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Session 1.1 Sustainable Construction Materials – Innovations and New Product Developments

Wood Based Construction Material Development in Hungary; Past and New Advancements

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Sustainable construction materials are fast becoming increasingly important in Hungary. As a Central European nation with a rich tradition of silicates-based construction, historically, wood-based construction was always secondary in this country. Nevertheless, Hungarian researchers have been working on developing wood-based construction materials using the relatively scarce and low quality local hardwood resources, since the 1960's. Recent construction material shortages reinvigorated interest in these materials. The objectives of the ERDOLAB (Forest Lab) research project include the development of new, economically viable and highly value-added construction materials. The presentation aims to review historical achievements briefly, and overview the newest efforts aimed at developing various new construction materials based on underutilized Hungarian wood species.

Wood Based Construction Material Development in Hungary; Past and New Advancements

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INTRODUCTION

Historical fears of wood shortages starting from the 15th century [1], as well as the negative perception of wood construction as inferior to brick- and stonemasonry, particularly in terms of fire performance, led to an increasing emphasis on silicates-based construction in Europe. Recent studies [2, 3] show that there is still a predominance of concrete and masonry in most European countries and regions. The same is especially true for Hungary, where stringent fire regulations [4] exclude or severely restrict the use of flammable materials, including wood, in multi-story buildings.

The increasing emphasis on sustainability highlighted the importance of the building sector, as one of the most significant polluters and natural resource consumers in the EU [5]. This gave rise to a multitude of research projects to find low environmental impact construction materials. In most of these studies, wood and wood-based materials emerged as strong contenders, due to their carbon storage potential, lower production and transportation emissions and recyclability, among other factors [6]. Researchers caution that these results vary based on geographical, temporal, and technological factors, as well as differences in the LCA or carbon footprint analysis methodology used [7,8]. Nevertheless, there seems to be a wide consensus that wood construction is an environment friendly alternative to silicate-based construction and may play an important role in solving our sustainability challenges [9].

The Hungarian forest and wood sector is in a special situation in that 85 % of its forests is high density hardwood [10], and of the remaining 15 %, most softwoods are of inferior quality. This has an additional discouraging effect in terms of wood-based construction. Nevertheless, over the past half a century, Hungarian researchers made considerable efforts to investigate the physical and mechanical characteristics, establish stress grading rules and find innovative uses for Hungarian raw materials in the construction industry. Unfortunately, success has been limited to a few demonstrative projects; Hungary is yet to achieve widespread utilization of its raw material base in this area.

Hardwood materials are generally less ideally suited to use as construction material, due to their growth characteristics, higher natural variability, and less researched technical characteristics. Wood based construction materials offer opportunities to extend their utility through value-added utilization as glued structural materials (e.g., glued-laminated or cross-laminated timber) or in wood-based structural composites (like Oriented Strand Board or Laminated Veneer Lumber). The strive for increased sustainability as well as recent inflationary trends and the related volatility in construction material prices led to renewed interest in the utilization of Hungarian hardwood raw materials as construction lumber and engineered wood products.

The aim of this study is to review past efforts to develop structural wood based materials from Hungarian hardwood resources, review the challenges and opportunities that Hungarian researchers face while trying to re-invigorate the research and innovation in this area, and introduce the newest efforts directed at developing innovative wood based structural materials from underutilized Hungarian hardwood resources. We will consider load-bearing applications only; other construction uses like flooring and paneling, insulation materials, etc. will not be included in this article.

A REVIEW OF PAST EFFORTS

In this chapter we would like to introduce past research efforts directed at developing various wood based construction materials using Hungarian hardwood species. This includes glued-laminated and cross-laminated timber, organic bonded structural wood composites, and inorganic bonded composites.

Glued-Laminated Timber

Structural glued-laminated timber (GLT) is one of the oldest engineered wood products. Even though nearly any species can be used to produce GLT, SPF lumber is most commonly used both in North-America and in Europe [11]. GLT research first started in Hungary in the early 1970s, using hybrid poplar (*Populus × euramericana*) materials [12]. Even though poplar wood is generally considered inferior to softwoods, hybrid poplars may be comparable to softwoods in terms of density and mechanical characteristics, depending on the variety [13]. The Robusta clone, in particular, but also Marilandica and Serotina hybrids showed promise, not only because they fulfilled the strength and density criteria, but because of their availability in the necessary quantities and in adequate lengths and cross sectional dimensions [14].

Based on the successful experiments, the first poplar glulam building was commissioned by the National Technical Development Committee. The curved beams of the 800 m² multifunctional hall were manufactured from the Robusta hybrid (*Populus × euramericana* cv. “Robusta”) at the Wood Research Institute in Budapest [15]. The height and span of the three-hinged structure were 18 m and 7.5 m, respectively (Fig. 1). The hall has been in commission for nearly 50 years, and based on recent visits it is in an excellent condition; no signs of deterioration.



Figure 1 – Multifunctional hall built using curved poplar GLT beams in *** Hungary.

Researchers later also considered high density hardwoods, but had various technical difficulties, mostly stemming from adhesion problems. Black locust (*Robinia pseudoacacia*) material, in particular, was very hard to glue using traditional (formaldehyde based) structural adhesives, and the full load-bearing potential of the material could not be exploited. Nevertheless, several smaller and larger structures have been erected [16].

More recently, Hungarian researchers examined the pressure treatment possibilities of the I-214 hybrid poplar (*Populus × euramericana* cv. I-214) GLT [17]. Both individual lamellas and glulam sections were pressure treated with a copper sulphate solution, and the preservative uptake measured. The authors established that the presence of glue did not impact the preservative uptake and recommended that impregnation should be performed after bonding.

Cross-Laminated Timber

Cross-Laminated Timber (CLT) is a relatively new engineered structural product, developed in Germany in the late 20th century. The product concept was developed in the 1970s and 1980s; after this it took around 20 years until the first technical approvals were given in 1998 [18]. The new product (almost exclusively manufactured from softwood materials) went through exponential growth in the 2000's and 2010s and is now extremely popular for fast erection of ecological and lightweight buildings worldwide. Austria and Germany are still the main producers of the material, but production facilities, as well as tall CLT buildings sprung up all around the world.

Austrian and German softwood raw materials are eminently suited for CLT production. However, at the current rate of production, the amount of available raw material may soon limit production capacity, and producers may turn to alternative raw materials like hybrid poplar. The first experiments to develop CLT made of Hungarian raw materials were conducted in the early 2010s [19]. A single 10 cm thick panel was produced using I-214 (*Populus × euramericana* cv. I-214) hybrid poplar lamellas. Poplar lamellas were stress graded prior to assembling them into a three-layer cross-laminated structure, using structural grade polyurethane adhesive. 4-point bending tests of the product (see Fig. 2) revealed that the MOR of the panels was comparable to, albeit somewhat lower than those of softwood CLT, but the MOE values fell short of expectations. Recommendations for further experiments included using larger sample sizes and combining poplar lamellas with softwood and high density hardwood lamellas.

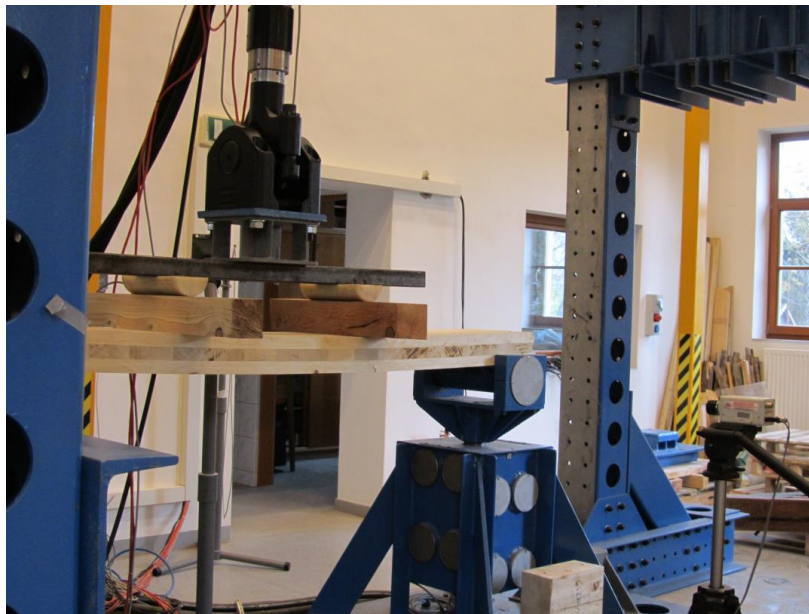


Figure 2 – 3-layer CLT panels being tested in 4-point bending

Structural composites

Traditional composite panel manufacturing and research has a long tradition in Hungary. However, until 2016, there was no structural composite production in the country. On the other hand, there have been several research projects, focusing primarily on Laminated Veneer Lumber development.

Laminated Veneer Lumber was first developed in the US in the 1940s to produce high-strength aircraft components, and later, construction components. It was also introduced in Europe by the KERTO[®] company in Finland (today part of the Metsä Wood concern), primarily based on softwood materials. The first internationally published research in hardwood LVL development was published in 2004 by Turkish researchers [20], and commercial production of beech (*Fagus sylvatica* L.) LVL started by the Company Pollmeier in Germany in 2013. Today, high strength BauBuche beech LVL is a very successful product used in many construction projects in Europe.

Hungarian researchers have also shown much interest in developing LVL from hardwood materials. The first investigations, which involved poplar, oak, and alder structural veneers, started back in the 1990s, but results have not been published for the wider public [21]. Later, a doctoral dissertation reported on laboratory and industrial experiments to develop practically viable poplar LVL, using I-214 and Marilandica hybrid poplar veneers. All design values exceeded those of KERTO-S spruce LVL, but MOE values were typically somewhat lower than the 5% percentile quoted for KERTO-S (but higher than those of KERTO-T, a lower strength product recommended to be used as wall studs.) Laboratory experiments also included mixed panels incorporating beech and turkey oak veneers that had even higher strength and stiffness values [22]. Later, Vilpponen et al. [23] found similar results using the same species and an additional combination using tree-of-heaven (*Ailanthus altissima*) veneers. Unfortunately, encouraging experimental results did not lead to industrial adoption in Hungary or anywhere else in Europe.

Up to date, there has been no significant research to develop any other engineered wood based composites using Hungarian raw materials. This seems like a missed opportunity to create high value-added construction products from underutilized Hungarian raw materials. On the other hand, in 2016 a new OSB plant was established by the Swiss-Krono concern in Eastern-Hungary that produces OSB mostly using poplar raw materials from Hungary and neighboring countries.

Inorganic bonded structural materials

Inorganic bonded materials have a heightened importance in Hungary. Due to their increased fire resistance, they can be used as inflammable and relatively lightweight load bearing elements or fire barriers when used as sheathing. This is one way to promote wood based construction in spite of stringent fire regulations.

One highly successful product is cement-bonded particleboard, whose production started in Hungary in 1977, as the second such facility in the world. The product was not developed in Hungary, but there was much research into various aspects of the production. This included using carbon-dioxide to accelerate the curing process [24], using poplar chips to replace Scots pine [25], and using various nanomaterials to improve the fire resistance and wood-cement interface bonding [26, 27], among others.

Another interesting experiment aimed at creating inorganic bonded engineered composite beams similar to PSL and LSL [28]. Several beams were created using Scots pine (*Pinus sylvestris*) strands and I-214 hybrid poplar veneer strips with a Portland cement matrix (Fig. 3). Unfortunately, the bonding strength was insufficient to create beams with satisfactory load-bearing capacities. Later experiments to create higher strength beams using LbL nanocoating on the fibre stock (unpublished) brought only marginal improvement.

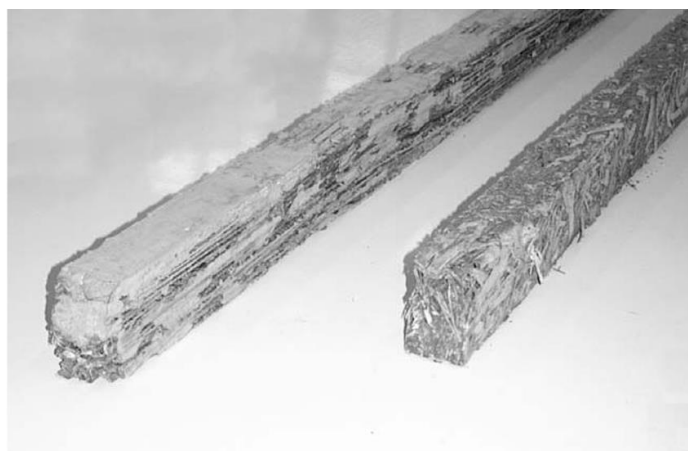


Figure 3 – LSL (left) and PSL (right) type experimental cement bonded beams.

NEW CHALLENGES AND OPPORTUNITIES

Recent geopolitical and economic developments, as well as the results of the latest climate modelling studies reinvigorated the interest in using Hungarian forest resources in the construction sector. This renewed interest offers both challenges and opportunities when it comes to developing of wood based construction materials.

Changes and challenges due to climate change and silvicultural practices

As mentioned before, Hungarian forests are predominantly deciduous, with a wide variety of temperate hardwood species ranging from high density species like oak and black locust, through beech, hornbeam, and alder, to lightweight broadleaved trees like poplar and willow, just to name a few. In the 20th century, the Hungarian forest products industry was first dominated mostly by beech and oak wood. Later, large scale plantation programs introduced considerable quantities of fast-growing and lightweight hybrid poplar, while black locust became popular, mostly for its outstanding natural durability [29].

The gradual transformation of the country's climate is causing monumental changes in the site conditions, and consequently in the species composition in Hungarian forests. Much of the country has already transitioned to the forest steppe category, and, according to some models, 60 % of the country will belong to a new, much warmer and dryer steppe climate class by 2070 [30]. This will, in turn, fundamentally change the raw material base, namely:

- Currently abundant beech material is projected to become increasingly scarce;
- Most of the high quality oak species (like sessile and pendunculate oak) will also lose ground, taken over by inferior quality species like Turkey oak (*Quercus cerris*) and hornbeam (*Carpinus betulus*);
- Black locust (*Robinia pseudoacacia*) will become even more important, and researchers are working on selecting and creating more heat and drought tolerant hybrids;
- The currently prevalent hybrid poplars will gradually become less ubiquitous, primarily due to forest managers replacing them with species considered higher value, like black locust, rather than climate change. On the other hand, there is a considerable domestic poplar stock, which is currently underutilized, due to inferior physical and mechanical properties compared to hybrid poplar.

The above examples show that the Hungarian forest products industry will have to adapt to major changes in the raw material supply. During the development of new applications for the construction industry, we should also consider current and future trends, rather than operating from outdated assumptions regarding the available raw material.

Market trends and raw material prices

In 2021, construction material prices in Hungary, like in other countries, exploded. Prices did not only increase two-to-threefold within the span of a single year, but also became volatile, to the point where contractors could not give exact quotes to customers, but rather made pricing contingent on raw material prices at the time of construction.

A report by the Hungarian Competition Authority [31] identified the causes of this extraordinary inflation and volatility. The main reason was increased international demand in the American and Chinese market, but there were other factors, like increased demand in the pandemic for hobby and renovation projects, as well as Hungarian government subsidies for residential construction. The report also emphasized the predominance of softwood construction material, almost exclusively from import sources, which made the Hungarian market especially vulnerable to international market trends.

The recommendations of the report point to existing research results regarding the potential of alternative hardwood resources. The report calls for further innovation and quick implementation in the area of wood-based construction materials made of Hungarian hardwood raw materials, to alleviate the vulnerability of the Hungarian construction sector to international market trends.

The ERDOLAB (Forest lab) research project, started in 2022 at the University of Sopron is part of this effort. The complex project covers all aspects of Hungarian hardwood production, from climate modeling and silviculture through environmental impacts, material properties, material science and consumer products, as well as market research and societal acceptance. Chapter 2.3 deals with wood based construction materials; the following chapter will introduce the main focus and preliminary results of this research.

CURRENT RESEARCH

The newest research efforts in developing engineered wood based products using Hungarian raw materials focuses on three main areas: CLT development, Oriented Strand Lumber (OSL) from poplar, and LVL development using high-density hardwoods. The first part of the research (which predates the ERDOLAB project) is nearing its conclusion, OSL experiments are currently underway, and LVL development is in the preparation stage. All three will be briefly introduced in this chapter.

CLT made of Hungarian hardwood

Based on recommendations from the earlier project [19], a more comprehensive CLT project was designed and implemented, involving several species. A detailed report on the experiments and their results is soon to be published; this chapter contains a brief and non-exhaustive report on the investigation.

Six panels were created using various combinations of spruce, beech and poplar lamellas, as outlined in Table 1, using structural polyurethane adhesives. Lamellas were pre-graded using the PLG+ lumber sorter developed at the University of West Hungary [32] (longitudinal lamella grades reached or exceeded C24 for spruce and poplar and D40 for beech in almost all cases, according to MSZ EN 338:2016 [33]). Due to the limitations of the available testing machine, lamella thickness was limited to 15 mm and panel dimensions were 1000 x 600 x 45 mm. Fig. 4 shows the lamination process and the completed panels.

Table 1 – Species combinations used in the CLT experiments

	Orientation	BBB	BPB	SPS	SSS	BSB	PPP
Top layer	Longitudinal	Beech	Beech	Spruce	Spruce	Beech	Poplar
Middle layer	Crossband	Beech	Poplar	Poplar	Spruce	Spruce	Poplar
Bottom layer	Longitudinal	Beech	Beech	Spruce	Spruce	Beech	Poplar



Figure 4 – CLT manufacturing and testing

Each panel yielded 10 specimens (two specimens from each top layer lamella). A total of 60 CLT specimens were tested in 4-point bending according to MSZ EN 408_2010+A1_2012 (global bending MOE method, [34]), following standard specifications in terms of testing parameters. After the completion of the test, the failure mode of the specimens was also documented. Most specimens exhibited a combination of several failure modes, all of which was recorded, starting with the most dominant one. Moisture content and density specimens were cut from the end of each specimen, measured for dimensions and weight, and dried at 103 ± 2 °C to determine the MC and density.

Fig. 5. shows the MOR values of the various combinations. All strength values exceeded the stated design stress for most commercially available CLT panels, and this is mostly true in terms of MOE as well (trends are similar for MOE to those shown in Fig. 5, but differences are less pronounced). Of all tested combinations, the spruce panel performed most poorly. Spruce lamellas also limited the performance of combined spruce-poplar and spruce-beech panels. (Notably, although spruce planks came certified C24, after repeated sorting, many pieces were downgraded, and in some panels, C22 material had to be used in the top layer. Spruce specimens also had significantly lower density compared to poplar.) The poplar panel had considerably higher strength and stiffness than those of spruce, although it was weaker than the beech panels, as expected. Also, replacing the center lamella in beech panels with poplar did not significantly decrease its strength or stiffness.

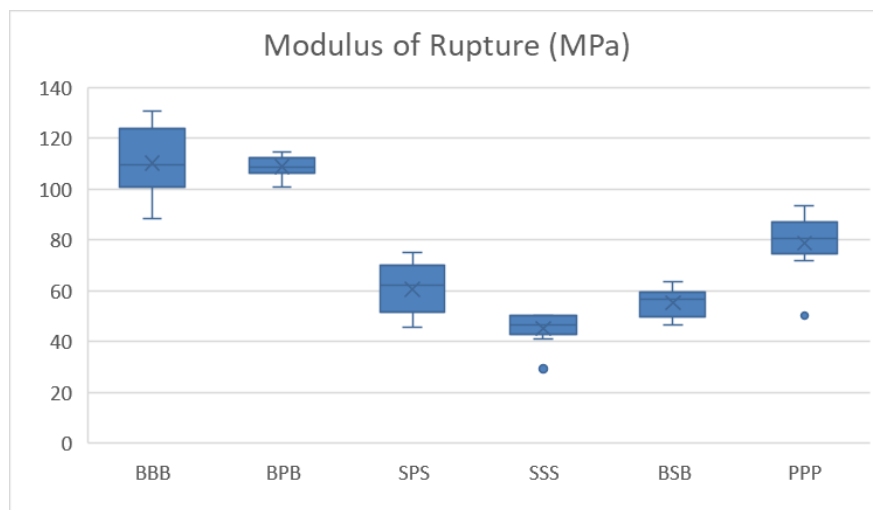


Figure 5 – Bending Strength values of CLT panels made using various species combinations (for the combinations see Table 1)

The above results show that, contrary to earlier experimental results (where the top layer stress grade was not optimized), poplar has good potential as CLT raw material. Unfortunately, CLT production also requires relatively large cross section, high quality poplar, which means that only a fraction of the raw material can be used for this purpose. There is also stiff competition for good quality, large poplar logs for plywood manufacturing and, lately, as pencil raw material. While using Hungarian poplar as CLT raw material is therefore theoretically possible, the Hungarian raw material base is unlikely to support large scale industrial CLT production.

