CaCO₃, several other polymers and ash, clay and various materials from the backing material. Although the average MOR of the particleboard containing 20% unseparated waste carpet declined 11.28% and average MOE declined 1% compared to the sheared face fiber based particleboard, it still exceeded the ANSI-H2 by 5% for MOR and 6% for MOE (Fig. 3-6). The average density of the particleboard containing 20% unseparated waste carpet is 0.748 g/cm³ (46.70 lb/ft³). Therefore, this particleboard is medium density but attains the requirements of high density ANSI-H2 grade material.

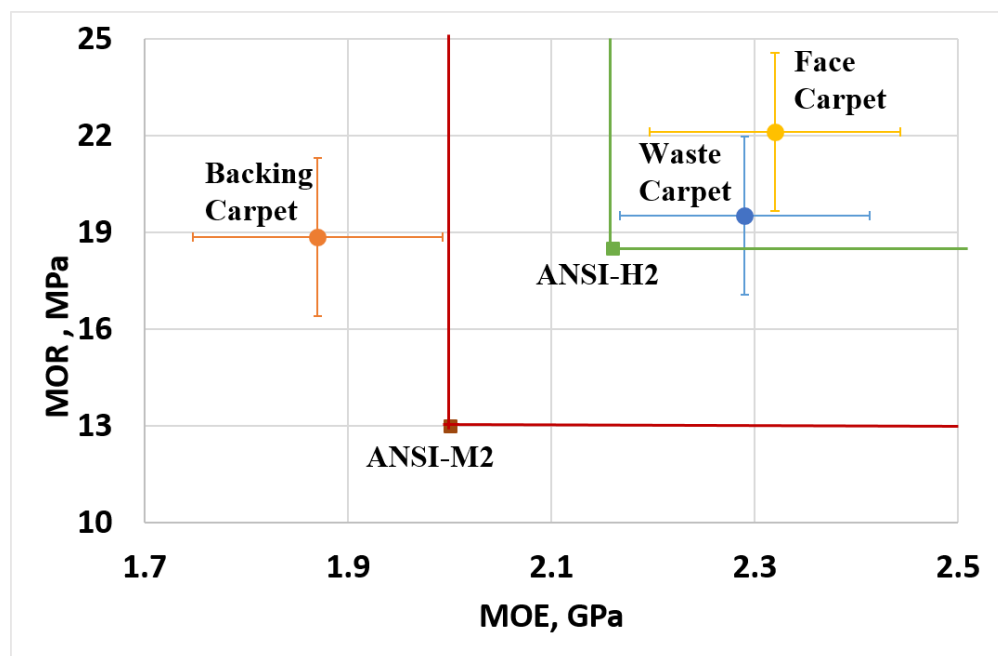


Figure 3-6. The MOR and MOE of particleboard made with 20% Face Fiber or 20% Backing Material or 20% Unseparated Carpet

3-3-4. Commercial Prototype Boards

Based on the results with the small boards produced in the UConn lab, commercial prototype boards were produced in the Kenway composite materials lab at the UMaine with size 1m x 1m x 18mm (34" x 34" x ¾"). The recipes of the panels made at UMaine are given in Table 3-1.

Boards 8 and 9 were produced with a 3-layer structure, which means that the center layer contained all of the shredded carpet and some of the bagasse, and the two outer layers contained only bagasse and no carpet. The 3-layer structure was produced for two reasons. First, the shredded carpet appears to lower the MOE of the board, so maximizing the stiffer bagasse towards the top and bottom surfaces is expected to increase the flexure stiffness of the panel. Second, some components of the shredded carpet begin to melt at the processing temperatures so shredded carpet at the surfaces can impact the surface finish of the board and make separation from the press more difficult.

Table 3-1. The recipe, density and moisture content of the panels made in UMaine

Panel Number	Recipe	Density lb/ft ³	Density g/cm ³	Moisture content Mass %
1	95% Bagasse/5% pMDI	46.36	0.7426	4
2	95% Bagasse/5% pMDI	49.76	0.7971	7.4
3	75%Bagasse/20%carpet/5%pMDI	48.50	0.7769	6.53
4	75%Bagasse/20%carpet/5%pMDI	50.27	0.8052	6.45
5	75%Bagasse/20%carpet/5%pMDI	48.94	0.7839	6.88
6	75%Bagasse/20%carpet/5%pMDI	52.17	0.8357	7.17

7	75%Bagasse/20%carpet/5%pMDI	53.73	0.8607	6.4
8	3 layer: 75%Bagasse/20%carpet/5%pMDI	47.55	0.7617	6.3
9	3 layer: 75%Bagasse/20%carpet/5%pMDI	47.33	0.7582	6.28

The first two panels were control samples, without any carpet. The average moisture content in the bagasse of board 1 is only 4% due to over drying in the dehumidification kiln. Water was added to the bagasse for all the other panels to control the moisture content in the range of 6% - 7.5%, which is more appropriate to properly cure the pMDI binder. The results of Board 2 provide good control data for all the other boards with 20% carpet (See Table 3-2). For ease of assigning each sample as medium or high density, the sample densities in Table 3-2 are given in units of lb/ft³, since 50 lb/ft³ demarcates medium from high-density particleboard.

Table 3-2. Individual flexure test results for prototype board 2.

Flex ID	weight (g)	width (in)	thick (in)	length (in)	span (in)	density (lb/ft ³)	MOE (GPa)	MOR (Mpa)
2-1	514.16	2.984	0.705	20	18	46.6	2.4	18
2-2	540.47	3.008	0.704	20	18	48.6	2.5	19.8
2-3	553.39	3.005	0.701	20	18	50.0	2.7	18.9
2-4	608.39	3.011	0.718	20	18	53.6	3	23
2-5	604.39	3.009	0.735	20	18	52.1	2.9	19.7
2-6	557.6	3.013	0.737	20.068	18	47.7	2.7	21.1
AVE	563.0667	3.005	0.71667	20.01133	18	49.76	2.70	20.08

The average MOE above for board 2 reached the M-3 and H-3 levels, but the average MOR only reached M-3 level. To cover both medium and high-density material, boards 3-7 were made with densities from 45-55 lb/ft³ (0.721-0.881 g/cm³). Each panel was cut into six samples for

MOR and MOE testing. The MOR and MOE values from the 30 samples tested from boards 3 – 7 are plotted in Fig.3-7a, and normalized to the M-2 standard values. In Fig.3-7a, the MOR and MOE from boards 3-7 increase with increasing density, and the trend lines of the data were obtained by linear least squares fitting.

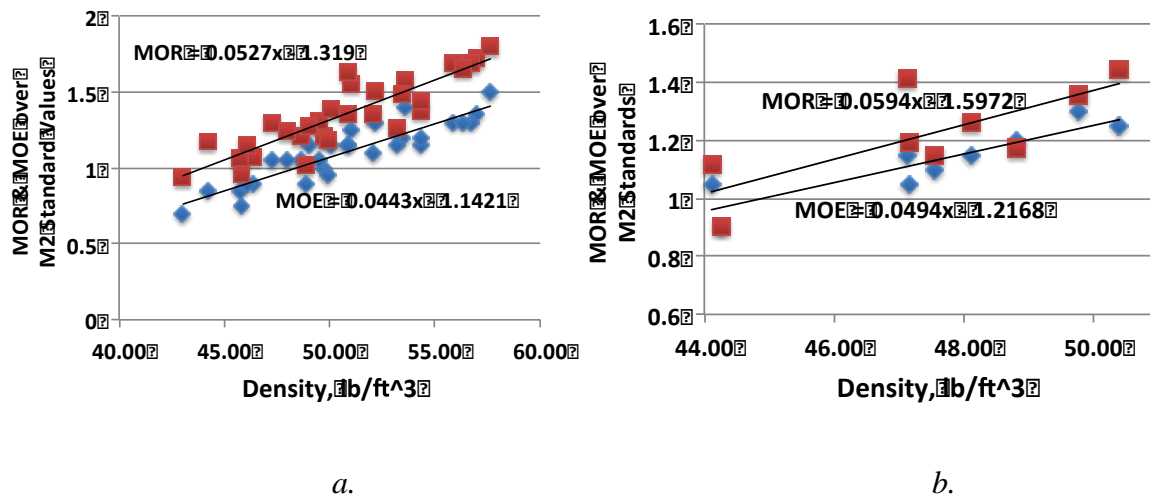


Figure 3-7. a. The MOE and MOR from boards 3-7, divided by M-2 standard value, b. The MOE and MOR from Boards 8 and 9, divided by M-2 standard value.

The MOR and MOE data for the 3-layer boards, 8 and 9, are shown in Fig.3-7b. Board 9 developed a crack on one edge after removal from the mold so only 3 samples were obtained from board 9, leading to a total of 9 samples for boards 8 and 9 (Table 3-3). The trend lines of data in Fig.3-7b are also shown for the 3-layer boards, and show the improvement in MOE compared to boards 3 – 7.

Table 3-3. Flexure test data from 3 layer boards 8 and 9.