Poplar OSL experiments

Oriented Strand Lumber is an extension of the technology used to produce oriented strand board (OSB), except all strands are oriented longitudinally to create engineered composite lumber. A considerable advantage, compared to CLT, is that it is a much higher value added product, creating large dimension, high load-bearing capacity structural elements from relatively small size raw material. As such, this product offers an excellent opportunity for the value added utilization of the bulk of poplar material that are of insufficient quality to produce appropriate CLT lamellas.

The raw materials for the OSL experiments is provided by the Hungarian OSB producer Swiss Krono Ltd. The same strands used in the top layer of commercial OSB is used for LSL production. In reality, this means that the strands are a mixture of various hybrid poplar varieties, domestic poplar with a small amount of scots pine strands added to the mix. On the one hand, this realistically simulates the raw material situation a future Hungarian OSL mill might

encounter. On the other, it would be of interest to create and compare homogeneous materials from the same poplar species / varieties, but at present, such pure raw material is challenging to obtain.

OSL experiments will consist of three stages:

1. Small scale laboratory production, using a 600 x 600 mm laboratory press to optimize production parameters. The effect of treating the strands with various nanomaterials and modifying agents will also be investigated in this phase.
2. Large scale beam production using a veneering press to produce beams of approx. 2 m in length. A limited number of panels will be produced based on the results of the small scale experiments.
3. Industrial trials at the Swiss Krono OSB plant. (The technology allows for trial runs, but not ideally suited for commercial production, which would require substantial modifications or investment in a new production line.)

The small scale OSL experiments started by investigating the effect of adhesive quantity, pressing time and pressure to optimize production parameters (see Fig. 6).



Figure 6 – Producing small OSL samples in the lab and the finished panel

LVL produced from high-density hardwood species

Based on the commercial success of the BauBuche product, high-density hardwoods have excellent potential as LVL raw material. Since in Hungary beech forests are expected to be phased out in the near future for climate change related reasons, we are concentrating on relatively low quality dense hardwoods like turkey oak and black locust to create strong and durable LVL with a high value added. Experiments are in preparation and are expected to start this year.

SUMMARY AND CONCLUSIONS

A review of past experiments in Hungary revealed many valuable results and learnings regarding the development of innovative engineered structural wood-based materials. Unfortunately, except for hardwood glulam, these efforts did not lead to the introduction of new construction materials in the Hungarian industry. Research efforts have been reinvigorated by recent market situations that exposed the vulnerability of the Hungarian construction industry to international market trends in wood and wood based material prices and availability, and underlined the importance of the domestic resources. When developing new engineered wood based composites, researchers should consider climate change induced changes in the availability of the raw materials as well. Taking all of these factors into consideration, the newest research efforts within the ERDOLAB project focus on developing high value added, practically feasible construction materials for the domestic market, based on underutilized hardwood resources available in Hungary.

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Session 1.3 Promoting Climate Smart Forestry through Forest Carbon and Sustainable Biomaterials

Does decreased forest harvest cause substitution of higher global warming products? An empirical study.

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Forests play an important role in climate change mitigation, but the question of how to manage forests for the greatest climate mitigation benefit remains uncertain. On one hand, standing forests remove CO₂ from the atmosphere. On the other hand, harvested forests provide a source of wood products, which generally have lower emissions associated with their production than concrete, metal or plastic alternatives. However, it is not well understood to what extent forest conservation will lead to substitution.

We analyzed changes in softwood lumber production, import, export, manufacturing, and substitution in the USA from 1988 to 1998; a period characterized by decreased forest harvests from public lands in the USA along with increased lumber prices and demand. To complete this study, we developed an analytical framework based on supply and demand but tracking volume of softwood lumber and its equivalents. We empirically quantified changes in eleven different aspects of the market in response to decreased harvest and increased demand. The results showed substitution of wood products by metal, concrete and plastic was less than 15%.

This research demonstrates the need for forest-based climate change mitigation strategies based on integrated global models that incorporate realistic estimates of substitution between wood products and alternatives, as well as other responses to shifts in wood products supply and/or demand. Given the uncertainty about potential substitution benefits of forest harvesting, we encourage people developing forest carbon strategies to implement a portfolio of options. We hope our study will stimulate further research in this area.

Session 2.1 Sustainable Construction Materials – Innovations and New Product Developments

Novel Methodologies to Expose the Impact of Mass Wood Walls on Building Energy Use, Peak Demand, and Thermal Comfort

Rob Pickett

Rob Pickett & Associates, LLC/International Mass Timber Alliance

For nearly a century, thermal energy demand calculations have been based on simplified models according to the technical potentials of the period. The first action took place in Germany and Austria in 1929, when the initial technical standards committee for heating was founded. The calculation methods initiated then, to a surprisingly significant extent, still apply today. In addition to the climate zones for German and Austrian locations, initial consensus established conductivity coefficients of building materials and heat transfer coefficients. In 1959, heat transfer coefficients and modern building materials were integrated. Ever since, at least for mass timber buildings, the coefficients for conductivity have been subject only to relatively insignificant innovative change. Steady-state hot box assessment methods have been used to assess mass timber buildings, generally ignoring thermodynamic characteristics, which have demonstrated significant advantages in mass timbers buildings in practice. Novel methodologies have been applied in the research performed at a US DOE national laboratory. The inclusion of the thermal comfort approach based on and in accordance with DIN 7730 and ASHRAE Standard 55 has demonstrated significant differences in the energy requirement assessments performed dynamically. The research results bring the assessment data much closer to the anticipated heating demand in practice. Thermal inertia, inner surface temperatures, thermal emissivity, solar gains, dynamic outer weather conditions, and thermal comfort characteristics are finally combined into a holistic assessment approach regarding thermodynamic relationships. These results can potentially be applied towards the contribution of energy-efficient mass timber buildings; and, moreover, to material-efficient mass timber buildings at the same time, while material efficiency is becoming ever more important.



Novel Methods to Assess Energy Efficiency in Mass Timber Buildings

Session 1.1- Sustainable Construction Materials - -
Innovations and New Product Developments

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Perpetuating mass timber building globally

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Diplom-Ingenieur (FH) Civil Engineering

Architecture, Engineering and Project Management,
Energy Research - Adapting to EU-legislature (PhD)



Primary goals

- ❖ Develop a method to quantify energy benefits of mass wood structures and optimize mass wood use for energy-efficient low-carbon buildings
 - ❑ Energy use
 - ❑ Peak demand
 - ❑ Thermal comfort
- ❖ Address climate dependency and measure impact on thermal comfort

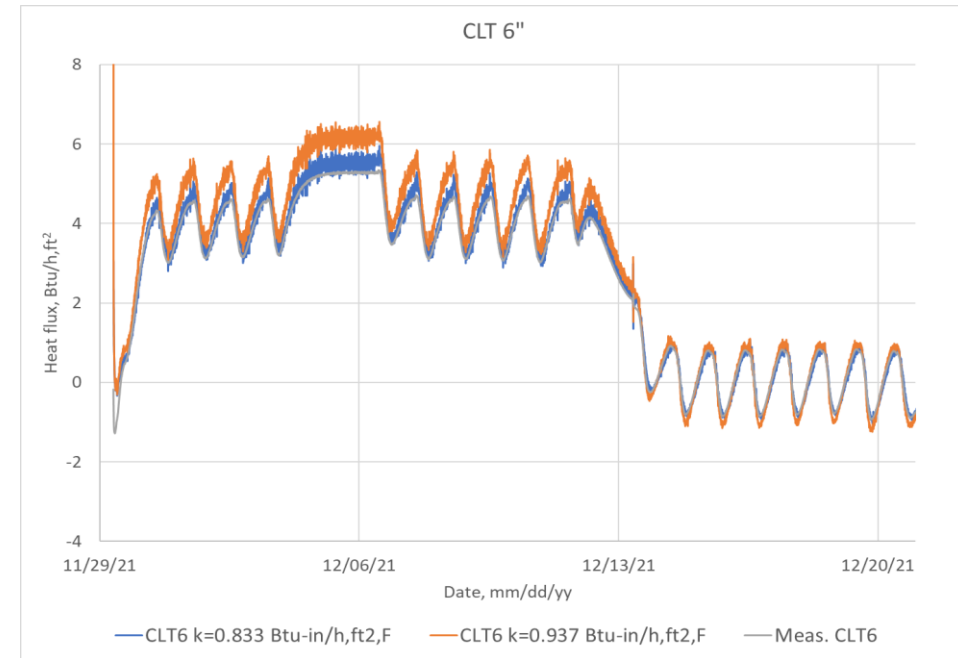
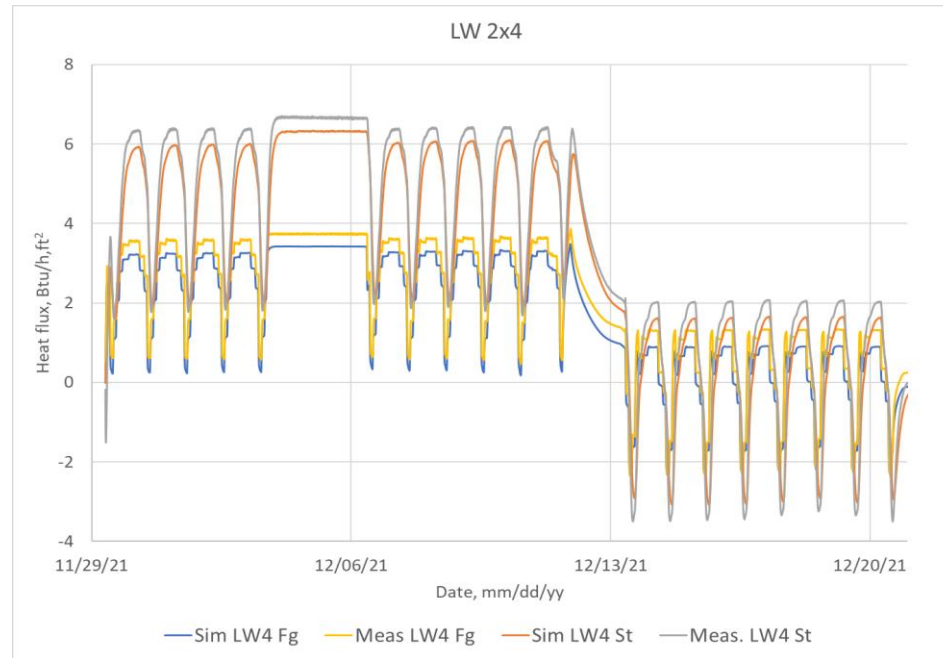


Phase I

Mass wood wall assemblies showed significant impact of thermal inertia as compared to lightweight walls.

- Annual energy savings up to 22%
- Peak demand was up to 50% lower with mass wood depending on the month and location
- Improved thermal comfort with thermal mass (up to 46% fewer uncomfortable hours)

Simulation model validation and development of whole building simulation



Wall	Description from indoors to outdoors
2×4 Lightweight	½ in. Gypsum board, R13 batts, studs at 16 in. on center (3.5 in. cavity), 7/16 in. OSB
2×6 Lightweight	½ in. Gypsum board, R23 batts, studs at 24 in. on center (5.5 in. cavity), 7/16 in. OSB
4 in. CLT	½ in. Gypsum board, 4 in. CLT
6 ¾ in. CLT	½ in. Gypsum board, 6 ¾ in. CLT

Phase I findings from interior surface temperatures - summer

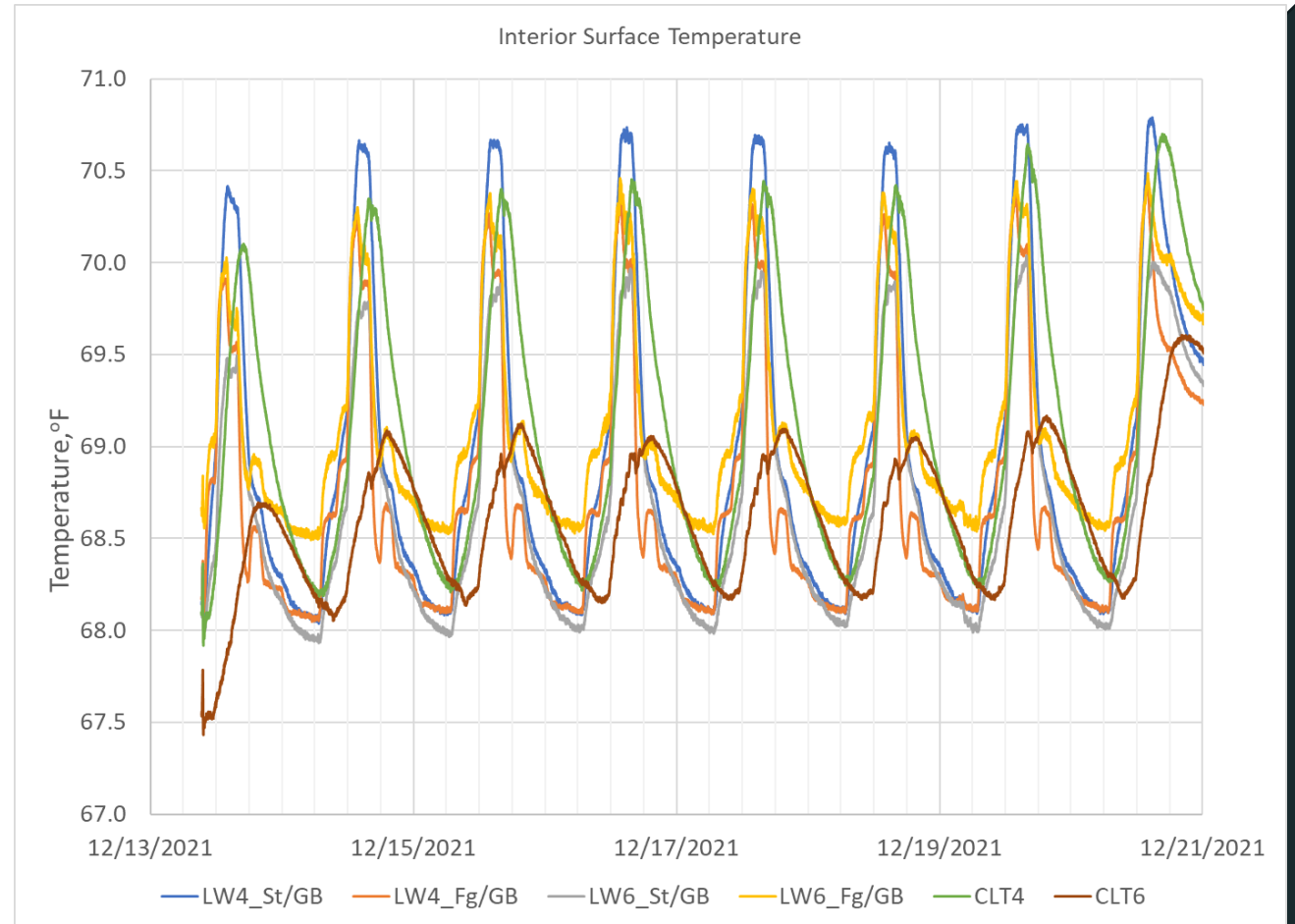
Dark brown line = CLT6

Dampening effect of mass timber.

- The surface temperature fluctuation in the 6" CLT wall (CLT6) is within 1°F, whereas the lightweight walls experience 2-2.5°F fluctuation.

- 4" CLT closer to lightweight walls in peak values except for delay.

Thickness of mass timber and its performance are not linearly dependent.



Phase I Analysis

Laboratory testing was carried out to validate energy modeling tool EnergyPlus, which was then used to model whole buildings to produce the energy savings:

- Building with mass timber walls with 55% higher U-value has 40% lower cooling demand, and 50% lower heat gain through walls than with 2x4 lightweight walls (LW).
- Building with mass timber walls with 55% higher U-value has 28% lower cooling demand, and 38% lower heat gain through walls than with the 2x6 lightweight walls (LW).
- Building with mass timber walls with exterior continuous insulation (MT-wCI) with the same U-value has 20% lower cooling demand, and 32% lower heat gain through walls than with the lightweight walls (LW).



A photograph of a laboratory testing facility. The ceiling is densely packed with numerous black, cone-shaped light fixtures. Below, several large, white, rectangular test cubes are arranged on a wooden floor. Wires and cables are visible on the floor and draped over the cubes. A dark blue rectangular box with the text 'Phase IIa' is overlaid on the left side of the image.

Phase IIa

Laboratory testing in Large-Scale Climate Simulator

Test four cubes, 1m x 1m x 1m

- 4" CLT, 7" CLT

Note that mass wood cubes have a much higher U-value than the framed walls of similar thickness.

- 2x4 R13, 2x6 R19

Simulate weather for Golden, CO

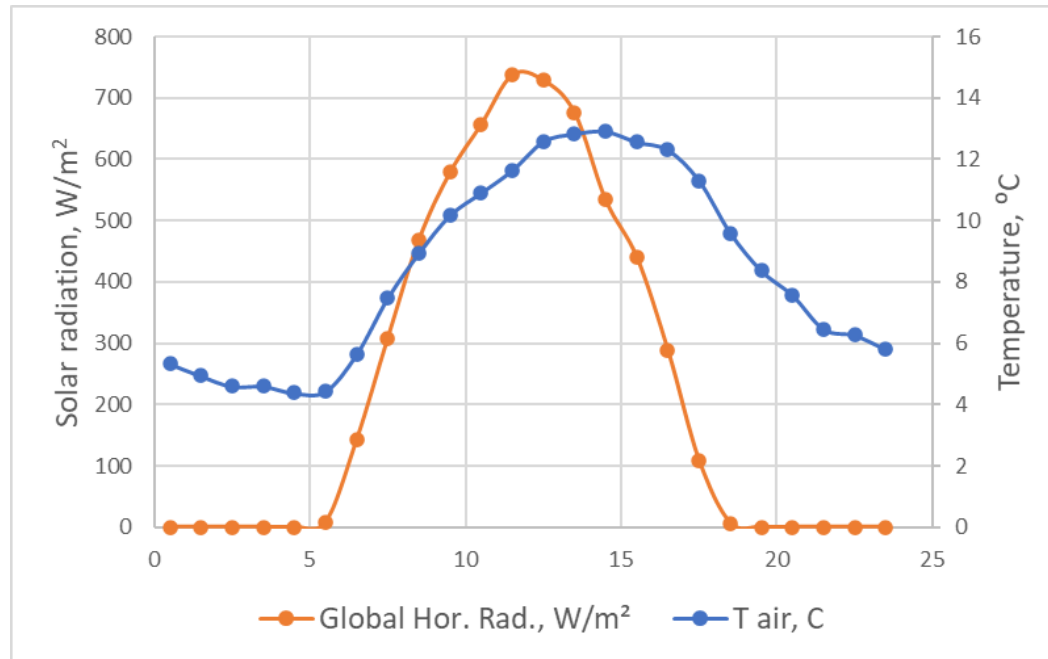
Control for heating

- Radiative vs. convective heating
- Control for fixed temperature range vs. thermal comfort

Simulate weather: Golden, CO

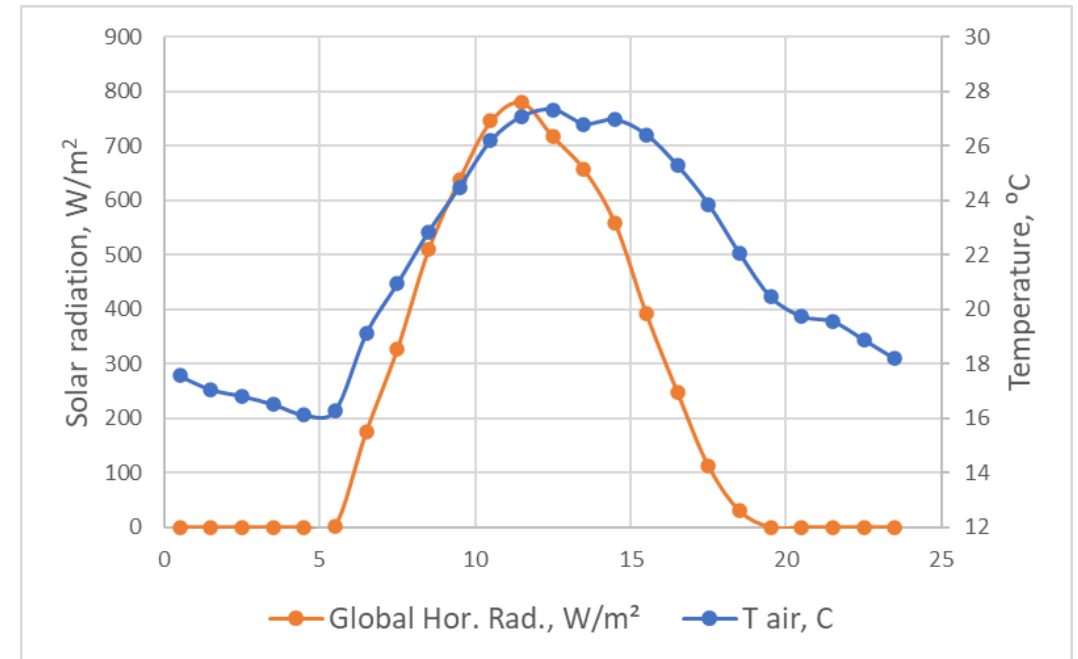
Exterior surface constants & weather conditions

Solar absorption = 0.5, Emissivity = 0.9. Wall edges: 1.1 m.