FlexID	weight(g)	width(in)	thick(in)	length(in)	span(in)	density(lb/ft ³)	MOE(GPa)	MOR(Mpa)
8-1	577.07	3.002	0.777	20	18	47.1	2.3	18.4
8-2	596.25	3.015	0.774	19.938	18	48.8	2.4	15.3
8-3	610.67	3.013	0.766	20	18	50.4	2.5	18.8
8-4	552	3.012	0.734	20	18	47.6	2.2	14.9
8-5	546	3.008	0.731	20.063	18	47.2	2.1	15.5
8-6	508.12	3.007	0.725	20.063	18	44.3	1.8	11.7
9-4	589.34	3.012	0.749	20	18	49.8	2.6	17.6
9-5	566.04	2.995	0.748	20	18	48.1	2.3	16.4
9-6	520.88	3.003	0.749	20	18	44.1	2.1	14.5

In order to directly compare boards 3 – 7 to boards 8 and 9, the trend lines in Fig.3-7 are replotted in Fig.3-8. The MOE trend lines from Figs.3-7a and 3-7b are plotted together in Fig.3-8a illustrating the improved stiffness achieved by the 3-layer construction in boards 8 and 9. For comparison to the ANSI standards, the M-2, M-3, H-2 and H-3 specifications are also plotted in Fig.3-7 as horizontal dashed lines. The trend lines of the data in Fig.3-8 can be used to predict the density required to produce each classification of particleboard. For example, the trend lines for the 1-layer boards, boards 3 – 7, predict that a density of 44 lb/ft³ is required to meet the M-2 requirement for MOR and a density of 48.4 lb/ft³ is required to meet the M-2 requirement for MOE. Thus, the trend lines indicate that the 1-layer boards at a density of 48.4 lb/ft³ will meet both MOE and MOR specifications for M-2 particleboard. Since $48.4 < 50$, it is feasible for 1-layer boards made with 20% unseparated waste carpet to meet M-2 specifications of commercial particleboard. Similar calculations yield the required densities for the 1-layer boards and 3-layer boards to meet the particleboard specifications for the various classifications. These results are summarized in Table 3-4, under the column heading, “Density from trend line only.” The required density for the 1-layer boards to meet the M-3 standard is above 50 lb/ft³, and it is

therefore not feasible to produce M-3 grade particleboard with the 1-layer configuration, so the entry in Table 3-4 is given in red colored text.

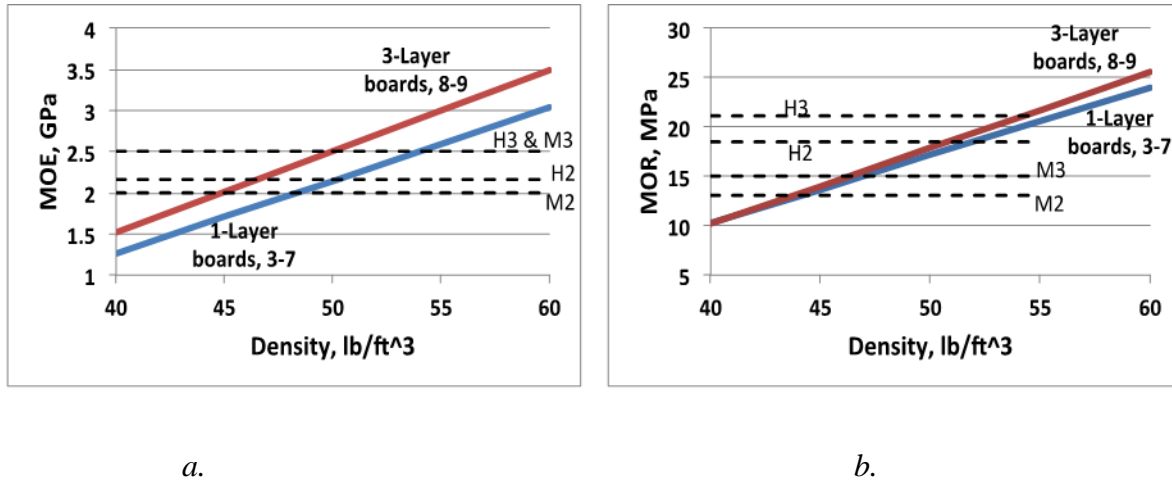


Figure 3-8. Trend lines for MOE (a) and MOR (b) for boards 3-9. The requirements for M-2, M-3, H-2, and H-3 particleboards are denoted in the figures by the horizontal dashed lines.

Figure 3-7 indicates significant scatter of the data about the trend lines. Therefore, if the density predicted by the trend lines is used to produce a certain classification, only about 50% of the produced boards would exceed the desired specifications and about 50% of the produced boards would not meet the desired specifications. To improve the reliability of the manufacturing process, a somewhat higher density than predicted by the trend lines is required. Therefore, the standard deviation of the data from the trend lines was computed. The required densities of the boards required to meet the MOR and MOE specifications of various classifications was also calculated accounting for one and two standard deviations of scatter of the data from the trend lines. With these considerations, the required board densities to meet the specifications are also given in Table 3-4, and are somewhat higher than the corresponding density values calculated

using only the trend lines. For example, a density of 48.4 lb/ft³ is required for the 1-layer boards to meet M-2 specifications if only the trend line is considered, but a density of 50.3 lb/ft³ is required for the same boards to meet M-2 specifications if 1 standard deviation of scatter is included in the calculations and a density of 52.1 lb/ft³ is required if 2 standard deviations of scatter are considered. Therefore, while it is feasible to produce M-2 grade particleboard from 1-layer boards with 20% waste carpet, it may not be possible to do so reliably or with a high level of confidence since the required density to reliably attain M-2 grade properties is above the threshold level of 50 lb/ft³.

Table 3-4. Required board densities to reach required MOR and MOE for each level

Level	Density from trend line only		Density from trend line + 1 standard deviation		Density from trend line + 2 standard deviations	
	Brd 3-7	Brd 8-9	Brd 3-7	Brd 8-9	Brd 3-7	Brd 8-9
M-2	48.4	44.9	50.3	46.0	52.1	47.4
M-3	54.0	49.9	55.9	51.0	57.8	52.1
H-2	52.0	50.9	54.2	52.7	56.3	54.5
H-3	55.8	54.2	58.0	56.1	60.1	57.9

For the M-2 and M-3 rows, the required density must be lower than 50 lb/ft³ (0.80 g/cm³) to qualify as medium density. As Table 3-4 indicates, the 3-layer boards can reach the M-2 specifications at density lower than 50 lb/ft³ with 2 standard deviations of reliability. In the case

of M-3 grade material, the 3-layer board can feasibly reach M-3 specifications at just under 50 lb/ft³, but it does not appear possible to attain a high level of reliability if 20% waste carpet is blended with random size bagasse. For the H-2 and H-3 classifications, the boards can reach those levels, but a very high density of 60 lb/ft³ appears necessary for the 1-layer boards with 2 standard deviations of reliability.

3-4. Conclusions

Post consumer carpet can be recycled by blending it with bagasse to produce particleboard using pMDI binder. A formulation that provided excellent mechanical performance comprises 75% bagasse, 20% waste carpet and 5% pMDI. Scale up studies illustrated that this formulation can be produced on standard production equipment. A 3-layer board structure improved MOE values to provide a high level of statistical reliability for manufacturing chosen particleboard grades such as M-2. A separate economic analysis indicates that this formulation is expected to be economically profitable as long as the feedstock costs of the bagasse and waste carpet remain at their current low values.

3-5. Reference

- [1] Mihut, C.; Captain, K. D.; Gadala-Maria, F., Polym Eng Sci, 2001, 41, 1457-1470.
- [2] Y. Wang, Polym-Plast Technol Eng, 1991, 38(3), 553-546.
- [3] Jain, A.; Pandey, G.; Singh, A. K.; Rajagopalan, V.; Vaidyanathan, R.; Singh, R. P., Advances in Polymer Technology, 2012, Vol.31, No.4, 380-389.

- [4] Clair, D., Floor Trends, 2014, Vol.16, 10, 25-27.
- [5] Cheng Diao et al, Composites, Part A, 8 (2014) 90–97
- [6] Braum, M.; Levy, A. B.; Sifniades, S., Polym-Plast Techol Eng, 1999, 38, 471.
- [7] Wright, J., U.S. Patent, 2008, 20080113146.
- [8] Y. Zhang,; Muzzy, J. D.; Kumar, S., Polym-Plast Techol Eng, 1999, 38(3), 485-498.
- [9] Mancosh, D.; Przybylinski, J.; Murdock, D. E., U.S. Patent, 20070173551.
- [10] Aigbodion et al , Journal of Minerals & Materials Characterization & Engineering, Vol 9, No.1, pp67-77, 2010
- [11] Barroso J, Barreras F, Amaveda H, Fuel 2003(82) 1451–1463
- [12] Marina Oliveira de Souza Dias et al, Environmental Development, 2015(15) 35-51
- [13] Sachin Kumar et al, Chemical Engineering Science, 2015(138) 524-530
- [14] Long Wu et al, Bioresource Technology, 2011(102) 4793-4799
- [15] Long Wu et al, Bioresource Technology, 2011(102) 11183-11188
- [16] Maria Carolina de Albuquerque Wanderley et al, Bioresource Technology, 2013(128) 448-453
- [17] Rafael Ramos de Andrade et al, Bioresource Technology, 2013(130) 351-359
- [18] Realff, M.J.; Lemieux, P.; Lucero, S.; Mulholland, J.; Smith, P.B., Conference Record Cement Industry Technical Conference, 2005, 212-228.
- [19] Bhatnagar, A.; Kesari, K. K.; Shurpali, N., Water Air Soil Pollut, 2016 227: 11.
- [20] Nahla, A. E.; Ragab, E. A.; Yehia, F.; Mohamed, A. Y., Journey of Applied Polymer Science, 2007, Vol. 106, 3592-3599.
- [21] Rowell, R. M.; Norimoto, M., Mokuzai Gakkaishi, 1988, 34, 627.
- [22] Vasisth, R. C.; Chandramouli, P., FAO Background Paper, 1975. FO/WCWBP/75.
- [23] Reconstituted Wood Product Manufacturing. Rep. N.p.: n.p., n.d. IBISWorld Industry Report. Web.
- [24] www.statista.com/forecasts
- [25] Khristova, P.; Yussifou, N.; Gabir, S.; Glavche, I.; Osman, Z., Cellul Chem Technol, 1988, 32, 327.

Chapter 4. Appendix for Bagasse Compression

Particleboard

4-1. Instruction

Chapter 3 are the part for published paper, the Chapter 4 are some parts that are not shown in the published paper. But those parts are still good for this project.

4-2. Materials and Method

4-2-1. Fresh Bagasse

Fresh Bagasse were obtained from the fresh sugar cane purchased from the supermarket. The fresh sugar canes were chipped into pieces and crushed the pieces to let the sugar juice out. The crushed pieces were sunk into the water for 3 hours and crushed again after 3 hours. Repeated the process of sinking and crushing for 3 times. The crushed pieces were dried in the vacuum oven at 50C and 0.05atm for 48 hours. And dried in the vacuum oven at 50C and 0.05atm for additional 16 hours before use.

4-2-2. Wet Bagasse from Louisiana

The domestic transportation for waste bagasse is easier than the international transportation. The Lula Westfield LLC in Louisiana could provide the waste sugar cane fibers after milling for free which are the almost same as the bagasse fibers we used from Haiti. Therefore, some batches of bagasse fibers from Louisiana were shipped and stored in the lab for the future research. The moisture content of the bagasse from Louisiana is around 16.6%, the bagasse fibers was shipped in a large plastic bag. The bagasse kept wet when we opened the plastic bag. The bagasse fibers from Louisiana were stored in the open area and dried for 16 hour in the same condition as the common bagasse fibers we used from Haiti before use.

4-2-2. Thermal gravimetric analysis (TGA)

Thermal gravimetric analysis (TGA) is a method of thermal analysis in which changes in physical and chemical properties of materials are measured as a function of increasing temperature (with constant heating rate), or as a function of time (with constant temperature and/or constant mass loss). In this project, the TGA was used for testing the moisture content of the bagasse fibers. The machine model of TGA is TA Q500 in UConn.

4-3. Results and Discussions

4-3-1. Freshness of Bagasse Fibers

The bagasse waste fibers were residual as the by-product of the sugar cane juice. After milling, the bagasse fibers were abandoned and heaped up for further treatment. The freshness of the bagasse fibers were depended on the time after milling. The bagasse in our project was stored in the open area in the lab. Assumed the bagasse were shipped from Haiti last for two weeks, the bagasse we usually used was two weeks ago or older. But the fresh bagasse we purchased from the market was less than one week ago. We used two different freshness of bagasse fibers to manufacture the compression particleboard. And two recipes were adopted to compare the MOR and MOE of the particleboard.

The first recipe of particleboard was 95% bagasse and 5% pMDI at 30000lbf and 160C for 20 minutes. The second recipe of particle board was 47.5% bagasse, 47.5% facing carpet and 5% pMDI. The only difference is the bagasse fiber. Each board was cut into two samples for mechanical test. The result was shown in Table 4-1. The bagasse fibers which was purchased from the market and crushed in the lab were called fresh bagasse, the bagasse fibers which was usually used in this project were called common bagasse.

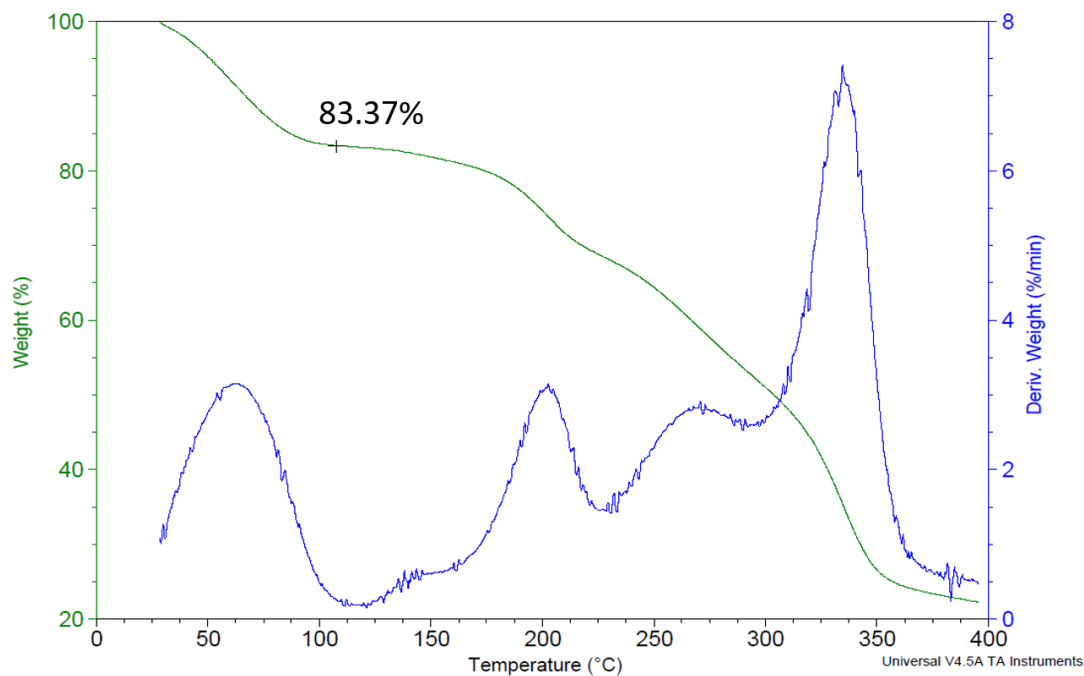
Table 4-1. Results of fresh and common bagasse particle board

	Recipe	MOR(MPa)	MOE(GPa)	Density(lb/ft3)
Fresh Bagasse	47.5% bagasse- 47.5% Carpet- 5%pMDI-1	11.8	1.04	51.76
	47.5% bagasse- 47.5% Carpet- 5%pMDI-2	11.8	1.06	51.25
	95%bagasse- 5%pMDI-1	13	1.86	40.27
	95%bagasse- 5%pMDI-2	15.3	2.1	41.83
Common Bagasse	47.5% bagasse- 47.5% Carpet- 5%pMDI-1	25.2	2.79	57.62
	47.5% bagasse- 47.5% Carpet- 5%pMDI-2	30.3	2.69	60.12
	95%bagasse- 5%pMDI-1	26.3	2.42	52.44
	95%bagasse- 5%pMDI-2	24.2	2.99	51.19

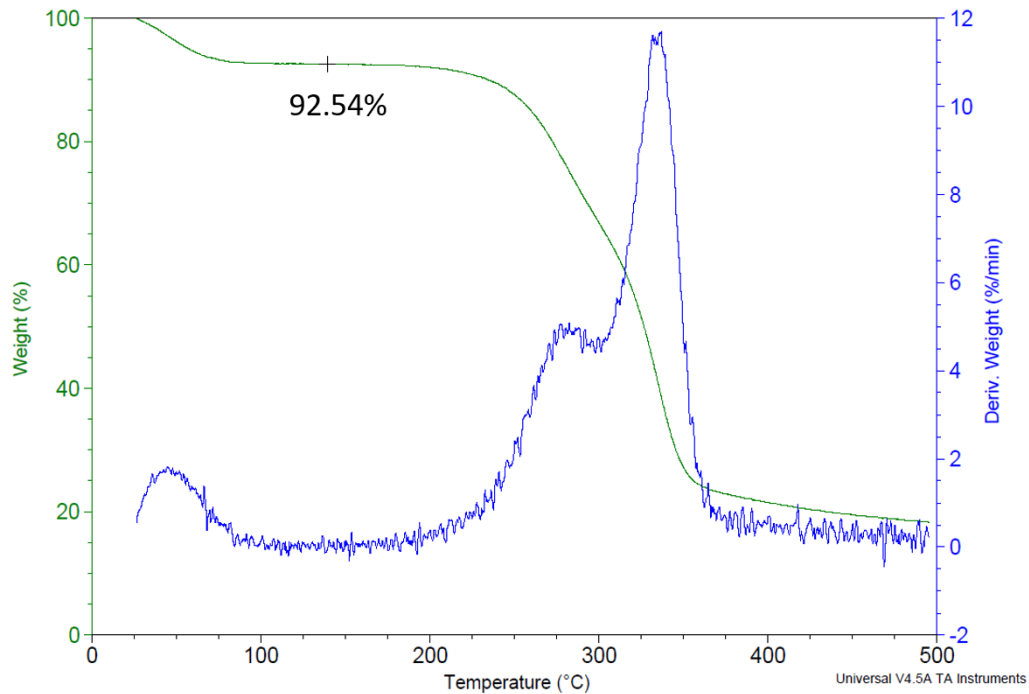
From the Table 4-1, the particleboards made with common bagasse have the better mechanical properties than the fresh bagasse. The density of particleboard under the same condition showed a large difference. The possible reason is that some sugar cane juice still remained in the fresh bagasse fibers, the remained sugar and water would decrease the mechanical properties of the particleboard. Because when we manufactured the fresh bagasse particleboard, we could still smell some melt sugar. And the water of bagasse would be discussed in the chapter 4-2-2.