February

Golden, CO

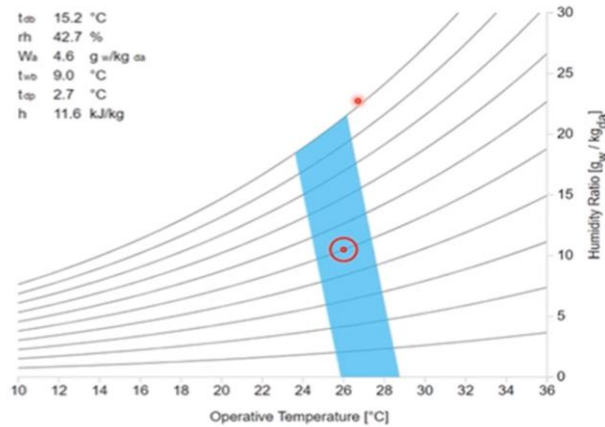


August

Thermal Comfort

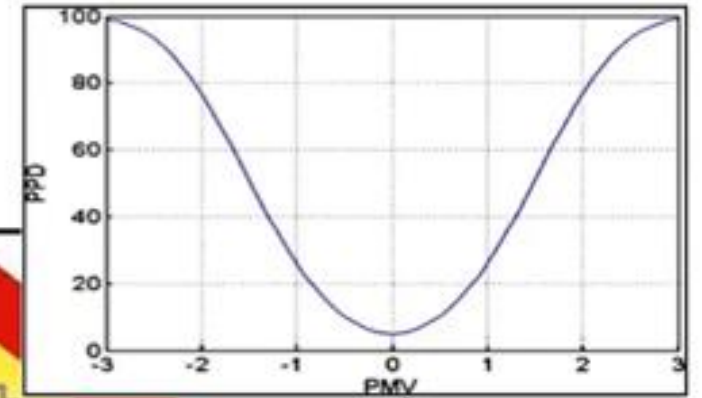
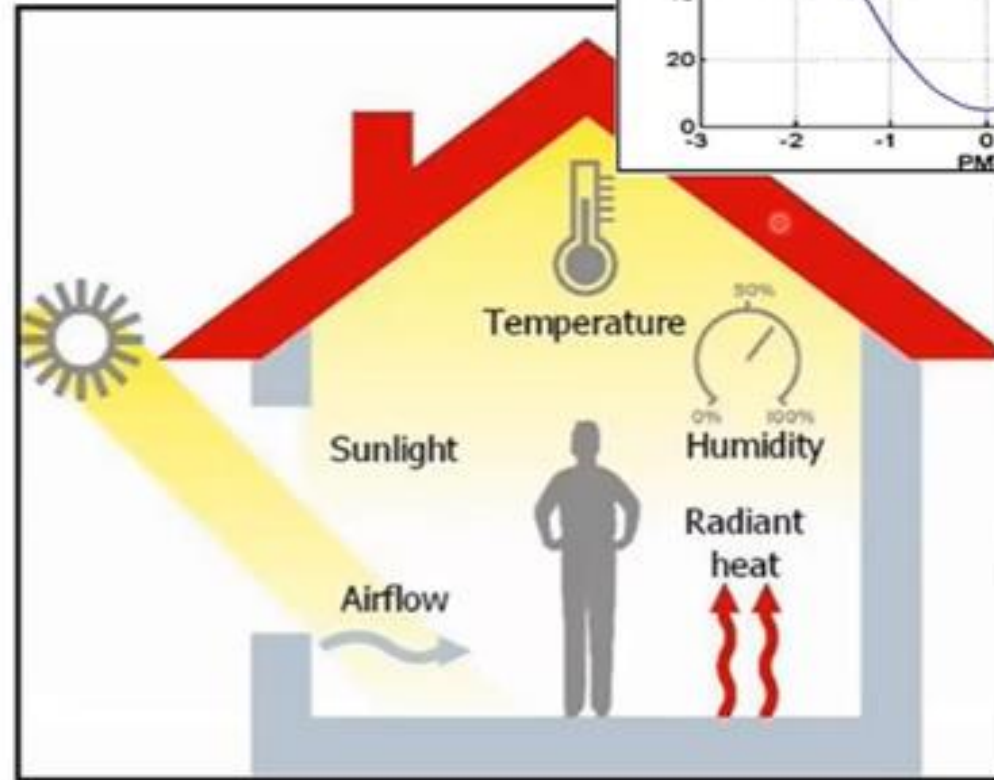
Impacted by

- Air temperature
- Air humidity
- Mean radiant temperatures
- Air speed
- Metabolic rate
- Clothing level



CBE Thermal Comfort Tool
<https://comfort.cbe.Berkeley.edu>

Standards:
ASHRAE 55 and DIN
SPEC 91420

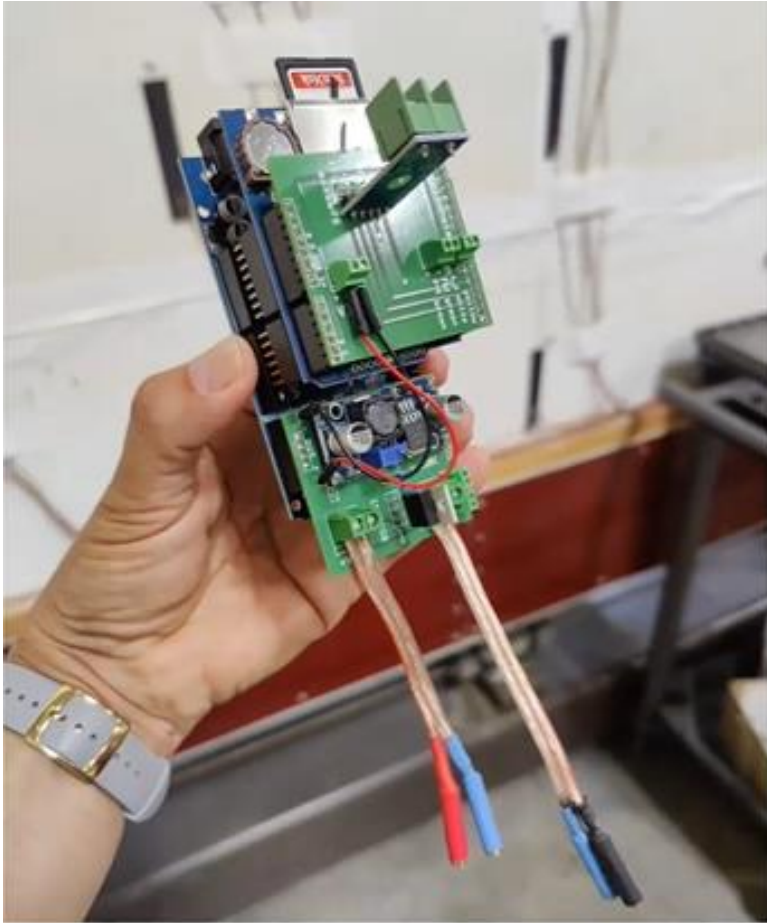


Operative temperature = average of air temperature (convective heat) and mean radiant temperature (radiation)

PMV=Predicted Mean Vote, PPD=Predicted Percentage of Dissatisfied

Image credit: Alwetaishi, Mamdooh. (2016). Impact of Building Function on Thermal Comfort: A Review Paper. American Journal of Engineering and Applied Sciences. 9. 928-945. [10.3844/ajeassp.2016.928.945](https://doi.org/10.3844/ajeassp.2016.928.945)

Lab test: Cube sensor/heater package



Control board

June 7, 2023



Convective heater and
thermal comfort sensor

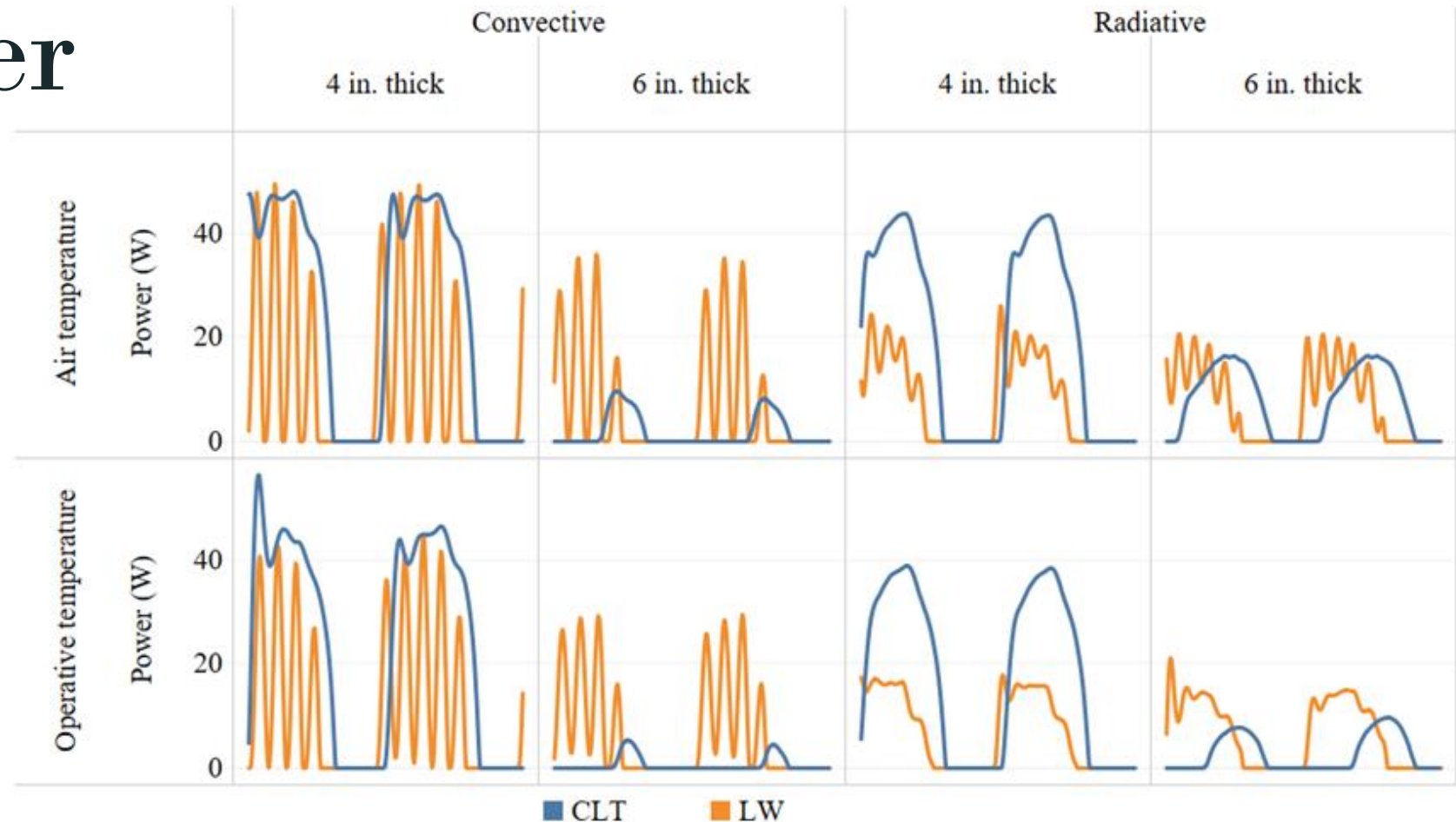


Graphene radiative heater

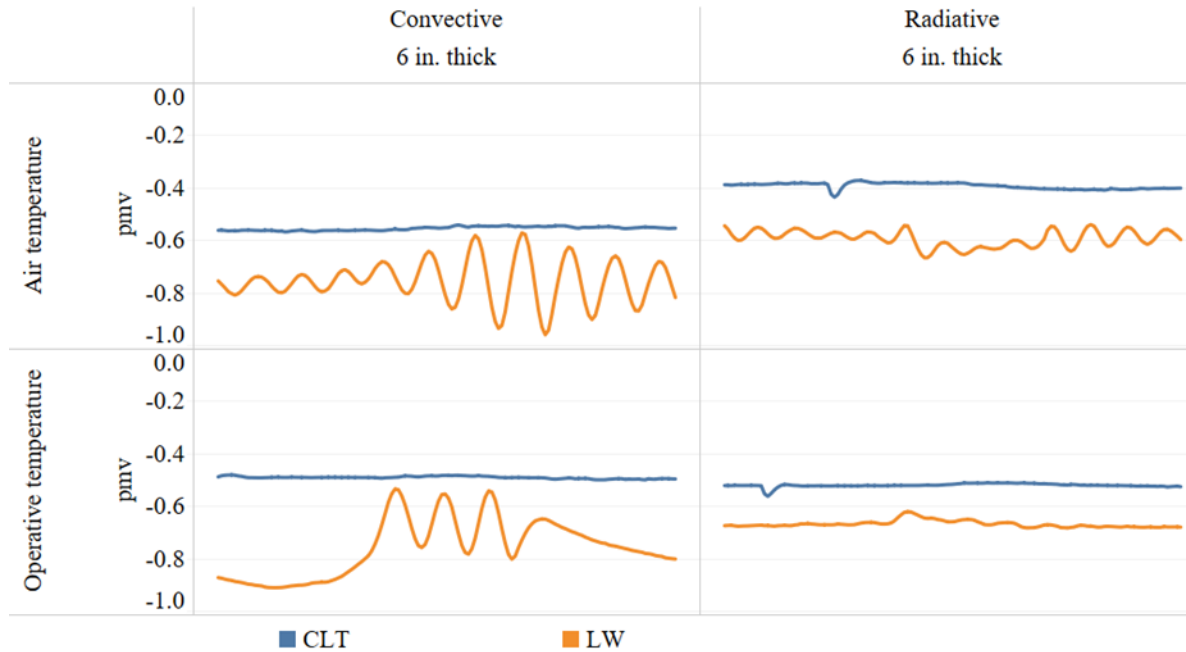
NOVEL METHODOLOGIES EXPOSE SIGNIFICANT
ADVANTAGES

Summer Test: Avg. Heater Power

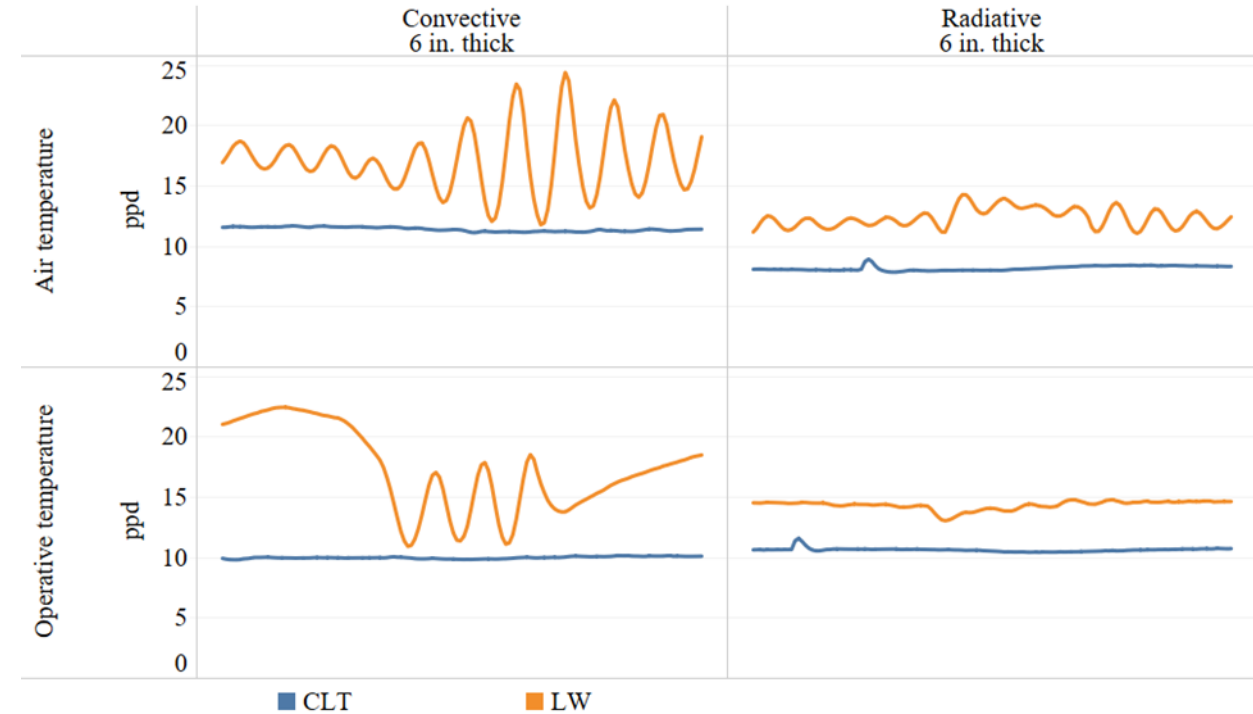
Heater power for 4 inch and 6 inch thick, CLT and LW wall, using two heater types (radiative and convective) and two temperature control (air temperature and operative temperature).



PMV → PMD



Predicted mean vote (pmv) for winter testing for 24-hour period



Predicted percentage of dissatisfied (ppd) for winter testing for 24-hour period

PMV is used to calculate the PPD

Next Steps

EVALUATE FIELD TEST CUBES IN THE THREE CLIMATES:

Two control modes for indoor conditions

- a. Indoor air temperature to fixed settings, e.g., 72 for heating and 75 for cooling
- b. Control for comfort based on operative temperature.

The operative temperature is approximately the average air temperature and the mean radiant temperature (surfaces the person is exposed to)

Two heating modes

- a. Convective heating, i.e., heat air only
- b. Radiant heating, i.e., providing radiant heat to the surfaces (and occupants) inside the cube

Cooling will be provided by the mini-split. No radiant cooling option here.

Measure the indoor air temperature and operative temperature, air humidity, and heating/cooling energy provided to the cubes.

Monitor heat fluxes through the walls on the interior surface and temperatures/humidities at the interfaces between material layers in the walls.

Use the monitored data to validate computer modeling (e.g., EnergyPlus and WUFI-Plus).

Apply the validated modeling tools to extrapolate the results from the small cubes to whole buildings in different climates.

Evaluate the building envelope criteria for mass wood walls compared to lightweight walls

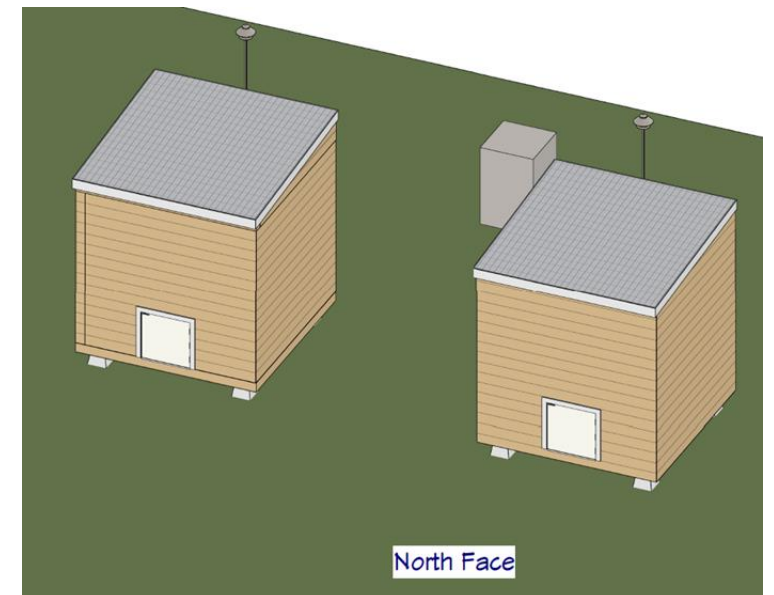
Field Testing: Large cube designs

PHASE IIB - ON-SITE MONITORING

	Finished inside dimension of 3m x 3m x 2.74m hgt.			
Location	TX	TX & TN	TN & CO	CO
Wall Type	2x4	6" CLT	2x6	8" CLT
	16" o.c.	NA	24" o.c.	NA
Framing Factor	18%	100%	16%	100%
Interior finish	1/2" Gyp. Bd.	None	1/2" Gyp. Bd.	None
	Gyp. Bd. Finish: Taped, spackled and primed.			
Flooring	5/8" Ply or eq.	CLT	5/8" Ply or eq.	CLT
Cavity/insulation	3.5 R13 FG UF Batt	4-1/8"	5.5 R21 KF FG Batt	6-7/8"
Underlayment	15# Felt or eq.		15# Felt or eq.	
Exterior sheathing	7/16" OSB	1.5" board	7/16" OSB	0.75" board
Exterior Finish	.354 in (8.9 mm)			
LP SmartSide	38 Series Cedar Texture Panel No Groove Shiplap Edge			
Overall thickness	123.825mm	152.4mm	174.625mm	203.2mm
	4 7/8 "	6 "	6 7/8 "	8 "

TWO CUBES: 10'X10'X9' WALL HGT.

- 1 - Lightweight construction
- 1 - Mass wood construction



Field Testing: Locations

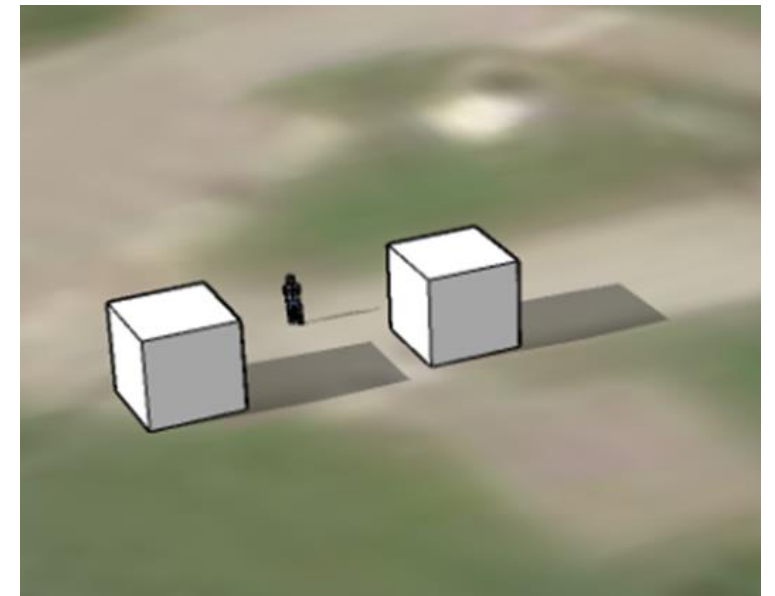
PHASE IIB - ON-SITE MONITORING

TWO CUBES: 10'X10'X9' WALL HGT.



Cube
arrangement:
2x height
apart (~20')

Shading at
noon in
December



Climate Zone 2A - Hot Humid: Nacogdoches, TX

Climate Zone 4A - Mixed-Humid: ORNL, Oak Ridge, TN

Climate Zone 5B - Cold-dry: Golden, CO (site shown above),

Timeline

TASKS AHEAD

SETUP – 3rd QTR 2023:

- Build cubes and deliver to field test sites
- Install cubes and confirm instrumentation, power and data connection

DATA COLLECTION – thru 3rd QTR 2024:

- Data streams collected remotely with weekly data checks to confirm quality data. The interior conditions will be controlled either by setting a fixed temperature or using thermal comfort-based control.
- Weather data collected from nearby sites and inserted to a file readable with the simulation software.

FIELD DATA ANALYSIS & REPORTING:

- Results from field tests showing performance of light-weight and mass timber cubes
- Simulated performance validated with field tests to generalize mass timber effects in building performance

FINAL REPORT:

- Timing for proposed changes for 2027 editions of ICC400 and ICC Building Energy Performance Standard.



Summary

Based on lab test validated simulation models, mass timber wall assemblies showed significant impact of thermal inertia as compared to lightweight walls.

- Annual total energy savings up to 19%.
- Peak demand was up to 50% lower with mass walls depending on the month and location.
- Improved thermal comfort with thermal mass walls (up to 46% fewer uncomfortable hours).

The field study will give further evaluation and is intended to confirm the modeling results.

Photo courtesy of Sterling Structural
<https://www.sterlingstructural.com/>

June 7, 2023

A close-up photograph of a tree trunk showing concentric growth rings in shades of brown, tan, and blue.

Thank you

Rob Pickett

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Session 3.1 Sustainable Construction Materials – Innovations and New Product Developments

Sequestering Carbon in Mass Timber Buildings

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In the not so distant past, it was common that large timber products companies were acquiring substantial volumes of timber from forest land they owned and managed. These so called vertically integrated companies could invest in silviculture practices that improved wood quality and reap the return on their investment through improvements in lumber grade and wood quality at the mill. In recent decades, the vertically integrated model of wood product manufacturers owning their own timber land has become rare. In many places the metrics used to buy and sell timber do not adequately value wood quality (e.g. it is not common for log sellers to receive a premium for logs from trees that were pruned to increase clear wood and uplift lumber grade milled from those logs). As a result, there is a lack of incentives for forest managers to invest in silviculture that could improve wood quality and uplift the value of manufactured products. In this talk, I will discuss how this disconnect and poor alignment of incentives affect forest management decisions that could contribute to lower quality in lumber and other manufactured wood products. I will draw examples from my past work for a vertically integrated company where I managed a tree farm and was responsible for addressing wood quality concerns in lumber and veneer production. In the future, global change may push forest managers to embrace more diverse species and less homogenous forest management, further complicating manufacturer's efforts to produce consistent, high-quality lumber and other products.

Session 4.1 Frontiers in Renewable Materials

Waste-Cannabis biomass, what do we do with it?

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As commodity products, particulate wood-based composites like particleboard and oriented-strand board are always subject to manufacturing-cost reduction. The maturity of these technologies makes it very difficult to innovate new materials and applications. We suggest that fundamental research can help reveal new innovations. In combination with recent trends in green building and circular production, fundamental research has the potential to increase social welfare by incentivizing the construction of low-cost housing and community-focused development. Such incentives arise from well-designed buildings that significantly decrease long-term costs. This work investigates the fundamentals of wax migration in such products. Paraffin wax is added to wood-particle composites for water resistance, and it is thought that hotpress-steam effects cause wax migration and possibly chromatographic fractionation that might affect panel performance. As this is a steam driven process, it is likely that wood-moisture content plays a role. For this study, a partially-sealed press system was developed to better simulate industry-scale hotpress conditions. This press-caul system also enables collection and analysis of expelled vapors. Conditions inside the wood mat are digitally monitored with a thermocouple and pressure transducer and controlled with an outlet valve. Gas chromatography is used to analyze wax content before and after pressing. This chromatographic methodology can individually quantify the wax by normal-alkane carbon number and may determine if shorter chains tend to migrate more. Finally, this presentation will attempt to connect the dots between such fundamental research and large-scale social change, and how such connections may require an interdisciplinary approach that draws from many fields of expertise.

Session 4.1 Frontiers in Renewable Materials

In situ pine-lignin repolymerization: can we control it for advanced materials?

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When lignocellulosic materials are subjected to thermal processing, lignin alkyl-aryl ether linkages undergo a cleavage reaction known as lignin acidolysis. The products often react, or repolymerize, by forming new carbon-carbon linkages in a remarkable self-healing process. Our objective is to determine if lignin acidolysis can be manipulated, in situ, to impart novel properties in advanced composite materials. To that end, this work seeks to correlate the incidence of lignin repolymerization within loblolly pine wood, and under the influence of catalytic changes in the lignin-acidolysis pathway.

Session 5.1 Durability and Protection of Wood and Wood Products

Mitigating Moisture Intrusion in Wood Buildings

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J. Vandenberg Lewis, Method Studio

Neil Bulger, A2 Efficiency

Michael Sawford, A2 Efficiency

Buildings are constructed to protect the inhabitants that reside within their walls and under their roofs, but buildings are also very smart in the ways they protect themselves. The primary vulnerability of any wood building (or of any other type for that matter) is moisture. Since the formative years of constructing structures, builders and architects have been concerned with finding solutions to protect buildings from the elements of nature. Water comes to buildings from the ground and from the sky, so it is necessary to understand the role and function of various construction assemblies in addressing water-born issues – namely, at the foundation, the wall, and the roof. This study examines how dew point is managed in three vulnerable building conditions in a typical mass timber structure.

Session 5.2 Frontiers in Renewable Materials

Isotope analysis, the final frontier in wood-composite formaldehyde emissions?

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Wood-based composites will likely be a critical feature of society's climate-change response, including structural and nonstructural materials. However, nonstructural wood composites face continued federal regulation on allowable formaldehyde emissions. Nonstructural wood composites are often composed of two main components: wood and urea-formaldehyde resin. To comply with regulations, advancements have seemingly pushed resin technologies to their logical limits. However, the regulations fail to consider that wood naturally generates formaldehyde, and in a highly variable, species-dependent fashion that is not well understood. Consequently, regulation compliance might be easy or difficult as the wood source changes. In an effort to inform and perhaps reshape future regulations, this work aims to develop a novel methodology for employing isotope analysis to determine the relative contributions of synthetic and biogenic formaldehyde towards total formaldehyde emissions from wood composites.

Session 5.2 Frontiers in Renewable Materials

Catechyl Lignin: Cell-wall structure/property relationships

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In 2012, a novel lignin in was reported in the seed coat of vanilla orchid (*Vanilla planifolia*), and in some *Cactaceae*. It is a linear homopolymer of caffeyl alcohol connected by benzodioxane linkages. This catechyl-lignin, or C-lignin, is the only lignin in vanilla-seed coat; but other plants exhibit seed coats (or nutshells) with both C-lignin and also guaiacyl/syringyl (G/S)-lignin, as in candlenut (*Aleurites moluccanus*), jatropha (*Jatropha curcas*), cleome (*Cleome hassleriana*), and tung tree (*Vernicia vordii*). The benzodioxane linkage is likely much stiffer than the alkyl-aryl ether linkage in G/S-lignins. Furthermore, the regular C-lignin structure might be expected to crystallize. Others have shown that the benzodioxane linkage renders C-lignin unusually stable against acid-catalyzed cleavage. These points motivated us to conduct cell-wall structure/property studies in vanilla seed coat, and candlenut nutshell, using x-ray diffraction, microscopy, and dynamic mechanical analysis (DMA). In order to measure the glass transition temperature (T_g), DMA was conducted in solvent-submersion mode using organic plasticizers in an attempt to reduce the T_g to non-damaging temperatures. Seed-coat and nutshell tissues are not conveniently sized and shaped for typical DMA. Therefore, we applied compressive-torsion DMA using a torsional rheometer; specimen gripping occurs by compression of specimens between parallel-plates, and low-amplitude torsional oscillation is used to measure the T_g. Vanilla bean seed coat measurements were particularly challenging because the tiny seed coat must be separated from the seed endosperm. Vanilla bean seed coat and candlenut shell exhibited a T_g onset near 120°C, suggesting a T_g perhaps as high as 160°C, and that cannot be measured safely. Relative to guaiacyl/syringyl-lignin, C-lignin clearly exhibits a much higher T_g as we expected. Aspects of DMA, x-ray diffraction, and some basic microscopy will be discussed in the context of plant evolution where the evolutionary basis for C-lignin is unclear.

Session 5.2 Frontiers in Renewable Materials

Wax migration in the wood-composite hotpress: Connecting fundamental science with social welfare

JC Stant and Chip Frazier

Wood-Based Composites Center Virginia Tech

For nearly a century, thermal energy demand calculations have been based on simplified models according to the technical potentials of the period. The first action took place in Germany and Austria in 1929, when the initial technical standards committee for heating was founded. The calculation methods initiated then, to a surprisingly significant extent, still apply today. In addition to the climate zones for German and Austrian locations, initial consensus established conductivity coefficients of building materials and heat transfer coefficients. In 1959, heat transfer coefficients and modern building materials were integrated. Ever since, at least for mass timber buildings, the coefficients for conductivity have been subject only to relatively insignificant innovative change. Steady-state hot box assessment methods have been used to assess mass timber buildings, generally ignoring thermodynamic characteristics, which have demonstrated significant advantages in mass timbers buildings in practice. Novel methodologies have been applied in the research performed at a US DOE national laboratory. The inclusion of the thermal comfort approach based on and in accordance with DIN 7730 and ASHRAE Standard 55 has demonstrated significant differences in the energy requirement assessments performed dynamically. The research results bring the assessment data much closer to the anticipated heating demand in practice. Thermal inertia, inner surface temperatures, thermal emissivity, solar gains, dynamic outer weather conditions, and thermal comfort characteristics are finally combined into a holistic assessment approach regarding thermodynamic relationships. These results can potentially be applied towards the contribution of energy-efficient mass timber buildings; and, moreover, to material-efficient mass timber buildings at the same time, while material efficiency is becoming ever more important.

Session 6.1 Durability and Protection of Wood and Wood Products

Decay Characteristic Assessment of Urban Trees Within The University Of Ibadan Community

Olusola S. Areo

Forestry Research Institute of Nigeria

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Wood decay is caused primarily by enzymatic activities of microorganisms which majorly affect roots, sapwood, or heartwood of a tree causes dead trees, smaller leaves and slower growth. Tree decays are among the most challenging forest health issues in forest management. Urban and suburban trees are more likely to have wounds and decay than trees in native stands because of anthropogenic activities which cause most wounds. This study was carried out to observe the decay characteristics of trees in the University of Ibadan. The assessments were done using visual assessment and laboratory identification of fungi species. One hundred and six (106) decayed trees were observed and identified along selected roads in the University of Ibadan community, and were expressed in the ranges of 0-9 per location. Result shows that *D. regia* had the highest number (18) and (16) *G. sepium* among the tree assessed and observed with decay, common indicator or defects of decay was observed among stem rot and dead branches with visible decay fungi species were *rhizopus nigricans*, *trichoderma spp* and *penicillium spp*, while *rhizopus nigricans* was predominant. In conclusion, most decay fungi observed invaded injured trees; therefore urban young trees should be protected from injuries.

Session 6.1 Durability and Protection of Wood and Wood Products

Development of Perservative-Treated Cross-Laminated Timber

Franklin Quin

Mississippi State University

Cross-laminated timber (CLT) is a mass timber product manufactured from softwood dimension lumber stacked in layers at 90° to the previous layer. CLT has enjoyed a major level of success in the European construction market for the last 20 years and is establishing a major presence in the North American construction market. CLT can be used for interior or exterior applications, such as balconies and ground-contact walls. Since CLT is constructed from wood which is a biological material that can degrade under certain conditions, such as exposure to moisture, decay fungi, and termites. In order to be expanded for use in exterior applications, the question of durability must be addressed. Pressure-treating of CLT panels with chemical preservatives can add protection against degradation. CLT panels can be either pre-treated or post-treated. Pre-treated panels involve the fabrication of panels from treated lumber. Post-treating of CLT panels involves treating CLT panels after fabrication with untreated lumber. There is a lack of information on the effects of the adhesive bonding of a post-treated CLT panel at a commercial treating facility. The goal of this research was to determine if a CLT panel can be treated at a commercial treatment facility without significant panel degradation. The bonding conditions of the CLT panels after post-treating were analyzed by following procedures in ASTM D2559. This study also focused on the failure modes of shear block specimens tested according to ASTM D905 from 3-ply and 5-ply post-treated CLT samples treated with a copper-based preservative system.

Development of Preservative-Treated Cross-Laminated Timber

**Presented by
Franklin Quin, Jr.**

Department of Sustainable Bioproducts
College of Forest Resources
Mississippi State University

June 8, 2023

Supervisor: Dr. Tamara Franca



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Outline

- Background
- Research Questions and Objective
- Materials and Methods
- Results and Discussion
- Conclusion and Recommendations



Background: Environment

- **Global** construction industry accounts for **39%** of energy and process-related **CO₂ emissions** into the environment



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Background: Environment

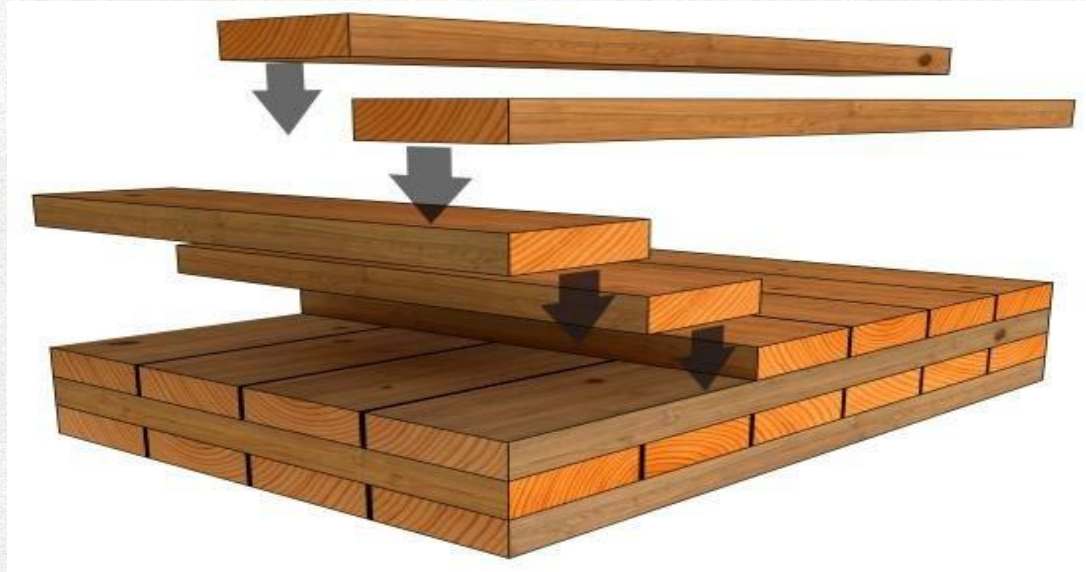
- **11%** of the **39%** comes from manufacturing building materials and products (steel, cement, and glass)

Background: Environment

- CO₂ emissions expected to increase as global population
- By 2050 most of the worlds population will be living in urban areas
- Demand for affordable housing



Background: Cross-Laminated Timber



Background: CLT and Biodeterioration



Wood Decay



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Research Questions:

1. Is it possible to post-treat a CLT panel at a commercial treating facility without the panel delaminating inside the treating cylinder?
2. What is a reasonable kiln drying schedule to prevent the degrading of a treated CLT panel from checking and delamination?



Research Objective

- The objective of this research was to evaluate the **bonding performance** and **durability** of post-treated CLT panels.