4-3-2. the moisture content of the bagasse

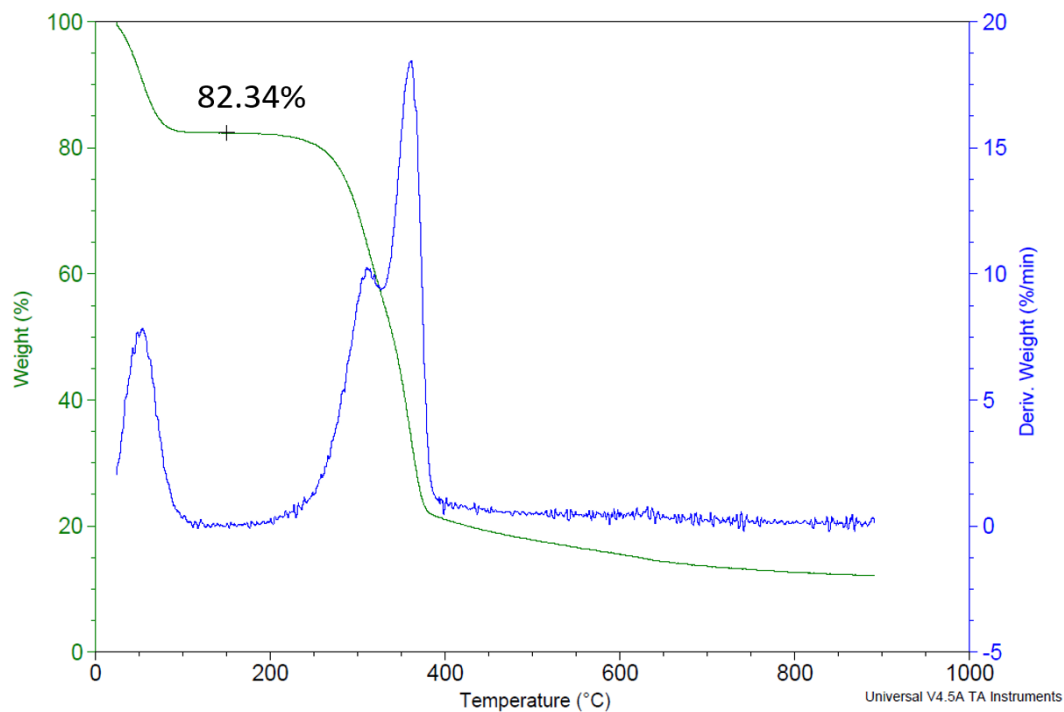
The test method for TGA was set that the temperature increased at the speed of 10C per minute. The fresh bagasse fibers before use, common fibers from Haiti before use, wet bagasse fibers from Louisiana before stored and bagasse fibers from Louisiana before use were picked and test in TGA. The results are shown in Figure 4-1. In Fig. 4-1a, the moisture content of the fresh bagasse fibers before use was around 17.6%. And in Fig 4-1b, c, d, the moisture content of Haiti bagasse before use, wet Louisiana bagasse and Louisiana bagasse before use is around 7.5%, 16.6% and 7.2%.



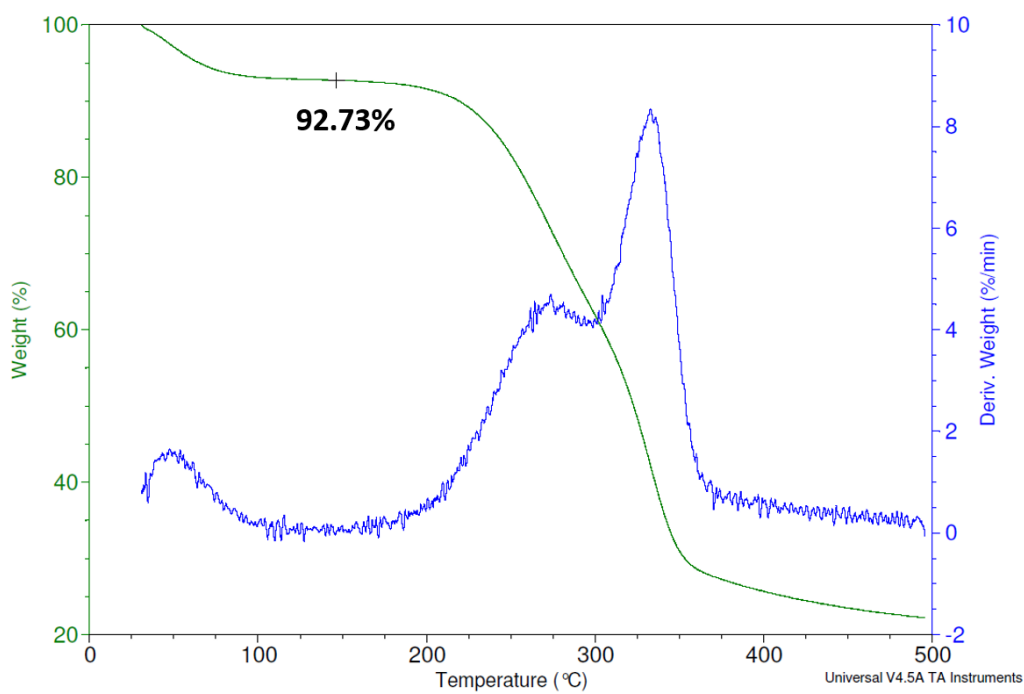
a. TGA of the fresh bagasse fibers before use



b. TGA of Haiti bagasse before use



c. TGA of wet Louisiana bagasse



d. TGA of Louisiana bagasse before use

Figure 4-1. TGA graphs of various bagasse fibers

Recall that the best fitted moisture content for pMDI was from 5% to 10% recommended by the Huntsman, the bagasse particleboards which consisted of the bagasse that their moisture content is higher than 10% shown a worse mechanical properties. That is why in chapter 3 the moisture content of bagasse fibers should be monitored during producing both small board in the UConn lab and big panels in UMaine. In Table 4-1, the particleboard made with fresh bagasse and common bagasse exhibited different mechanical properties. Due to the moisture content of fresh bagasse is up to 17.6%, the MOE and MOR was lower than the common bagasse. Because pMDI would have a chemical reaction with the water. And also, with the high temperature during the compression, some water would vapor and decrease the density of the particleboard. Therefore, as the Table 4-1 shown, the fresh bagasse particleboards have lower density than the common bagasse particleboards.

The wet and dried bagasse fibers from Louisiana which their moisture contents were test as 16.6% and 7.2% were used to made particleboards for comparing their mechanical properties. The recipe of the particleboards is 95% bagasse fibers and 5%oMDI at 160C and 14000lbf for 20 minutes. Each board was cut into two samples for test. The results are shown in Table 4-2. The dried bagasse particleboards obviously have better mechanical properties and a little bit higher density. Because the length of bagasse fibers from Louisiana (average length is 3cm) is shorter than the length of bagasse fibers from Haiti (average length is 4cm), following the conclusion obtained in chapter 3, the bagasse particleboard of Louisiana shows lower values in the MOR and MOE than the bagasse particleboard of Haiti.

Table 4-2. Mechanical properties of Louisiana wet and dried bagasse particleboard

	95% dried bagasse – 5% pMDI		
Sample #	MOR (MPa)	MOE (GPa)	Denisty (lb/ft3)
1	18.5	2.92	50.43
2	18.9	2.86	44.94
3	17.6	2.21	48.52
4	19.1	2.65	46.23
Average	18.5	2.66	47.53
	95% wet bagasse – 5% pMDI		
Sample #	MOR (MPa)	MOE (GPa)	Density (lb/ft3)
1	8.52	1.68	49.02
2	9.5	1.25	43.82
3	10.2	1.72	44.85
4	9.62	1.45	43.46
Average	9.46	1.53	45.29

4-4. Conclusion

The moisture content of the fresh surplus the recommended level over around 7.6%. Due to the sugar and water were got rid of and decomposed clearly, the fresh bagasse fibers shows lower mechanical properties than the old bagasse waste fibers whatever with or without the carpet fibers. For the future research, the moisture content of different fiber must be monitored and controlled in the range between 5% and 10%.

Because the bagasse fibers from Louisiana are mostly shorter than fibers from Haiti, the particleboard was manufactured with lower MOR and MOE. Compared with the wet bagasse, the step of drying in the vacuum oven is foremost and important for the experiments.

Chapter 5. Flame Retardant improvement to the particleboard.

5-1. Introduction

In the recent years, flammability of both synthetic and natural textiles and construction materials has become a significant question, leading to appropriate treatments to increase their flame resistant properties. ^{[1][2]} It is reported that there are totally 1345500 fires in the United States during 2015, which increased 3.7% from 2014. The fires during 2015 results in 3280 civilian fire deaths and 15700 civilian fire injures and 14.3 billion dollars for property damage. And 501500 fires were classified as structure fires, that is to say, there would be one fire reported in every 63 second. ^[3] In order to eliminate the expense from the fires and protect people's lives and property, the flame retardant materials could widely been used indoor and outdoor. Flame retardants are inhibit or delay the spread of fire by suppressing the chemical reactions in the flame or by the formation of a protective layer on the surface of a material. Additive flame retardants are mixed with the base material, such as mineral flame retardants. Most of reactive flame retardants do not react to attach themselves into their surroundings like additive flame retardants but the future work in this field are underway to graft further chemical groups onto these materials to enable them to become integrated without losing their retardant efficiency and making the flame retardants eco-friendly. ^[4]

Additive and reactive flame retardants can both function in the gas or solid phase. The basic mechanisms of flame retardants vary depending on the specific flame retardant and the substrate. Some basic retardation mechanisms are following:

Endothermic degradation, some compounds break down for absorbing the heat and cooling the materials.

Thermal shielding, creating a thermal insulation barrier between the burning and unburned parts.

Dilution of gas phase, inert gases (often carbon dioxide) produced by the thermal degradation of some chemicals dilute the content of combustible gases.

Gas phase radical quenching, released hydrogen chloride or hydrogen bromide from some special materials could reduce the potential for some reactive radicals to avoid burning.

Chih Pong Chang and Szu Chia Hung used phenol formaldehyde resin and waste papers for fiberboard. The phenol formaldehyde resin is known as excellent flame resistance and high mechanical properties. The burning time increased with the decline ratio of phenol formaldehyde added into the fiberboard. According to ANS8736, the fiberboard will be qualified if the burning time is less than 10 seconds. Therefore, the fiberboard which carve the standard of ANSI-8736 is added 11% phenol formaldehyde resin in it. However, this paper is lack of control sample, which is manufactured without the phenol formaldehyde resin. ^[5]

Mateos et al used layer-by-layer deposition of flame retardant on cotton fabric. The fabric was immersed into polycation, rinse water, polyanion and rinse water until the desired number of bilayers is achieved. All the samples show good properties for flame retardant. The samples coated by hand show better properties than the samples coated by machine, so layer-by-layer deposition operated by machines will show a lower properties than making the coating by hand if

possible. Cotton and bagasse are natural fibers, they could be coated by layer-by-layer for flame retardant. But more than 15.8% add-on weight increases the density of the particleboards, leading to high density of particleboards which exceeded the target medium density.^[6]

Leistner et al used water-based chitosan and melamine polyphosphate multilayer nanocoating on polyester-cotton fabric. And that multilayer nanocaoting is also good for PET fibers used for particleboard in flame retardant property. Although the flame retardant property is still good, the based water have a negative influence on pMDI used for particleboard, which leads to poor mechanical properties for particleboard. ^[7]

The target in our project is try to make flame retardant coating particle board in medium density, which could have the mechanical properties over ANSI-M2.

5-2. Materials and method

5-2-1. Coating bagasse and carpet fiber

The Bagasse and carpet fibers were obtained from Dr. Sun's Group after coating. The coated fibers were vacuum dried for 16 hours at 50 C and 0.05 atm before use. The moisture content of coated bagasse fiber is lower than the moisture content of normal bagasse fiber in use. All the bagasse fiber in use for coating is from Haiti and the carpet fiber for coating is face carpet fiber from CARE.

5-2-2. Compression method

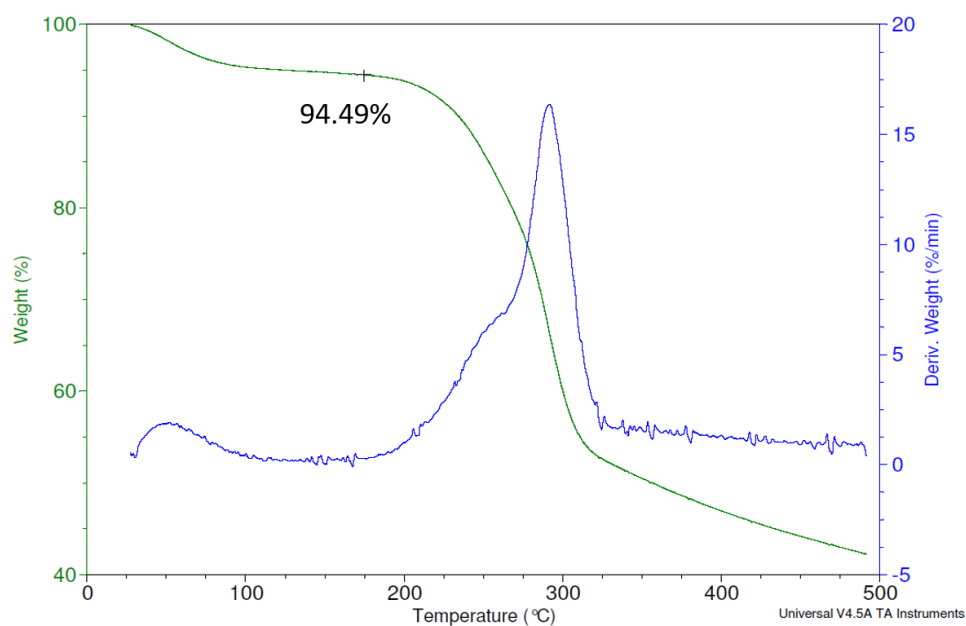
The coated bagasse fibers must be vacuum dried overnight before use for maintaining its moisture content is fit for the binder. A typical formulation is 75% coated bagasse fibers, 20% coated face carpet and 5% pMDI binder. The total mass of the materials would decide the density of boards, most of the mass of boards is 110 grams. If the total mass of one particle board is 110 grams, the mass of each materials could be calculated. The mass of coated bagasse fibers is $110 * 75\% = 82.5$ grams. The mass of coated face carpet fibers required is $110 * 20\% = 22$ grams. The mass of binder is $110 * 5\% = 5.5$ grams. Using the electrical balance to obtain the given amount for each materials. The binder should be weighed in a beaker for further use. Mix the coated bagasse and carpet fibers together in a plastic container and dilute the binder with 100 milliliter acetone. Stir the acetone to make the binder spread even in the acetone. The binder solution was sprayed onto the mixture of coated bagasse and carpet to obtain an even dispersion, and the materials left in the hood for 20 minutes to allow acetone to evaporate. The materials were evenly layered into the compression mold and compressed under 14000 lbf and 160 C for 20 minutes. After 20 minutes, take the mold out of the hot compressor and let the mold cool down into the room temperature. Open the mold and pick the particle board out.

5-3. Results

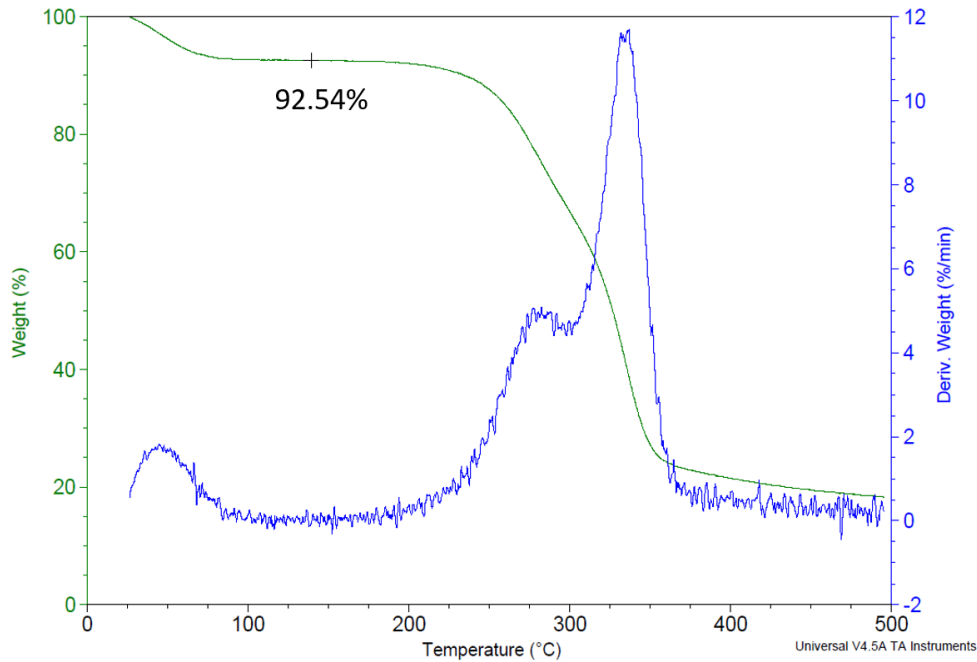
5-3-1. TGA of coated bagasse fiber

As the conclusion in the chapter 3, the bagasse fiber must have a fitted moisture content for pMDI binder. TGA test must be operated before making particle boards for monitoring the moisture content of coated bagasse fiber. If the moisture content of bagasse is lower than the

fitted range, the coated bagasse was sprayed water into them to obtain the fitted moisture content before use. The normal moisture content of bagasse after coating is shown in Fig. 5-1a. It is around 5.5%, which is a little bit lower than 7%. Usually, the coated bagasse fiber need to add water for achieving the moisture content we need. Compared Fig. 5-1a&b, when the temperature achieved around 500 °C, the pure bagasse fibers before use had about 20% weight residue. But the coated bagasse fibers had over 40% weight residue, which proved that the flame retardant coating material still left in 500 °C.



a.



b.

Figure 5-1. a. Moisture content of the coated bagasse fibers with 12% add-on weight before adding water b. moisture content of bagasse fibers before use

5-3-2. MOR & MOE of coated particle board

The recipe of particle boards is 75% coated bagasse, 20% coated face carpet and 5% pMDI in 14000 lb force, 160C for 20 minutes. The control particle board is 75% bagasse, 20% face carpet and 5% pMDI in 14000lb force, 160 C for 20 minutes. The flame retardant coating leaded to add-on weight for both bagasse and face carpet fiber. The results are shown in Table 5-1, each particle board was cut into two sample for test. The two control boards were made and cut into four samples for testing. The letter a&b in the sample number mean two samples from one particle board. The add-on weight means the weight increased after coating and the data obtained from Dr. Sun's group. The ANSI-M2 standard is also shown in this table.