Material and Methods

- SYP
 - Select Structural Grade (2 x 6 x 8)
 - No. 2 Grade (2 x 6 x 8)
- Adhesive
 - One Component PUR (Polyurethane)
- CLT Layup
 - 3-ply and 5-ply top (parallel direction)
 - 3-ply top (perpendicular direction)
- Preservative Treatments
 - CA-C (copper azole - type C)
 - MCA (micronized copper azole)



- Variables collected:
 - Wood failure
 - Shear strength
 - Delamination rate

CLT Panel Configurations



Material and Methods



CLT Panels in Dieffenbacher Laboratory Hydraulic Press



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Material and Methods



Treated according to 2 inch dimension lumber protocol
UC4A (ground contact or fresh water) (2.4 kg/m^3)(0.15 lb/ft^3)



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Material and Methods



Boring samples to check for preservative penetration of charge



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Air Drying



Kiln Drying SYP Timber Schedule



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Delamination on End of CLT Panel during Air Drying

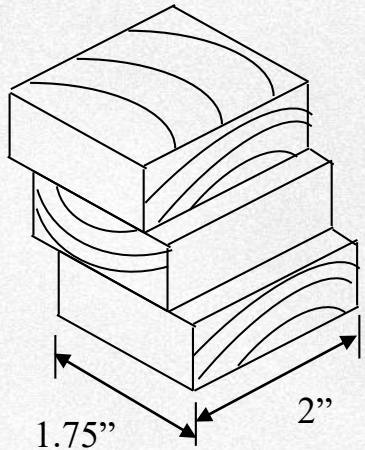
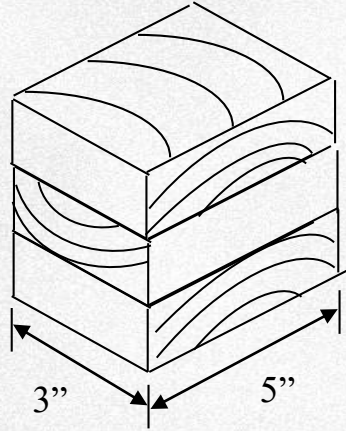


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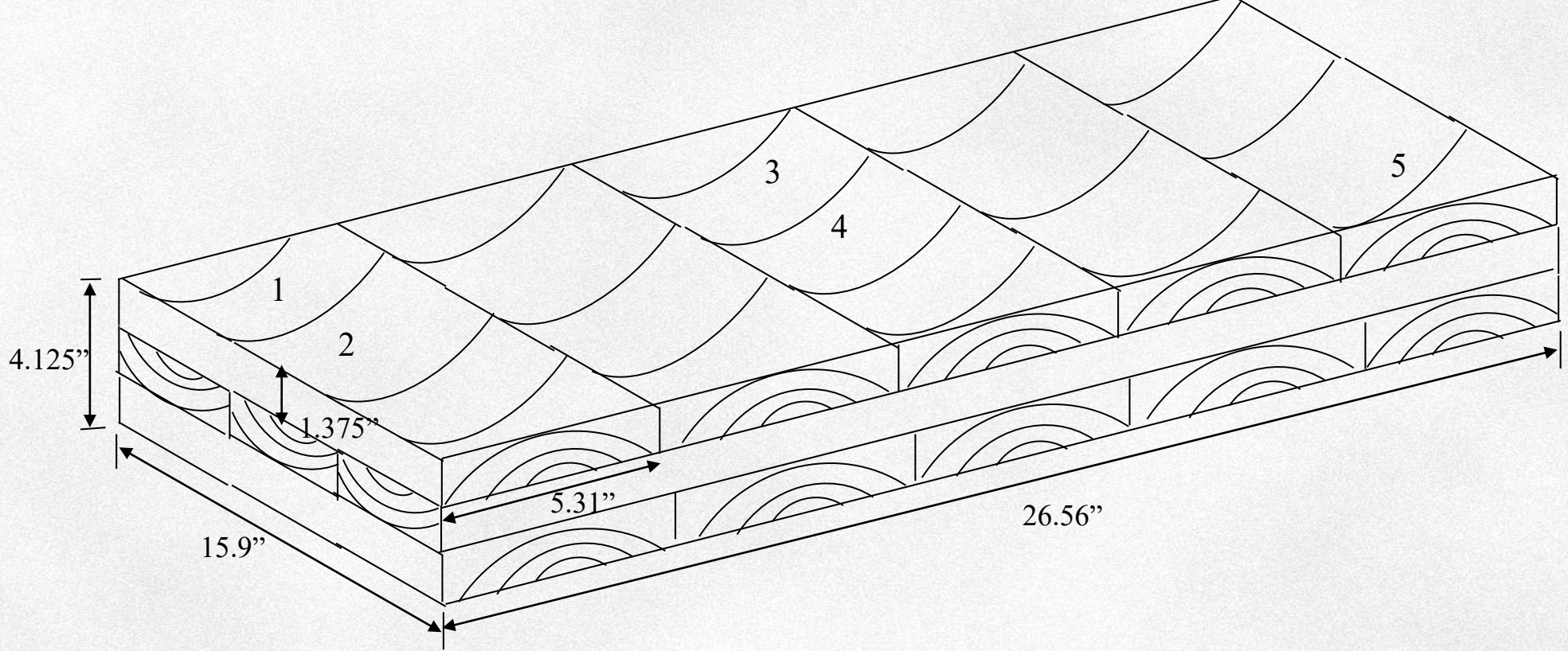
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Delamination



Shear



3-Ply Panels Shear and Delamination ASTM D2559 and ASTM D905

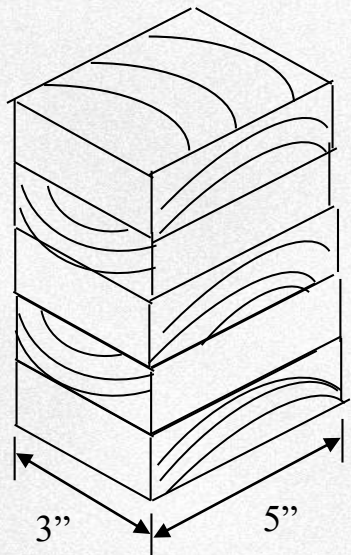


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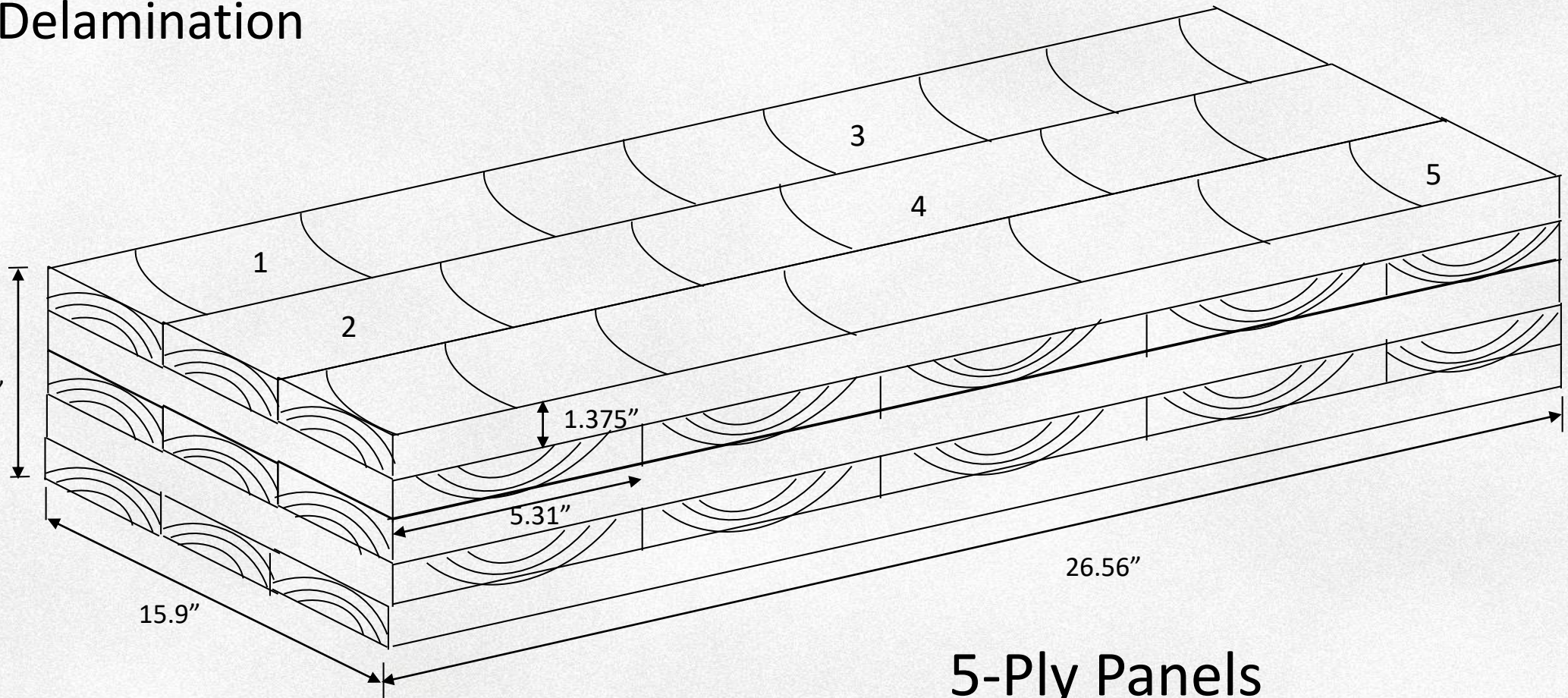
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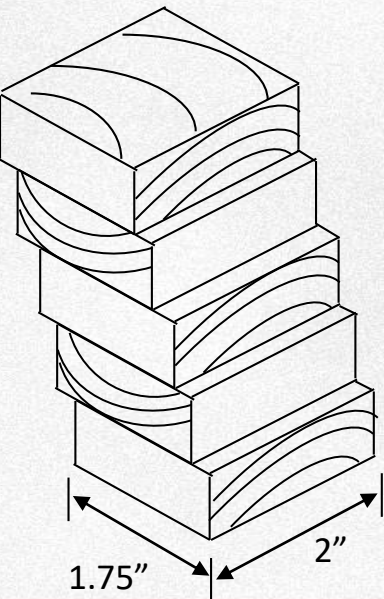
Delamination



6.875"



Shear



5-Ply Panels
Shear and Delamination
ASTM D2559 and ASTM D905



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Cutting CLT Panel into 5.25 x 5.25 Blocks



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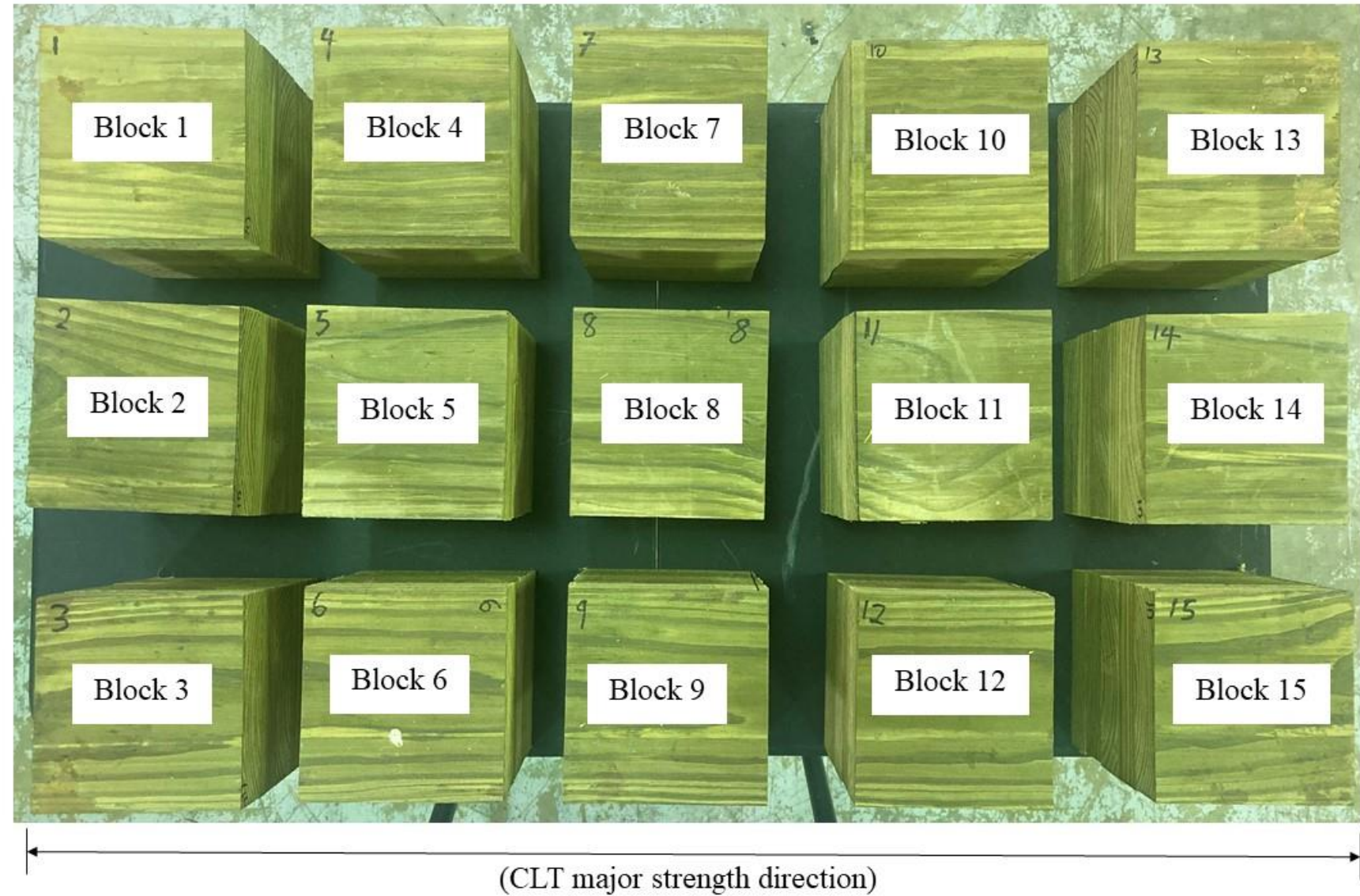
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Blocks 1 and 15 Corner

Blocks 2 and 7 End

Block 8 Middle



Shear Block Specimen in Testing Machine ASTM D905





Delamination ASTM D2559

Results

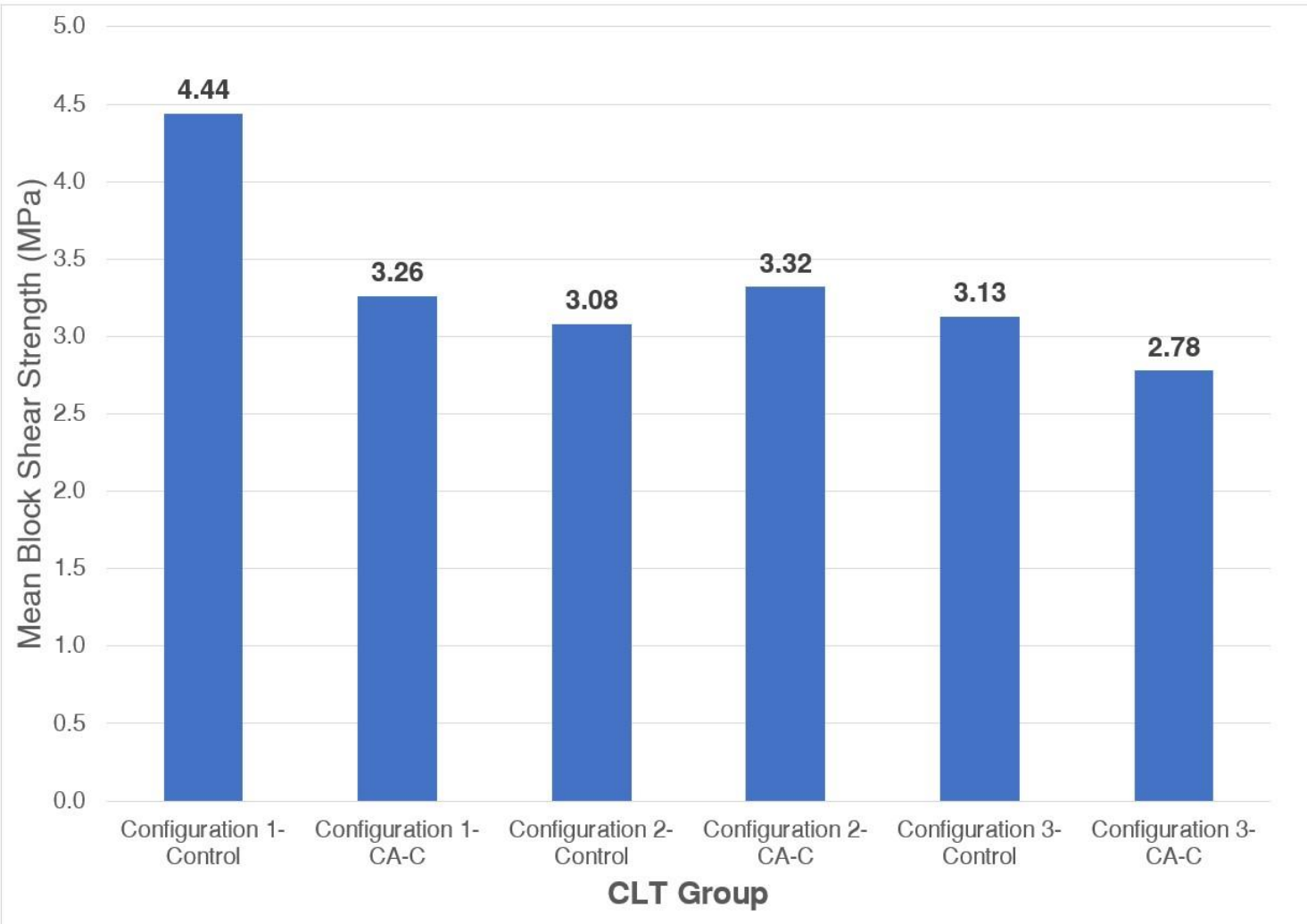


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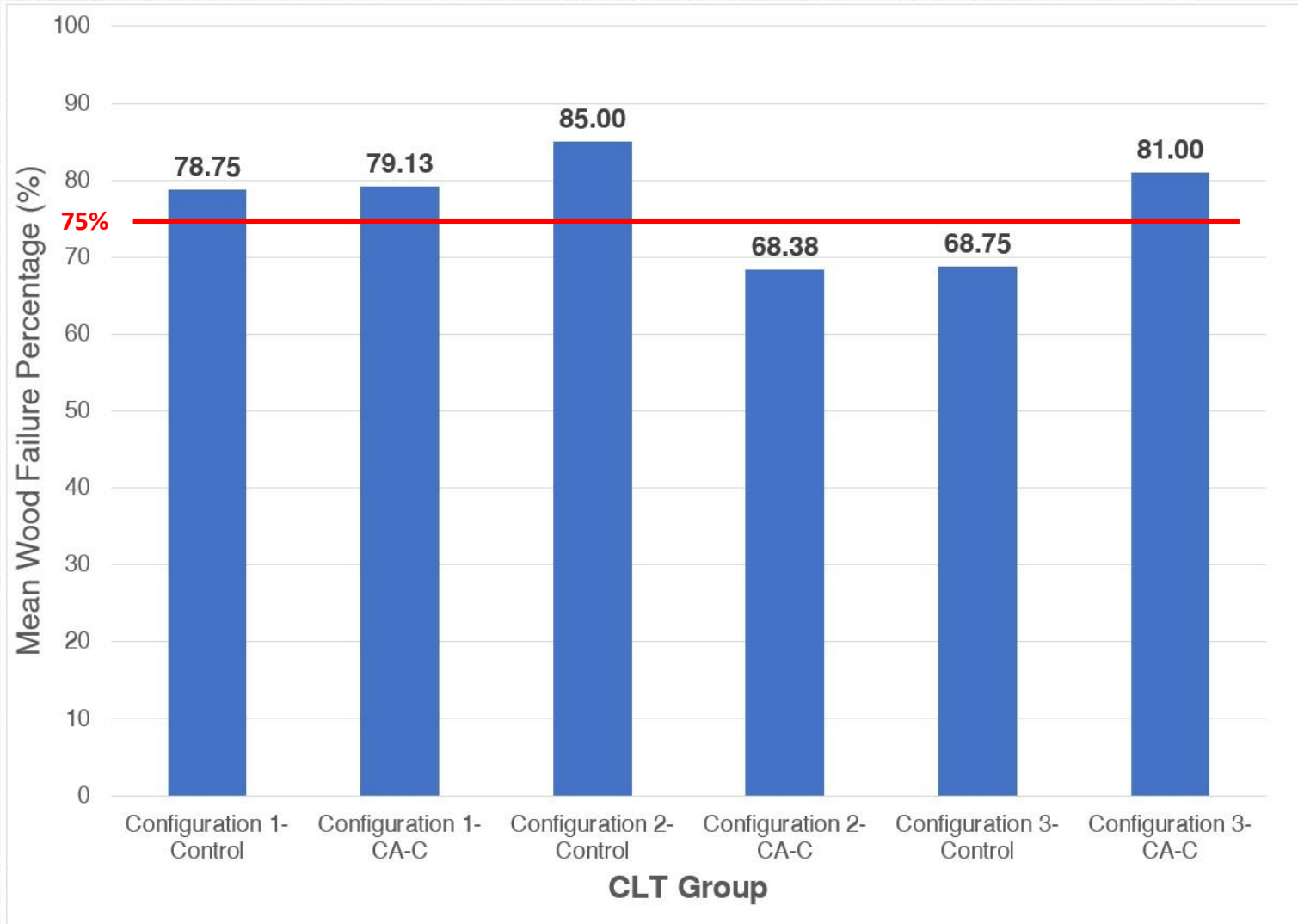
Mean Block Shear Strength



CA-C treated specimens measured a lower mean block shear strength (BSS)