Table 5-1. Mechanical properties of coated and uncoated particle boards

Sample #	Add-on weight (%)	MOR (GPa)	MOE (MPa)	Density (lb/ft ³)
ANSI-M2	-	13	2	< 50
Control sample	0	22.1 ± 2.4	2.32 ± 0.12	47.36 ± 2.13
Coating-1a	2	14.2	2.09	53.41
Coating-1b	2	12.5	2.02	53.64
Coating-2a	2	15.3	1.92	52.34
Coating-2b	2	15.7	1.96	53.16
Coating-3a	8	11.6	1.96	51.92
Coating-3b	8	9.43	1.86	47.38
Coating-4a	8	5.68	1.73	47.14
Coating-4b	8	7.32	1.75	46.58
Coating-5a	12	11.2	1.95	44.09
Coating-5b	12	11.4	2.01	45.77
Coating-6a	12	6.76	1.41	50.9
Coating-6b	12	8.43	1.5	51.3
Coating-7a	12	9.43	1.78	47.14
Coating-7b	12	11.8	1.96	51.12

Coating-8a	22	9.09	1.8	44.19
Coating-8b	22	12	1.95	45.72

5-3-3. Flame retardant property

The particle board was cut into a flame sample which the size of the sample is 7x1 inches. The vertical flame test was operated in Dr. Sun's group. The results are shown in Fig 5-2. For sample a, flame extended to 2 inches in only exterior for coated sample with 22% add-on, and lasted for 16 seconds after removal of ignition flame. For sample b, the flame extended to about 3 ½ inches in only exterior for Coated sample with about 12% of add-on , and lasted for 25 seconds after removal of ignition flame. For sample c, the flame extended to almost the whole particle board for the sample with 8% add-on, but mostly on the exterior, and lasted for 127 seconds after removal of ignition flame. Coated sample d with about 2% of add-on was completely consumed, no matter interior or exterior, and the burning lasted for 160 seconds after removal of flame, and the afterglow time was 14 seconds. Control sample was completely consumed, no matter interior or exterior, and the burning lasted for 200 seconds after removal of flame.

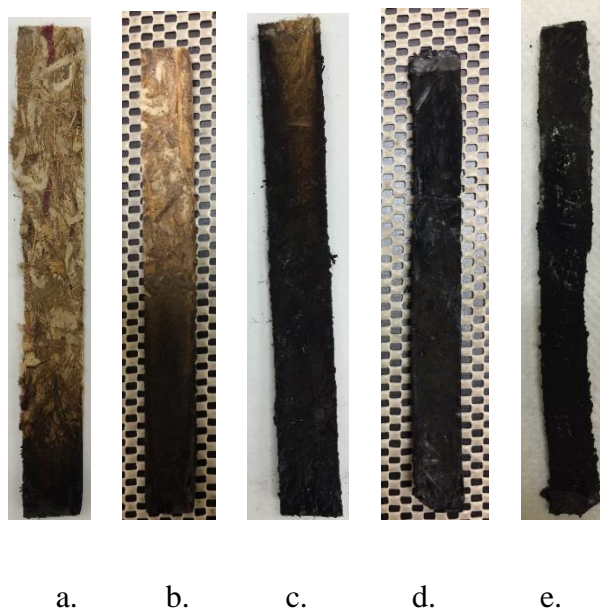


Figure. 5-2. Photos of the coated and control samples after vertical flame test a. sample with 22% add-on b. sample with 12% add-on c. sample with 8% add-on d. sample with 2% add-on e. control sample without coating

5-4. Discussion and Conclusion

In Table 5-1, all the coated samples had a much lower properties than the control sample. Most of coated sample only have half of MOR compared to the control sample, the MOE values don't achieve 2 MPa. According to ANSI-M2, the samples with 22%, 12% and 8% add-on weight don't achieve the standard of MOR and MOE. Although they have a good flame retardant property, the mechanical properties fail themselves to be a nice particleboard for use. For the samples with 2% add-on coating, they have a little higher MOR and almost same MOE of ANSI-M2. However, the density of those samples is higher than 50 lb/ft³, meaning that they are not in medium density and cannot compare with ANSI-M2.

In summary, the coated boards have a good property for flame retardant. The mechanical properties of the coated boards fail the standard of ANSI, so they are not good enough for the target we want.

5-5. Acknowledgements

Thank Dongqiao Zhang, who is the graduated student in Prof. Sun for coating the bagasse and face carpet fibers and testing the flame retardant property of particleboard sample.

5-6. Reference

- [1] Federico Carosio, Galina Laufer, Jenny Alongi, Giovanni Camino, Jaime C. Grunlan, Layer-by-layer of silica-based flame retardant thin film on PET fabric, *Polymer Degradation and Stability*, 96(2011), 745-750
- [2] https://en.wikipedia.org/wiki/Flame_retardant
- [3] Hylton J.G. Haynes, NFPA's "Fire Loss in the United States during 2015", Sep 2016
- [4] Hidenori Matsukami, Tomohiro Kose, Mafumi Watanabe, Hidetaka Takigami, Pilot-scale incineration of wastes with high content of chlorinated and non-halogenated organophosphorus flame retardants used as alternatives for PBDEs, *Science of the Total Environment*, 493(2014), 672-681
- [5] Chih Pong Chang, Szu Chia Hung, Manufacture of flame retardant foaming board from waste papers reinforced with phenol-formaldehyde resin, *Bioresource Technology*, 86(2003), 201-202
- [6] Arturo J. Mateos, Amanda A. Cain, Jaime C. Grunlan, Large-Scale Continuous Immersion System for Layer-by-Layer Deposition of Flame Retardant and Conductive Nanocoatings on Fabric, *Industrial & Engineering Chemistry Research*, 53(2014), 6409-6416
- [7] Marcus Leistner, Anas A. Abu-Odeh, Sarah C. Rohmer, Jaime C. Grunlan, water-based chitosan/melamine polyphosphate multilayer nanocoating that extinguishes fire on polyester-cotton fabric, *Carbohydrate Polymers*, 130(2015), 227-232

Chapter 6. Sound dampening of particle board

6-1. Introduction

Noise is an irritant in people's daily lives and sound pollution has been listed as harmful to human beings. There are four common technologies for noise control. They are sound insulation, sound adsorption, vibration dampening and vibration isolation.

Sound insulation prevents the transmission of noise by the introduction of a mass barrier.

Common materials have high-density properties such as brick, thick glass, concrete, metal etc.

Sound absorption: a porous material which acts as a 'noise sponge' by converting the sound energy into heat within the material. Common sound absorption materials include decoupled lead-based tiles, open cell foams and fiberglass

Vibration damping: applicable for large vibrating surfaces. The damping mechanism works by extracting the vibration energy from the thin sheet and dissipating it as heat. A common material is sound deadened steel.

Vibration isolation means preventing transmission of vibration energy from a source to a receiver by introducing a flexible element or a physical break, such as rubber. Common vibration isolators are springs, rubber mounts, cork etc.

Most particleboard is made for construction and furniture use. The sound dampening properties of particleboards should be considered because its effect on the acoustic behavior in the spaces where it is used is important to the living experience of the occupants.

6-2. Sound dampening test equipment

To perform preliminary tests of the sound dampening performance of the boards produced in this project, a sound dampening test rig was constructed. The sound dampening test equipment consists of some PVC parts, rubber pads, metal bolts, plastic frames, one speaker and one microphone. All the PVC parts were purchased from www.pvcfittingsonline.com and the speaker and microphone were purchased from www.amazon.com. The sound dampening test equipment is shown in Fig 6-1.



Figure 6-1. Photo of sound dampening test equipment in Uconn lab

5 feet of PVC pipe of 6 inches inside diameter was cut into 2.5 feet pieces for each side. PVC slip flanges and male threaded adapters were installed on the ends of each piece of the cut pipe. A 3D printed plastic frame to support the speaker was set at the end of one of the pipes near the

male threaded adapter end. A 3D printed plastic frame to support the microphone in the other pipe was also set at the end of the pipe near the male threaded adapter side. One female PVC cap with a drilled one-centimeter diameter hole in the center allowed wire to the microphone. The rubber pads were set between the slip flange and test samples. The metal bolts are used for fastening the test sample. The schematic view of the sound dampening test equipment is shown in Fig 6-2. The green rectangle in the middle is the test sample.

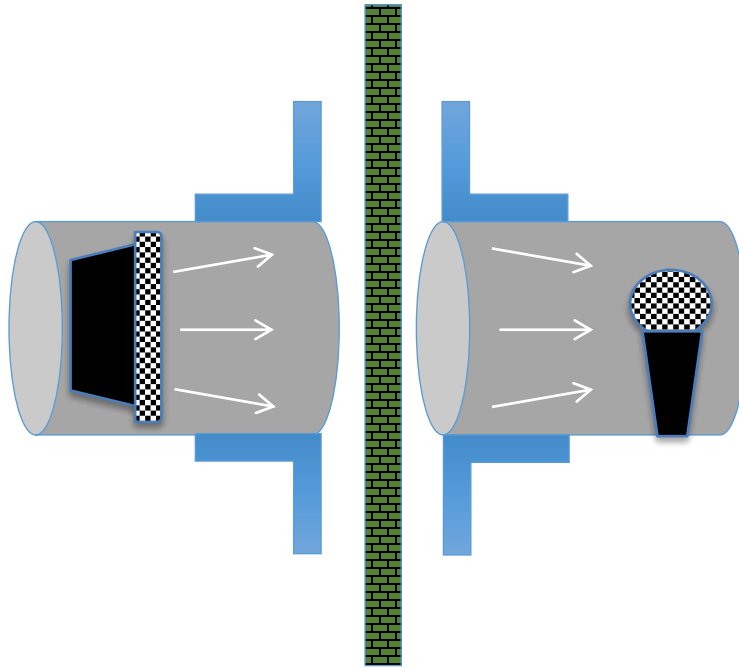


Figure 6-2. Model of sound dampening test equipment

6-3. Sound dampening test

The video called The Human Hearing Range, was downloaded from https://www.youtube.com/watch?v=yKhT6_sPU0Y&t=54s, and played in the speaker. The software operated is Visual Analyser 64 downloaded from the website Sillanum Software website. The control test is operated without any test board sample between the speaker and microphone pipes. In all the sound tests, we selected six specific frequencies (100Hz, Middle C 261.626Hz, 500Hz, 1000Hz, 2000Hz and 3000Hz) at which to record data. The sound intensity at those frequencies was captured with the VA64 software. Data at each frequency was captured three times and the control and board tests were repeated alternately three times. Therefore, for each test, 9 sound dampening values were acquired. The average of the control and board tests were calculated, and the dampening data were obtained as the difference between the average value of the control and the average of the board test taken at the same frequency.

6-4. Results

6-4-1. Sound dampening test for $\frac{3}{4}$ inch thick panels

The $\frac{3}{4}$ inch thick particleboard panels manufactured at the UMaine were used for sound dampening tests. They are compared with an M-2 grade commercial board sold in the Home Depot market. The panel of the commercial board is about $\frac{5}{8}$ inch in thickness. The 3 quarters inch particleboard panels designated numbers 2, 4 and 9 in Ch.3 were selected and tested. The recipe of board number 2 is 95% bagasse and 5% pMDI. The recipe of board number 4 is 75% bagasse, 20% waste carpet and 5% pMDI. The recipe of board number 9 is three layers with 75% bagasse, 20% waste carpet and 5% pMDI, where the surface layers are made with bagasse and

pMDI only. The test results are shown in Fig 6-3, the vertical axis is the sound dampening of the board relative to the control.

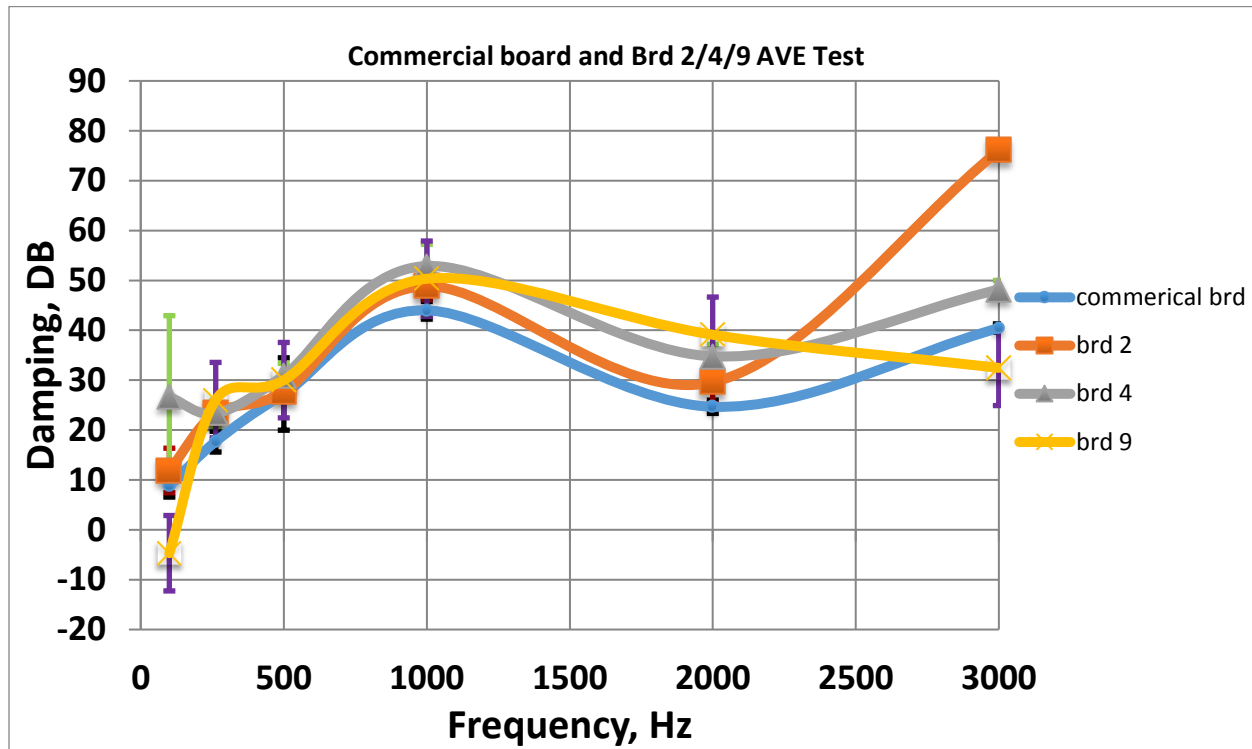


Figure 6-3. Sound dampening property for commercial board and 3 quarters inch particle boards manufactured in UMaine

6-4-2. Sound dampening tests for lab particleboard

Some of the particleboard samples noted in Chapters 3 and 4 were also tested for sound dampening properties. The samples selected are the recipe with 75% bagasse, 20% face carpet and 5% pMDI and the recipe with 47.5% bagasse, 47.5% face carpet and 5% pMDI. They are compressed under 14000lb force, 10000lb force and 8000lb force to get various density and thickness. The sound dampening results of 75% bagasse, 20% face carpet and 5% pMDI with different compression force are shown in Fig 6-4. The sound dampening results of 47.5%

bagasse, 47.5% face carpet and 5% pMDI with different compression force are shown in Fig 6-5. All the six boards were compressed at 160 C for 20 minutes. Their Density and thickness are shown in Table 6-1.

Table 6-1. Density and thickness of particle board in different compression force

	75% bagasse, 20% face carpet and 5% pMDI		47.5% bagasse, 47.5% face carpet and 5% pMDI	
Compression force (lb)	Thickness (mm)	Density (lb/ft ³)	Thickness (mm)	Density (lb/ft ³)
14000	5.53	47.08	4.24	58.33
10000	5.64	41.5	4.98	48.9
8000	6.12	39.69	6.17	39.36

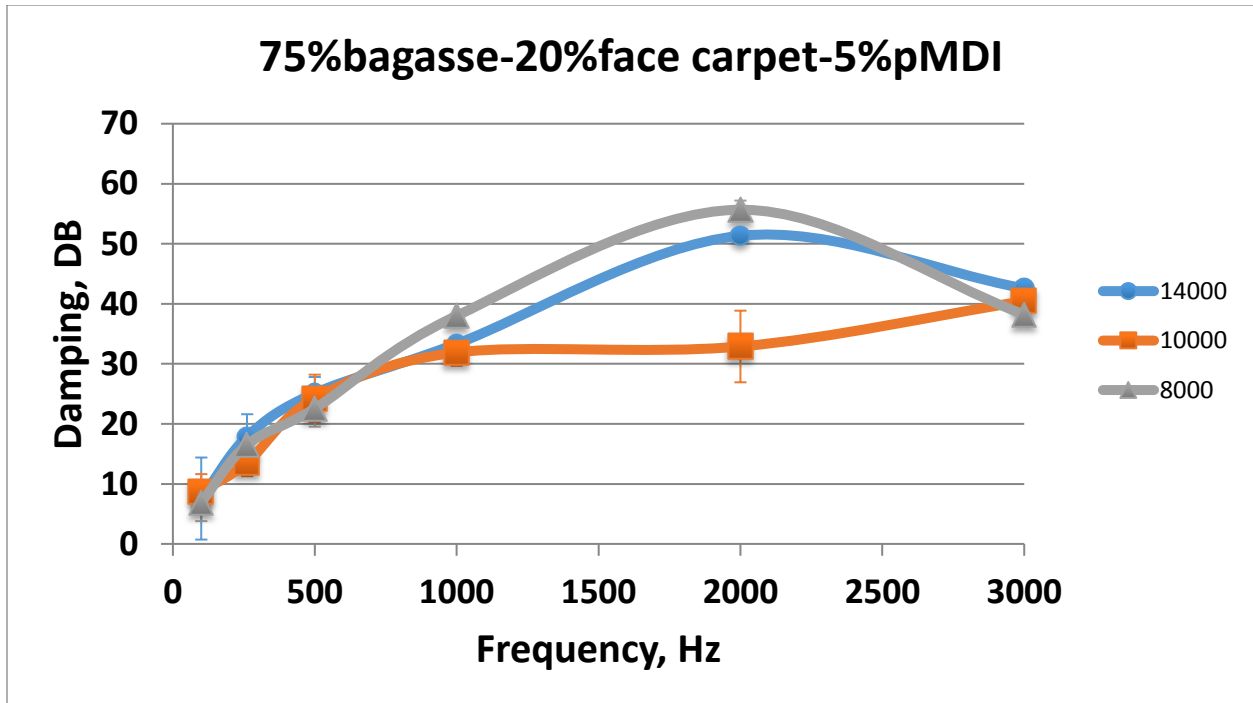


Figure 6-4. Sound dampening data for 75% bagasse-20% face carpet-5% pMDI in different compression force