Mean Wood Failure Percentage



Shear Block Modes of Failure

Adhesive Failure



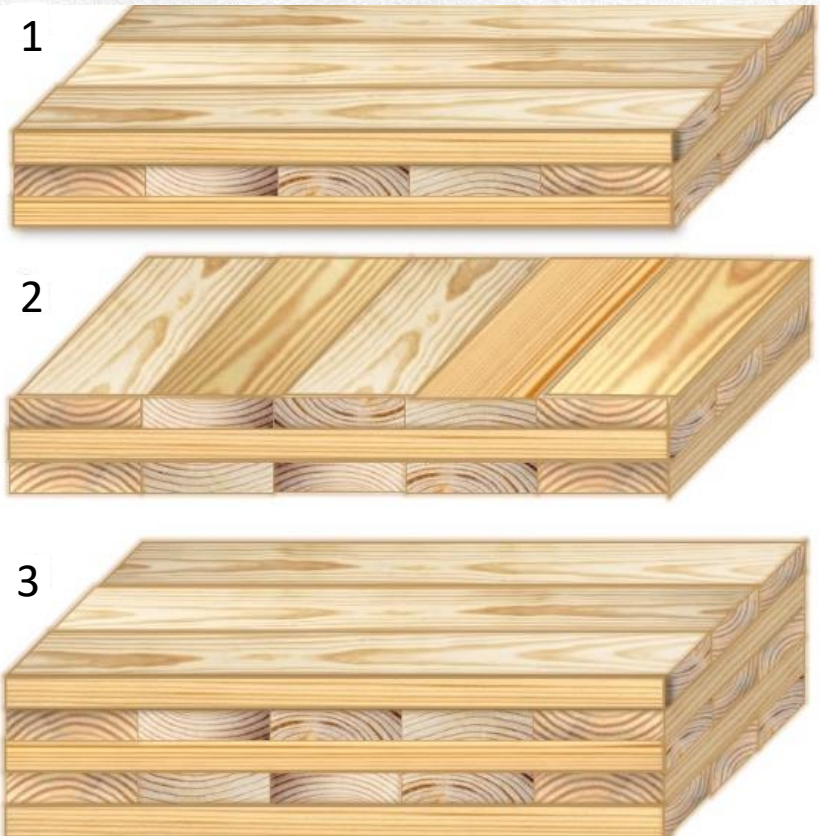
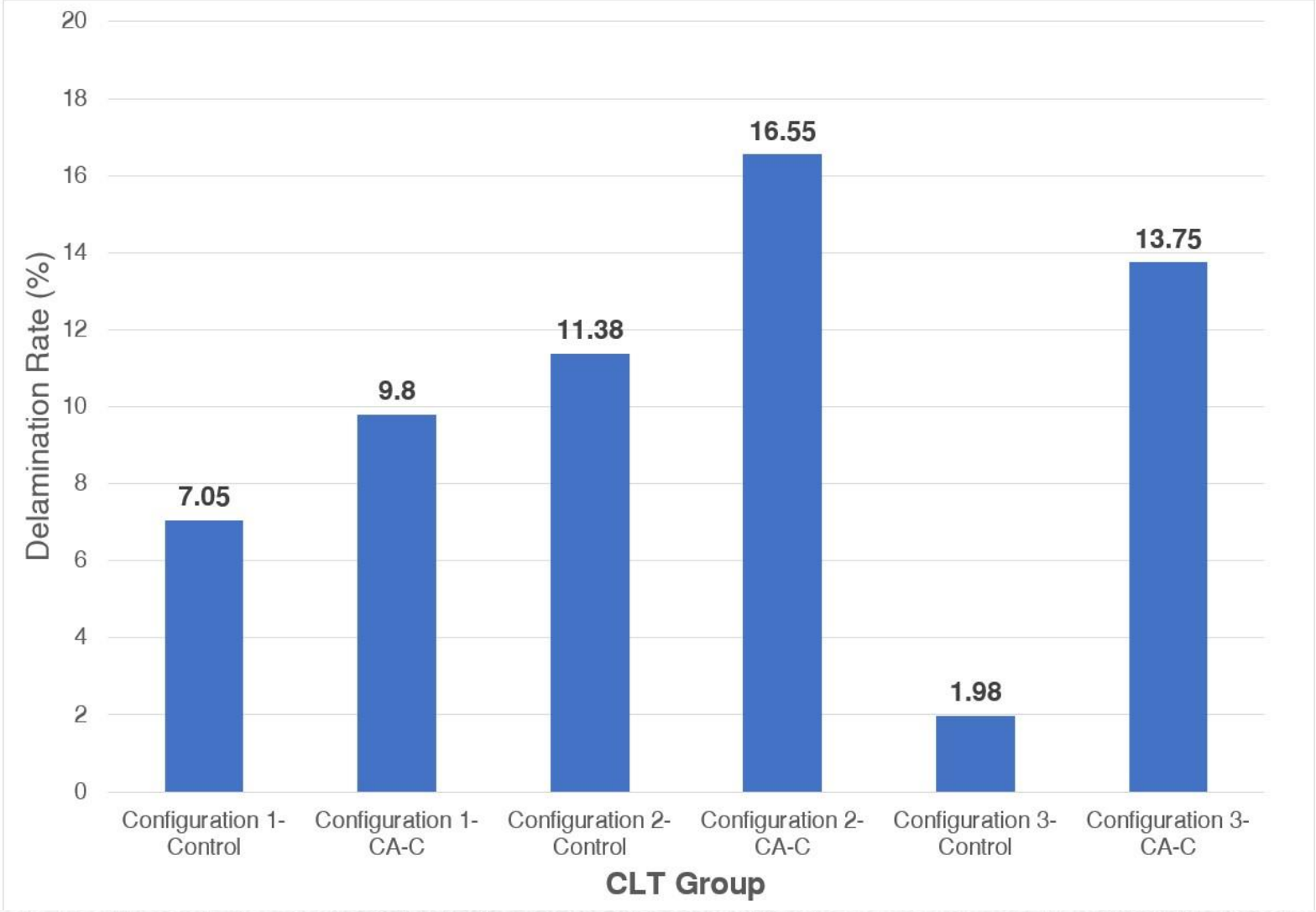
Wood Failure



Wood Failure



Delamination Rate



Conclusion and Recommendations



Conclusion

- Preservative treatment influenced the shear bonding strength and delamination rate of the CLT Panel.
- CA-C panels tended to measure a lower bonding strength and delamination rate than the control panels.
- Rolling shear was the predominate mode of failure for the shear block samples



Conclusion

- The wood failure percentage was similar for the control and the CA-C treated panels. Close to passing ASTM D2559 requirement of 75% average wood failure.
- Study shows the potential of post-treating CLT panels with MCA preservative.



Recommendations for Future Testing

- Treating of a commercial size CLT panel at a commercial treating facility.
- Developing a kiln drying schedule that will limit CLT degrade after post treating needs to be studied.

Recommendations for Future Studies

- Test the mechanical properties (rolling shear strength and rolling shear modulus) of a CLT panel after post-treating.
- Field durability testing of the post-treated CLT panel.

Acknowledgements

- Project funded by a Wood Innovation Grant from the USDA Forest Service. The authors would like to thank Shuqualak Lumber Company for providing the lumber, Henkel Corporation for providing the PUR adhesive for this research, and DeForest Wood Preserving and Koppers Performance Chemicals for providing preservative treatment.



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Questions?



Session 6.2 Processing and Wood Quality

Wood quality and forest management: when interests don't align and the future is uncertain

Austin Himes

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In the not so distant past, it was common that large timber products companies were acquiring substantial volumes of timber from forest land they owned and managed. These so called vertically integrated companies could invest in silviculture practices that improved wood quality and reap the return on their investment through improvements in lumber grade and wood quality at the mill. In recent decades, the vertically integrated model of wood product manufacturers owning their own timber land has become rare. In many places the metrics used to buy and sell timber do not adequately value wood quality (e.g. it is not common for log sellers to receive a premium for logs from trees that were pruned to increase clear wood and uplift lumber grade milled from those logs). As a result, there is a lack of incentives for forest managers to invest in silviculture that could improve wood quality and uplift the value of manufactured products. In this talk, I will discuss how this disconnect and poor alignment of incentives affect forest management decisions that could contribute to lower quality in lumber and other manufactured wood products. I will draw examples from my past work for a vertically integrated company where I managed a tree farm and was responsible for addressing wood quality concerns in lumber and veneer production. In the future, global change may push forest managers to embrace more diverse species and less homogenous forest management, further complicating manufacturer's efforts to produce consistent, high-quality lumber and other products.



WOOD QUALITY AND FOREST MANAGEMENT

When interests don't align, and the future is uncertain

Austin Himes



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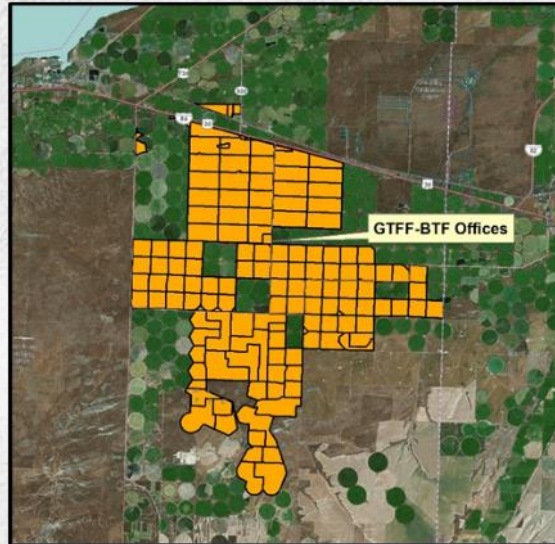
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Background

My experience with the intersection of wood quality and silviculture

Boardman Tree Farm

- 10,000 + ha irrigated plantation
- Owned by a TIMO, but vertically integrated
- Manufacturing on site
 - Collins Co. Sawmill
 - Columbia Forest Products veneer mill
 - Shared merchandising and infeed



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Background

The “Disintegration” of forest products and forest management

Table 1. Top 15 Industrial Timberland Owners and Managers, 1969 versus 2016

1969			2016	
Rank	Firm	Type	Firm	Type
1	International Paper	Forest Industry	Weyerhaeuser	Public REIT
2	Weyerhaeuser	Forest Industry	Hancock Timber Resource Group	TIMO
3	Georgia-Pacific	Forest Industry	The Forestland Group	TIMO
4	Great Northern Nekoosa	Forest Industry	Campbell Global	TIMO
5	St. Regis Paper	Forest Industry	Resource Management Services	TIMO
6	Boise Cascade	Forest Industry	BTG Pactual	TIMO
7	Scott Paper	Forest Industry	Forest Investment Associates	TIMO
8	Champion International	Forest Industry	Rayonier	Public REIT
9	Kimberly-Clark	Forest Industry	Molpus Woodlands Group	TIMO
10	Burlington Northern	Railroad	Sierra Pacific	Forest Industry
11	Union Camp	Forest Industry	The Nature Conservancy	Conservation
12	Continental Group	Forest Industry	Potlatch	Public REIT
13	Crown Zellerbach	Forest Industry	Green Diamond Resource Co	Forest Industry
14	Potlatch	Forest Industry	Wagner Forest Management	TIMO
15	Diamond International	Forest Industry	J. D. Irving	Forest Industry

By mid-2000s, most forest products companies furnish their mills with timber from private land owned by someone else

1990: Northern Spotted Owl listing

1980ish: IRS ruling confirm timber harvest revenue is not UBTI for pension funds

1986: Favorable capital gains tax rate no longer applicable to income from commercial timber harvest

1974: ERISA law requires pension funds to diversify beyond stocks and bonds

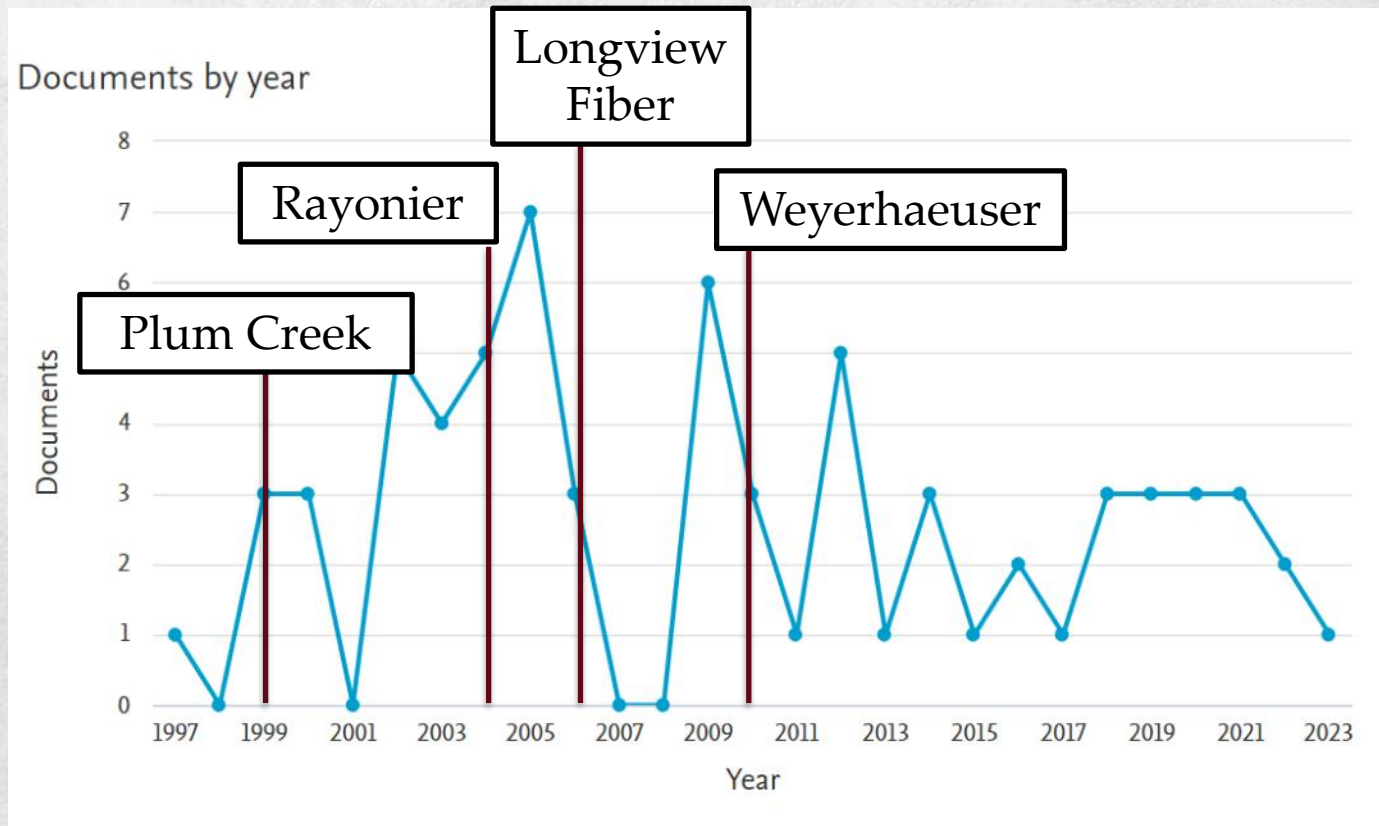
Inheritors of the timber barons own and manage forest land to furnish their mills, complimented by timber from public lands



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Trends in research and REITs



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TIMOs/REITs and forest products want different things from forests

Forest Management Interests

- Return on investment from land and timber
- High discount rate = shorter rotations
- Silvicultural investments must return value in log sales

Forest Products Interests

- Maximum sustainable yield of desired spec lumber
- Larger piece sizes
- Logs that will provide high grade lumber

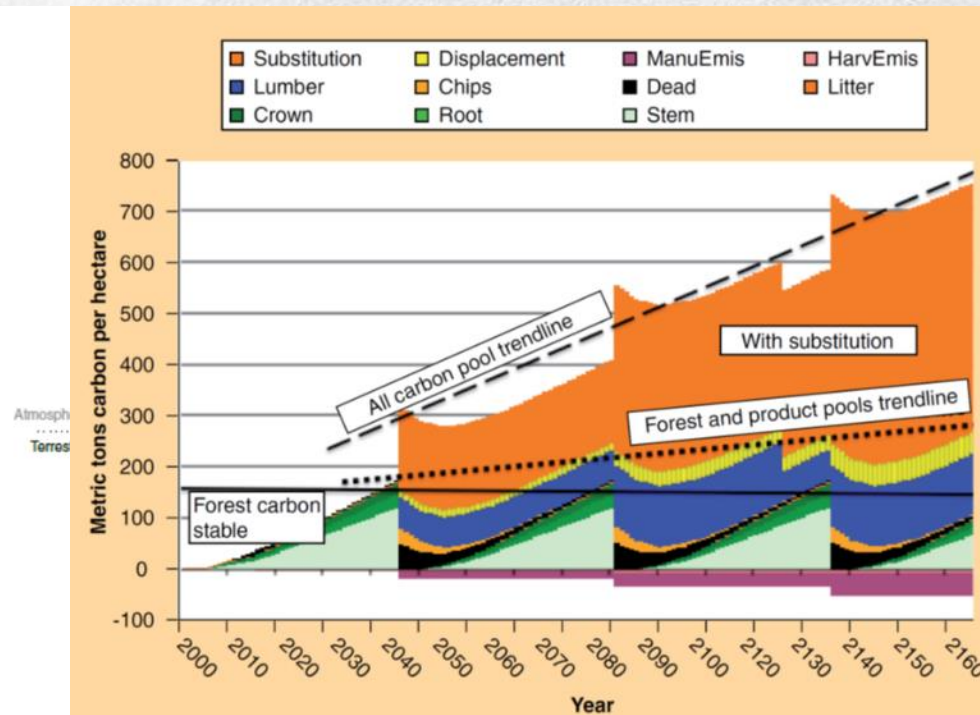


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Potential for lost value

- Reduced potential for forests and forest products to combat climate change



Churkina, G., Organschi, A., Reyer, C. P. O., Ruff, A., Vinke, K., Liu, Z., Reck, B. K., Graedel, T. E., & Schellnhuber, H. J. (2020). Buildings as a global carbon sink. *Nature Sustainability*, 1–8. <https://doi.org/10.1038/s41893-019-0462-4>

Oliver, C. D., Nassar, N. T., Lippke, B. R., & McCarter, J. B. (2014). Carbon, fossil fuel, and biodiversity mitigation with wood and forests. *Journal of Sustainable Forestry*, 33(3), 248–275.



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Potential for lost value

- Reduced investment in research to improve wood quality

Table 2. Mean Wood Property Values with SD in parenthesis

	BC78	BC79	BC81	PC1	All Clones
Trees	3	2	2	1	8
Boards	92	64	68	27	251
Green SG	0.34 (0.04)	0.36 (0.04)	0.32 (0.02)	0.33 (0.02)	0.34 (0.04)
Oven-Dry SG	0.38 (0.04)	0.4 (0.05)	0.35 (0.03)	0.36 (0.03)	0.37 (0.04)
Radial Swelling (%)	3.91 (0.01)	4.01 (0.01)	4.44 (0.01)	4.38 (0.01)	4.13 (0.01)
Tangential Swelling (%)	5.41 (0.01)	6.49 (0.01)	5.59 (0.02)	5.88 (0.01)	5.78 (0.02)
T/R Ratio	1.38 (0.69)	1.62 (0.67)	1.26 (0.60)	1.34 (0.75)	1.40 (0.68)
Radial Hardness (N)	1791 (624)	1979 (397)	1647 (380)	1813 (329)	1802 (495)
Tangential Hardness (N)	1932 (526)	2157 (473)	1756 (380)	1903 (410)	1939 (484)
MOR (N/mm ²)	57 (10)	68 (12)	58 (9)	57 (8)	60 (11)
MOE (N/mm ²)	7285 (1060)	7482 (1461)	7101 (1306)	6236 (822)	7172 (1265)
Screw Withdrawal (N)	2559 (463)	3375 (654)	2550 (493)	2273 (208)	2733 (635)

Himes, A., Leavengood, S., & Polinko, A. (2021). Variation in wood properties of hybrid poplar lumber by radial and vertical position in stem; a case study from Boardman, OR. *Wood and Fiber Science*, 53(3), Article 3.

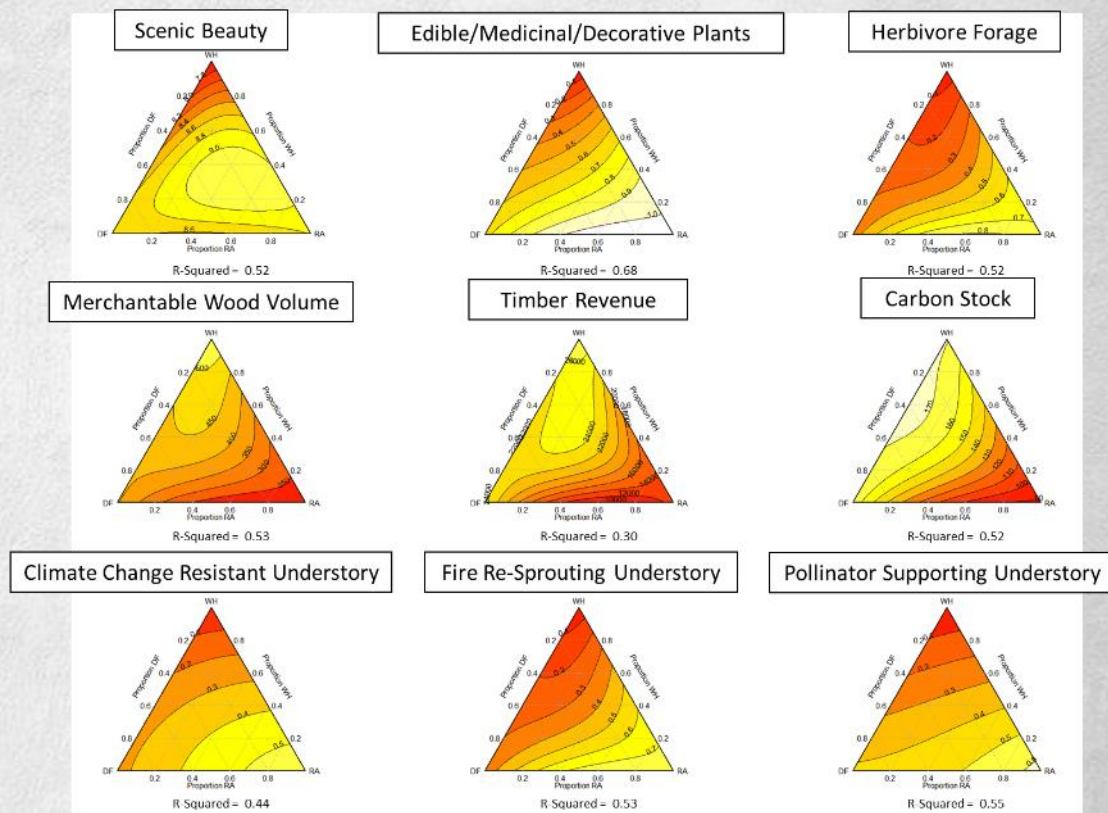


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Things are going to change. How do we adapt?

- For forest management, the future is about reducing risk
- Diversity reduces risk by providing options and reducing negative impacts



Himes, A., Puettmann, K., & Muraca, B. (2020). Trade-offs between ecosystem services along gradients of tree species diversity and values. *Ecosystem Services*, 44, 101133. <https://doi.org/10.1016/j.ecoser.2020.101133>



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Things are going to change. How do we adapt?

- In forest products, *Consistency* might be as important as *Quality*
- Variation tends to reduce efficiency and scare consumers

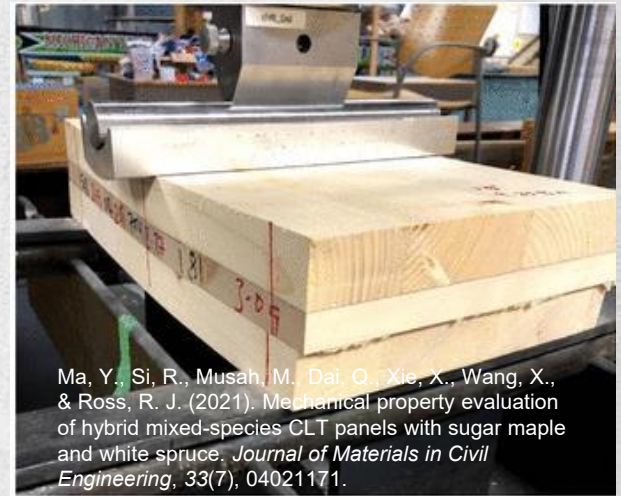


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Things are going to change. How do we adapt?

- Design mills with flexibility in mind
- Innovative ways of incentivizing wood quality
- Engineered wood products



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Conclusion

- Silviculture can improve wood quality
- If you want better wood quality, pay for it. Silviculturists must justify treatments based on ROI.
- Global change creates challenges for growing trees. Both forest managers and forest products manufacturers will have to adapt. *The question is, will their adaptations be complimentary or counter acting?*



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Questions

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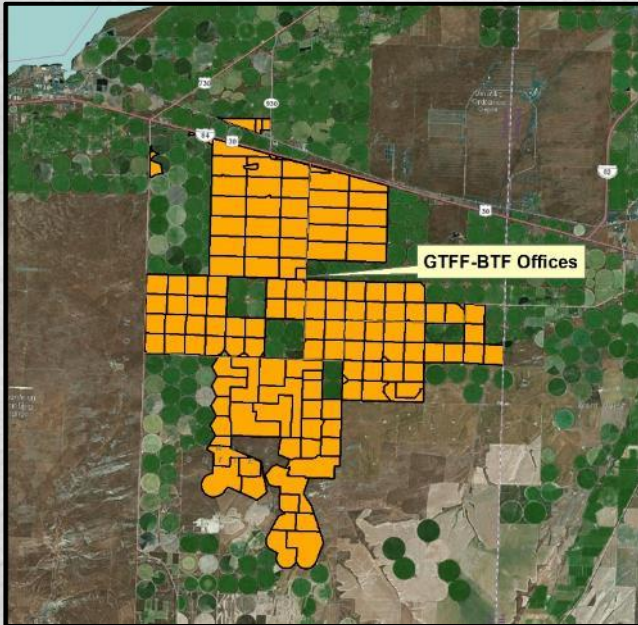
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Session 6.3 Wood Identification

How the Proliferation of Field-deployable Nonconventional Wood Identification Methods Could Impact Lumber Markets in Developing Countries

Frank Owens

Mississippi State University

The development of field-deployable wood identification methods has been largely motivated by the global problem of illegal logging and timber trade. While the expansion of global wood identification capacity through the advancement of computer vision and other nonconventional wood identification methods can potentially reduce illegal harvesting of controlled wood species, it also has the potential to positively impact developing hardwood lumber markets such as the Middle East and South Asia – even when illegal logging is not at issue – by addressing the often-lamented-but-rarely-discussed (at least in academic literature), and even more rarely measured, issues of product adulteration and asymmetry of information between buyers and sellers. This presentation describes with existing economic theories and documented examples how product adulteration and asymmetrical information adversely affect developing hardwood lumber markets and demonstrates how field-deployable nonconventional wood identification methods such as computer vision can potentially mitigate those effects.

How the Proliferation of Field-deployable Nonconventional Wood Identification Methods Could Impact Lumber Markets in Developing Countries

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Mississippi State University

Coauthors



Prabu Ravindran
Univ. Wisconsin
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Alex Wiedenhoef
CWAR, USDA
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Adriana Costa
Miss. State Univ.



Frank Owens
Miss. State Univ.



Background



Conventional Wood ID

- Human-based
- Hand lens and/or microscope
- Observation of anatomical features
- Reference descriptions or specimens
- **Requires extensive training in wood anatomy**

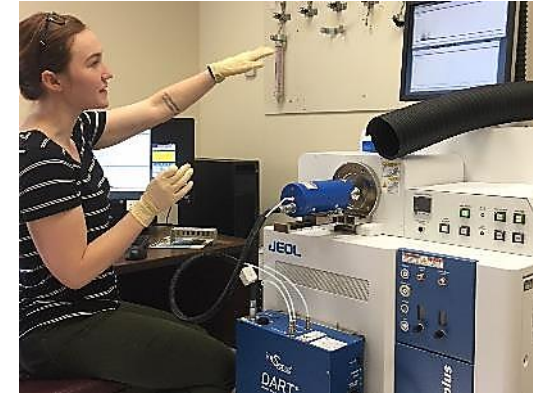
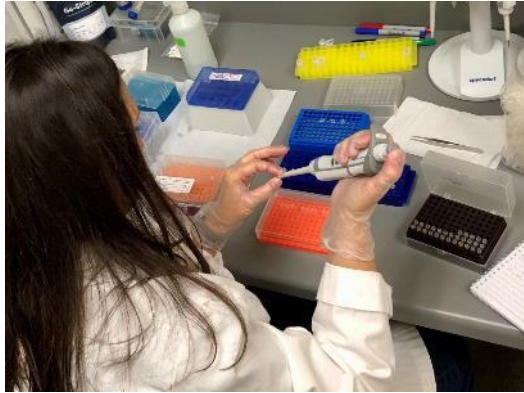


The Problem

- Most people can't identify wood.
- Even “experts” may not be very skilled (Wiedenhoeft et al. 2019).
- Few skilled trainers.
- Overall small wood ID capacity to meet current needs.
- We need methods that don't rely on human expertise.



New Nonconventional Wood ID Methods



DNA barcoding, qPCR, laptop and smartphone-deployed computer vision, Near-Infrared Spectroscopy (NIRS), DART-TOF Mass Spectrometry.

Primary Motivation: Illegal Logging



Illegal rosewood (*Dalbergia* spp.) stockpiles in Antalaha, Madagascar.

My Motivation: Lumber Markets like U.A.E.

- Difficult market
- Poor quality lumber
- Very low prices
- Widespread species and grade mixing



Frank managed one of the largest hardwood lumber programs in the Arabian Gulf 2009-2010.

Product Adulteration

Adulteration is “any act that renders an article other than of the nature, substance, and quality demanded by the purchaser or other than of the nature, substance, and quality the purchaser is presumed to have expected.”

Alsberg (1931, p.2)



Species Adulteration

- Mixing lumber of lower value into bundles of a higher value species.
- **Not necessarily illegal wood.**
- Rampant in many markets.



Bundles marketed as “Meranti” (*Shorea* spp.).

Adulteration Data Is Lacking

- Adulteration often goes undetected.
- Difficult to measure.
- Academic literature is sparse.

Sri Lanka (Kannangara et al. 2020)

- Species adulteration is under-studied.
- Currently no method for tracking it.

USA (Wiedenhoeft et al. 2019)

- “There is no published scholarly data establishing the presence or scope of [species fraud and misrepresentation] in forest products” (p. 2).





Anecdotal Evidence



Sri Lanka
(Kannangara et al. 2020)

- Species adulteration is prevalent.
- Substitution of a lower value wood for a higher value one is common.

<u>Survey Question</u>	<u>Patrons</u>	<u>Manufacturers</u>	<u>Carpenters</u>
Awareness of adulteration	92.5%	73.3%	96.7%
Can't tell adulterated timber from genuine	47.5%	40.0%	63.3%



Anecdotal Evidence



India
(Dev et al. 2014)

- East Indian sandalwood (*Santalum album*)
- Highly prone to adulteration in commercial markets
- Common adulterants include
 - Nepal sandalwood (*Osyris wightiana*)
 - Indian bastard sandal (*Erythroxylum monogynum*)



Anecdotal Evidence



China
(Pan et al. 2021)

“[T]he supply of wood raw material in China is mainly by importation. Consumers know little about exotic wood, and fakes and adulterants of wood products are challenging for the forest products industry” (p. 1).



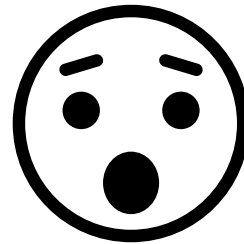
Anecdotal Evidence



UAE
(Frank Owens)



Bundles like this sold as 100%
“Meranti” (*Shorea* spp.)



0% *Shorea*



100% *Calophyllum*
(Bintangor)

Food for Thought

1. What impact does species adulteration have on lumber markets?
2. How could new wood ID methods address that issue?



Theory



Adulterated Product Can Drive Out the Genuine

Alsberg (1931)

- Sole leather in the U.S. used to be sold by the piece.
- Then it came to be sold by weight.
- Sellers began to “load” the leather with cheaper and heavier material.
- This unfair advantage led virtually all tanners to **follow suit**.
- **Unadulterated sole leather** all but **disappeared** from the U.S. market.



Asymmetry of Information between Buyer and Seller

“The Market for Lemons” Akerlof (1970)

- In the pre-Carfax and pre-internet U.S. used car market...
- **The seller knew more** about the quality of the car than the buyer (asymmetry of info).
- **Buyers could not distinguish** a good car from a bad car.
- Buyers were **willing to pay more** for a good car.
- But buyers knew there were bad cars in the market.
- So buyers were willing to pay **only an “average” price** to mitigate risk.
- That price was **less than the price for a good car**.
- That **drove good cars out** of the market.
- And so on until **only rubbish cars were left**.



How Information Asymmetry Impacts a Market

“Typical Quality”
33.3% Split



100% Adulterant



50% Meranti
50% Adulterant



100% Meranti

Seller Would Accept:

USD 100

USD 200

USD 450

Buyer Would Pay:

USD 0

USD 250

USD 500

Buyer's Ave. Price: **USD 250**



How Information Asymmetry Impacts a Market

“Typical Quality”
50% Split



100% Adulterant

Seller Would Accept:

USD 100

Buyer Would Pay:

USD 0



50% Meranti
50% Adulterant

USD 200

USD 250



100% Meranti

USD 450

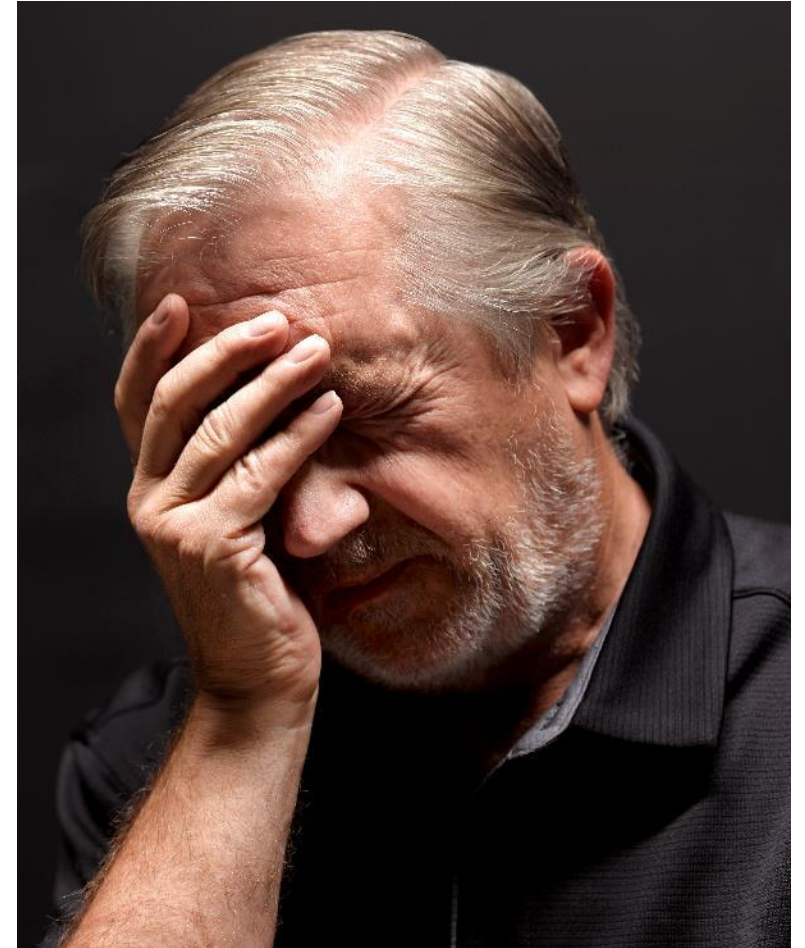
USD 500

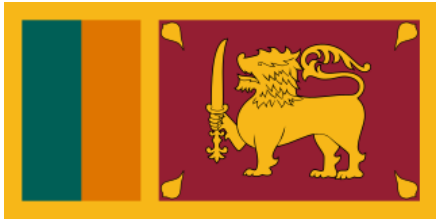
Buyer's Ave. Price: **USD 125**

Inevitable Conclusions

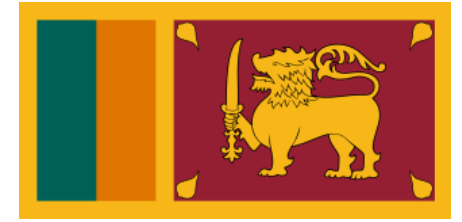
Adulterated Lumber +
Asymmetry of Information =

- Low prices
- Nothing but rubbish quality
- Impossible to sell good quality/genuine products **even when some are willing to pay for them.**





Desire for Remedies



Sri Lanka
(Kannangara et al. 2020)

- “Timber adulterations result in the declination of the sales of the timber products and the violation of consumer rights” (p. 1)
- “Authentication of timber products, which involves the accurate identification of timber species, is vital to gain the end-user trust and sustain the timber industry” (p. 1)

	Patrons	Manufacturers	Carpenters
An accurate wood ID method would help build trust in the market.	67.5%	70.0%	60.0%



Desire for Remedies



India
(Dev et al. 2014)

- “The ability to track or identify timber resources of economic value is therefore critically essential for the effective management and appropriate regulation of timber trade” (p. 518)

(Pande et al. 2007)

- “[I]dentification to check adulteration or misuse has become important” (p. 1748).



Desire for Remedies



China
(Pan et al. 2021)

“Therefore, an on-site, accurate wood identification technique is necessary for the industry” (p. 2)

Possible Solutions?

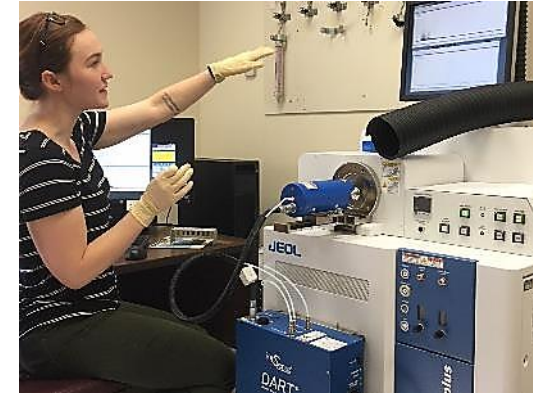
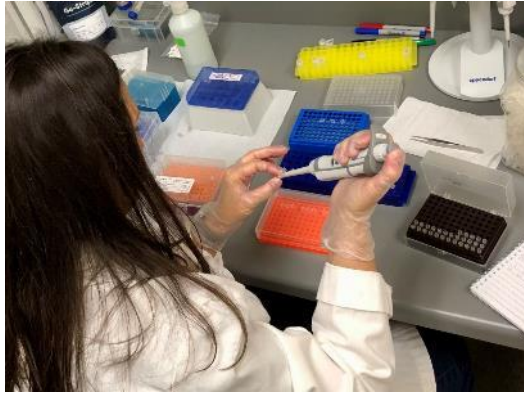


Proposed Remedy for Species Adulteration

- Democratize wood identification.
- Employ nonconventional wood ID methods.
- Make them rapid, affordable and field-deployable.
- Disrupt the *status quo*.



Rapid, Affordable and Field-deployable



DNA barcoding, qPCR, laptop and smartphone-deployed computer vision,
Near-Infrared Spectroscopy (NIRS), DART-TOF Mass Spectrometry

Rapid, Affordable and Field-deployable



DNA barcoding, qPCR, laptop and smartphone-deployed computer vision,
Near-Infrared Spectroscopy (NIRS), DART-TOF Mass Spectrometry

Expected Results



Expected Results

- The proliferation of rapid, affordable and field-deployable wood ID methods could empower all lumber buyers (big and small) to accurately ID wood.
- Asymmetry of information regarding species should start to evaporate.
- Species adulteration should be deterred.
- Buyers and sellers of good quality, unadulterated material should start to return to the market and get higher prices for their genuine products.



One more thing...



Grade Adulteration



Debasement of a higher grade of lumber with pieces of a lower grade (or grades)

North American-based lumber trader sold us 100% FAS/1F Red Oak (*Quercus* spp.). Upon inspection, we discovered approx. 35% was off grade (1C and 2C).

Next Steps

- Species adulteration is only part of the equation.
- The other big factor is grade adulteration.
- Automated grading of hardwoods requires lab or factory-based equipment.
- The goal should be to develop and deploy automated grading technologies on a smartphone as has been done with nonconventional wood ID.