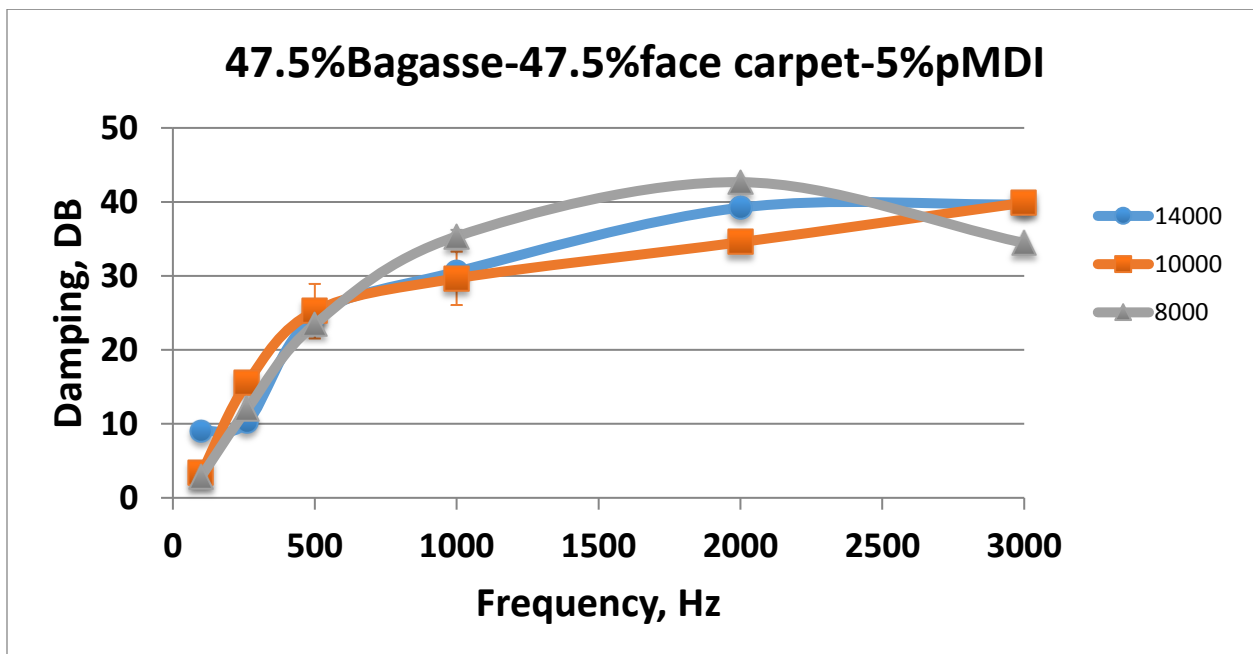


Figure 6-5. Sound dampening data for 47.5% bagasse-47.5% face carpet-5% pMDI in different compression force

6-5. Discussion and Conclusion

6-5-1. three quarters inch particle board

From Fig 6-3, the shape of sound dampening with different recipes are similar. In 100Hz, board 4 shows the best dampening property, it reduces around 21.5dB. Board 2 and commercial board show the similar dampening property, they reduces around 13dB. Board 9 have a bad dampening property, it increases the sound by 5dB. In middle C, 500Hz, 1000Hz and 2000Hz, board 2, 4, 9 show better sound dampening property than the commercial board. In Middle C, 500Hz and 2000Hz, board 9 show the best sound dampening property among these four board. In 1000Hz, board 4 show the best sound dampening property and board 2 shows the best sound dampening property in 3000Hz. But in 3000Hz, board 9 have a lower sound dampening property compared to the commercial board. Compared their standard deviations, commercial board has a smaller standard deviation than other three particle boards. That maybe because the material in commercial board was separated more even than the particle boards we made in UMaine.

6-5-2. lab particle board

From Fig 6-4 & 6-5, the shapes of sound dampening with different compression force are similar. The Fig 6-4 shows sound dampening data of 75% bagasse, 20% face carpet and 5% pMDI board in different pressure. In Middle C, 500Hz, 1000Hz and 3000Hz, compression lab sample board compressed by 14000lb force shows the best sound dampening property. In

1000Hz and 2000Hz, lab sample board compressed by 8000lb force shows the best sound dampening property. In 100Hz, lab sample board compressed by 10000lb force shows the best sound dampening property.

The Fig 6-5 shows sound dampening data of 47.5% bagasse, 47.5% face carpet and 5% pMDI board in different pressure. In Middle C, 500Hz and 3000Hz, the lab sample board compressed by 10000lb force shows the best sound dampening property. In 1000Hz and 2000Hz, the lab sample board compressed by 8000lb force shows the best sound dampening property. In 100Hz, the lab sample board compressed by 14000lb force shows the best sound dampening property.

6-5-3. Sound dampening compared between bagasse and carpet

From the Table 6-1, the boards with two different recipe compressed under 8000lb force have the almost same density and thickness. The rate between bagasse and face carpet is the only distinction, and the sound dampening property of bagasse and face carpet could be compared in this case. We picked the data of boards under 8000lb force in Figure 6-4&5, and combined in Figure 6-6. Only in 500Hz, the board with 47.5% bagasse, 47.5% face carpet and 5% pMDI has a better sound dampening property than the board with 75% bagasse, 20% face carpet and 5%pMDI. In other frequencies, the board with more bagasse shows a better sound dampening property especially in 2000Hz.

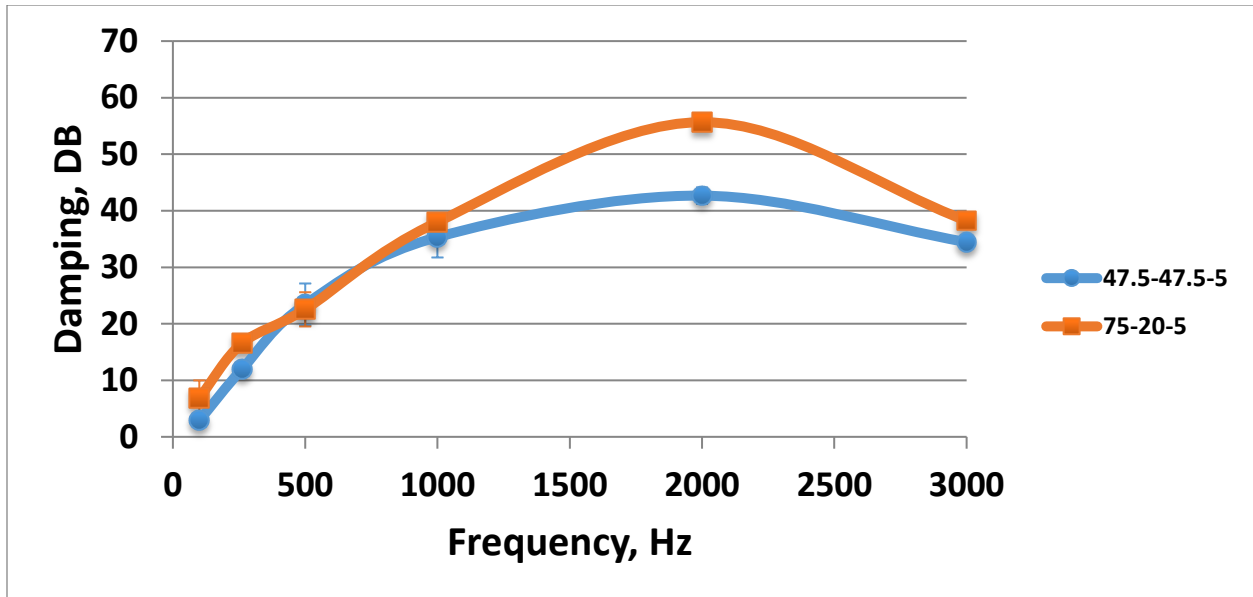


Figure 6-6. Sound dampening property of the boards with 47.5% bagasse-47.5% face carpet-5% pMDI and 75% bagasse-20% face carpet-5% pMDI under 8000lb force

Chapter 7. Future Work

7-1. The recipe of flame retardant board

In chapter 5, all the flame retardant coating boards we manufactured fail to reach the ANSI-M2 and ANSI-H2. Therefore, the recipe of both coating and the compressed boards must be fixed in order to reach the grade of ANSI-M2 and ANSI-H2. And the density of most flame retardant coating boards are in high density, but balancing their cost and property, the market prefer the particleboards in medium density.

Therefore, the future work should focus on how to make the compressed particleboard with flame retardant coating in medium density. The flame retardant recipe and the compression board recipe should be considered and tried for approaching to the final goal.

7-2. Sound dampening

In chapter 6, our project test some sound dampening property of the particleboard. Because the thickness and density of particleboard are hard to control by the compression pressure, the limited factors are hard to set in the same level for comparing.

The future work should be set the two boards in all the similar conditions expect for their density. From the sound dampening data, we can draw the conclusion of the relationship between the density and sound dampening. And also, keep the thickness of the particleboard different with other same conditions, the relationship between the thickness and sound dampening could be test. With the same method, we can also tell the better sound dampening property of face carpet or the bagasse fiber.

7-3. Eco-friendly binder

The binder we used in this project is pMDI, which we purchased from Huntsman Chemical Co.

The cost of pMDI is very high and the pMDI is harmful for the environment. In the future work, it is better if we can find or synthesis some chemical binder which has the similar property as the pMDI and is eco-friendly for the environment.

In our group, some graduated students considered to use wheat gluten (WG) as the binder.

Compared to pMDI resin, WG is less expensive and completely biodegradable, which results in fewer environmental problems. Although WG suffers from inferior performance resulting in less adhesion, instability, and high water absorption, the WG/copolymer blends have more reactive functionalities and less water absorption, therefore, better adhesion and less expansion would be expected. The more stable interfacial properties would generate a fiberboard with better performance.