How the Proliferation of Field-deployable Nonconventional Wood Identification Methods Could Impact Lumber Markets in Developing Countries

Frank C. Owens
Assistant Professor
Mississippi State University

The development of field-deployable wood identification methods has been largely motivated by the global problem of illegal logging and timber trade. While the expansion of global wood identification capacity through the advancement of computer vision and other nonconventional wood identification methods can potentially reduce illegal harvesting of controlled wood species, it also has the potential to positively impact developing hardwood lumber markets such as the Middle East and South Asia – even when illegal logging is not at issue – by addressing the often-lamented-but-rarely-discussed (at least in academic literature), and even more rarely measured, issues of product adulteration and asymmetry of information between buyers and sellers. This presentation describes with existing economic theories and documented examples how product adulteration and asymmetrical information adversely affect developing hardwood lumber markets and demonstrates how field-deployable nonconventional wood identification methods such as computer vision can potentially mitigate those effects.



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- 33. Frank Owens
- 34. “Walking to the future,” publicdomainvectors.org (n.d.), Accessed 29 Apr 2021: <https://publicdomainvectors.org/en/free-clipart/Walking-to-the-future/51619.html>



Session 6.3 Wood Identification

How Surface Preparation Quality Affects the Performance of a Computer Vision Wood Identification Model

Frank Owens

Mississippi State University

Field-deployable computer vision wood identification typically involves four steps: 1) transverse surface preparation of the wood specimen, 2) digital imaging of the transverse surface under magnification, 3) running the image through a pretrained deep learning algorithm, and 4) evaluating the output. Macroscopic training and testing images of transverse surfaces published in previous studies have varied greatly in respect to visibility of anatomical features due to, among other factors, varying qualities of surface preparation. As a computer vision model presumably uses differences in wood anatomical features to discriminate one class of wood from another, the clarity of those features in the image has potential to influence model performance. As such, it is important to investigate to what degree varying qualities of surface preparation can affect model accuracy – if at all. To this end, a 24-class deep learning model was tested on images of tropical wood specimens polished to various degrees. The transverse surfaces of the training specimens were polished to 1500 grit. Images were captured with the XyloTron device and used to train the convolutional neural network model. Test specimens from a separate xylarium were polished regressively at seven increments from 1500 to 80 grit. Images were captured for all specimens at each increment. Image datasets for each grit were used to test the model. Accuracies among datasets will be compared to determine to what extent (if any) performance drops as grit decreases. Results will inform future studies on best practices for surface preparation in the field.



How Surface Preparation Quality Affects the Performance of a Computer Vision Wood Identification Model

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Clemson Univ.



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Funding



Background



Conventional Wood ID

- Human-based
- Hand lens and/or microscope
- Observation of anatomical features
- Reference descriptions or specimens
- Requires training in wood anatomy



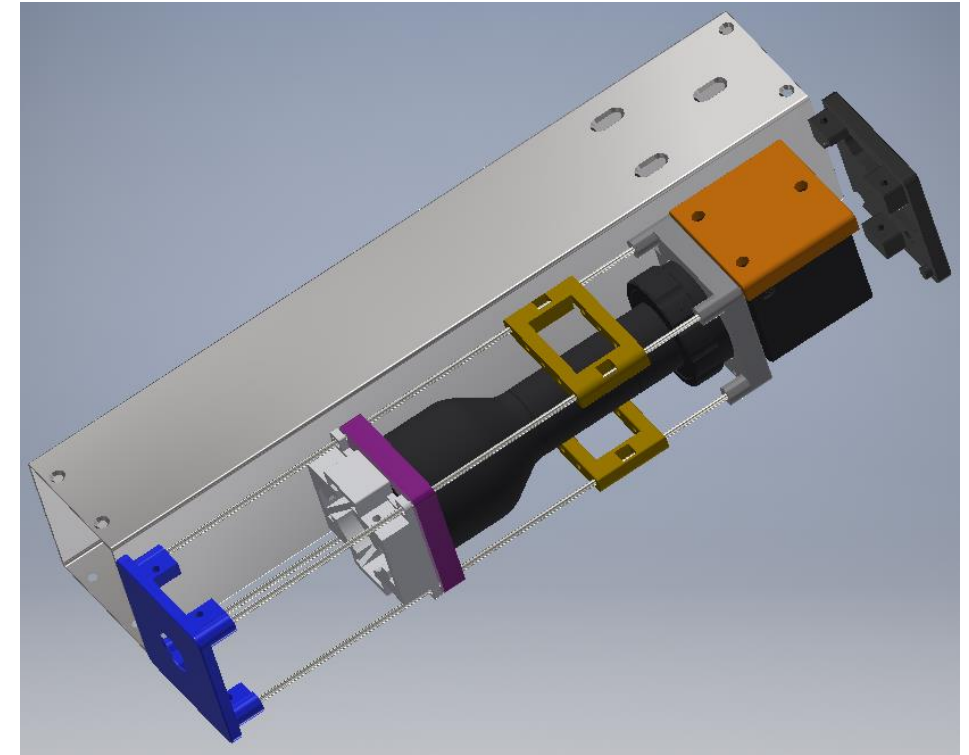
Computer Vision-Based Wood ID

- Computer analysis of digital images
- Hardware: digital camera, lens, and computer
- Software: feature detection and classification algorithms (A.I.)
- Requires little human training to operate device
- Minimal-to-no wood anatomy knowledge required



The XyloTron

- A computer vision-based system
- Designed at USDA FPL
- Open source
- Field deployable
- Hardware: “XyloScope” (camera & lens) & laptop
- Software: convolutional neural network (CNN) for identification

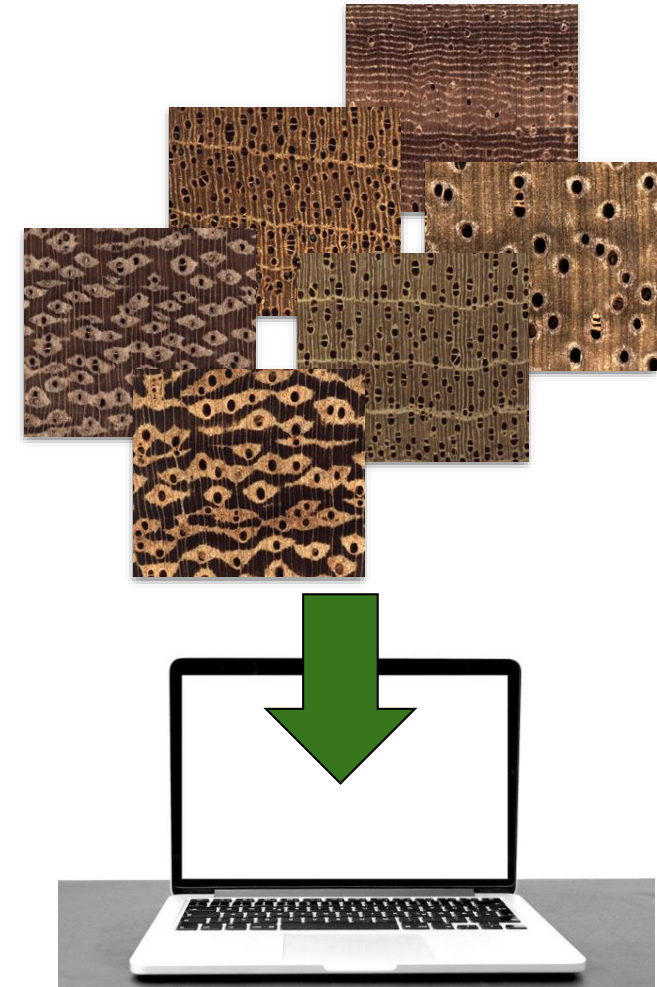


The XyloScope

The XyloTron

Model Training:

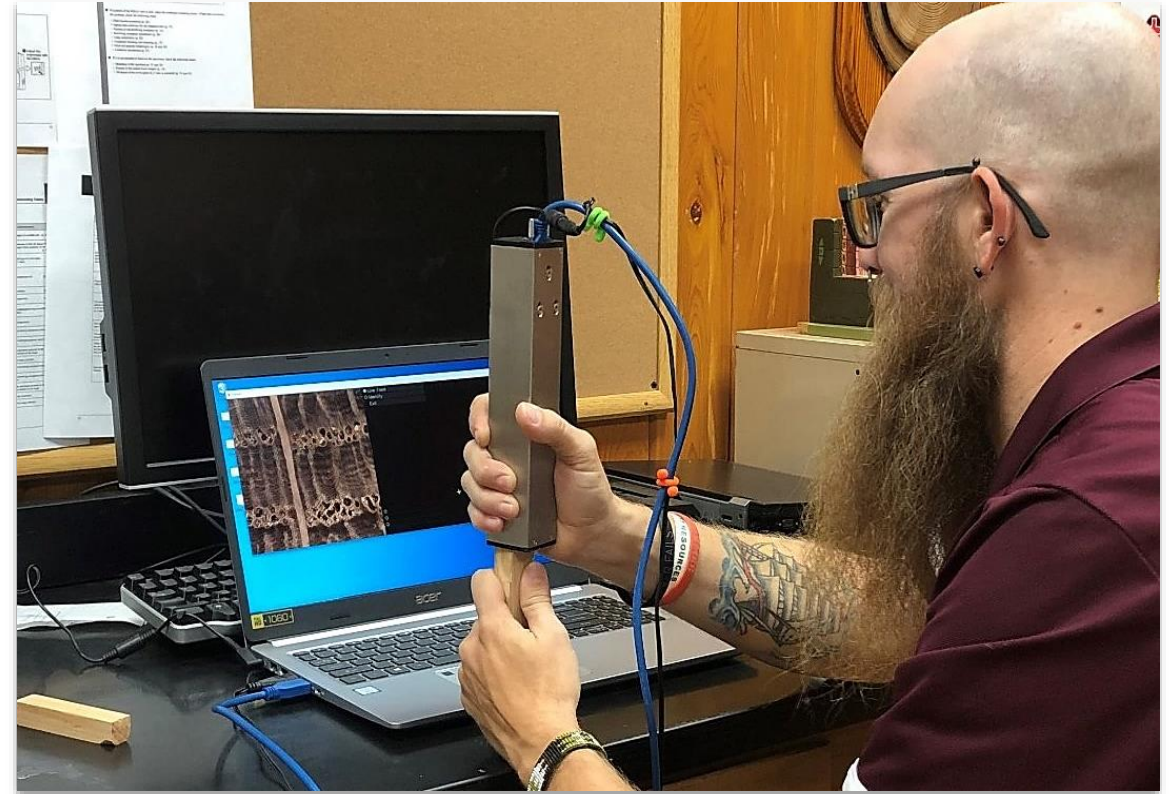
- Prepare specimens' transverse surfaces
- Capture many images of each specimen
- Designate class membership of images
- Train model
- Evaluate performance
- Iterate as needed
- Finalize metrics-driven deployment model



The XyloTron

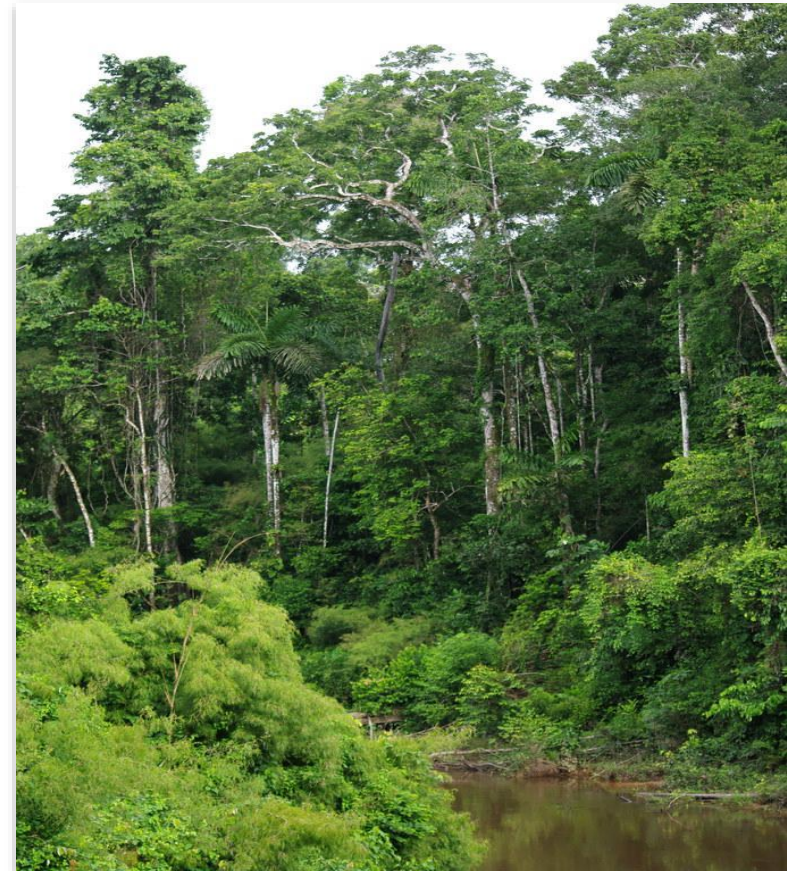
Operation and Specimen ID:

- Prepare specimen's transverse surface
- Place XyloScope flush on the specimen
- Capture image
- Wait ~ 1 second
- Read the output (confidence 0-100% for top 3 classes)



The Peruvian Wood ID Model

- Ravindran et al. (2021)
- Largest tested computer vision wood ID model for Peruvian woods
- Specimen level evaluation
- Surrogate Field Testing:
Model tested on test specimens from a separate xylarium



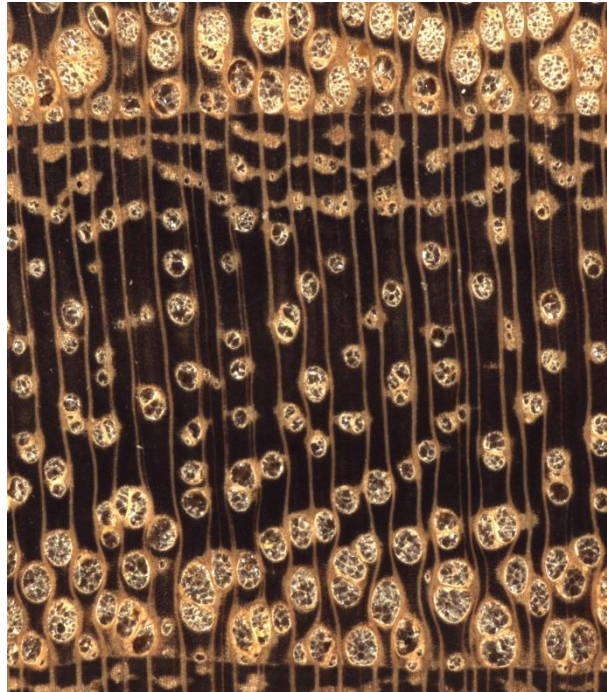
Surface Preparation



Good Quality Knife-Cut Images



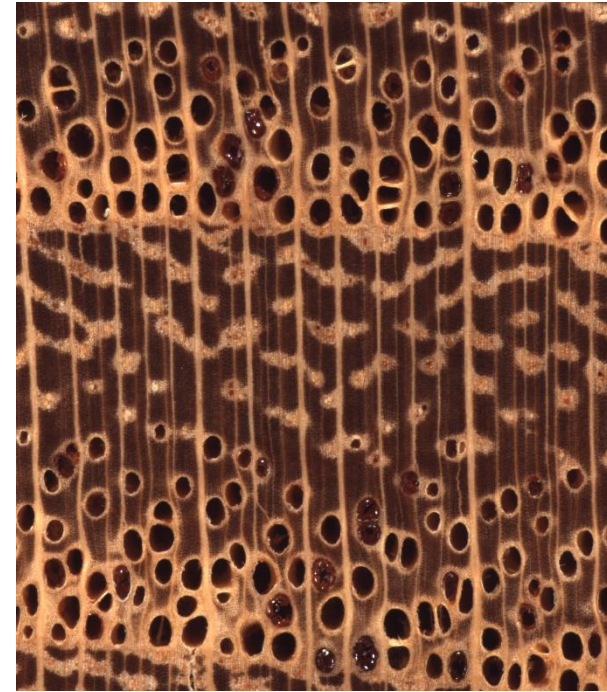
Ulmus americana



Robinia pseudoacacia



Celtis occidentalis



Gleditsia triacanthos

Poor Quality Images from Other Studies



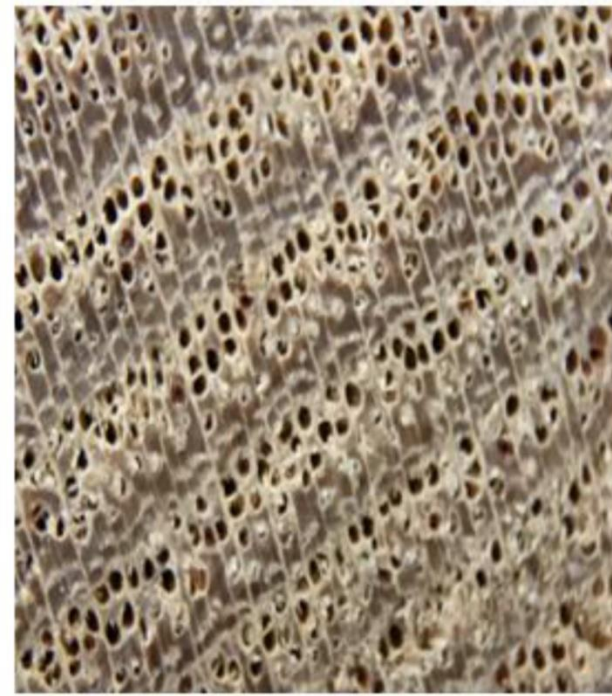
Ulmus americana



Robinia pseudoacacia



Celtis occidentalis



Gleditsia triacanthos

Some Questions

1. Does surface prep quality matter?
2. When does it start mattering?
3. How much does it matter?



Objectives



Objective

To evaluate the predictive accuracy of Ravindran et al.'s (2021) 24-class Peruvian model on images of test specimens prepared across a series of progressively coarser sanding grits (1500, 800, 600, 400, 240, 180 and 80) and high-quality knife cuts to determine if the reduction in surface quality leads to any reduction in model performance.



Methods



Test Specimen Preparation

Depolishing

- Transverse surface
- All specimens start at 1500 grit
- Six progressively coarser grits down to 80 grit
- Knife cuts at the end



Imaging

- Captured up to 5 images from each specimen at each grit with XyloTron



Training Images

(FPL Collections)

- 24-classes of Peruvian woods
- 1300 specimens
- All sanded at 1500 grit

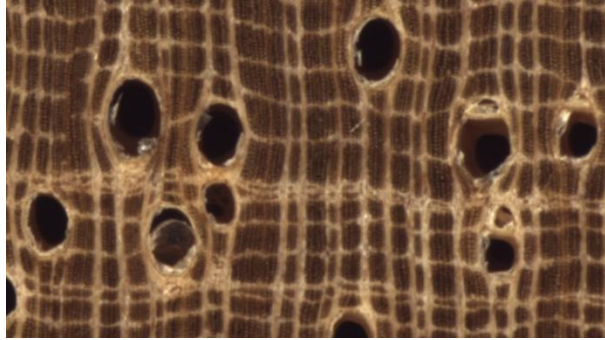
Class Label	Sanded	Knife-cut
Amburana	2	1
Aniba	2	1
Aspidosperma	5	2
BrosimumA	9	4
BrosimumU	2	2
Calycophyllum	7	2
Cariniana	8	4
Cedrela	20	7
Cedrelinga	6	6
Chorisia	5	4
Copaifera	3	3
Dipteryx	5	4
Eucalyptus	28	11
Guazuma	5	1
Hura	4	3
Maquira	2	1
Myroxylon	6	3
Ormosia	6	1
Pinus	2	1
Poulsenia	1	--
Pouteria	4	3
Schizolobium	3	--
Swietenia	15	8
Virola	17	3
Total	167	75

Testing Images

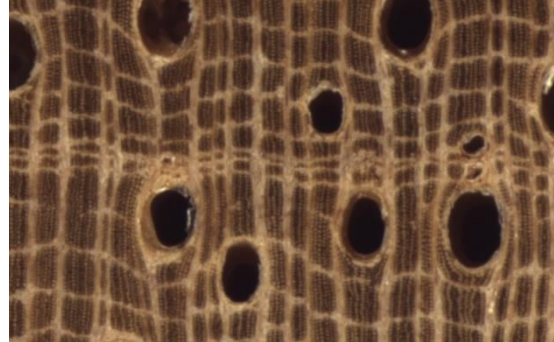
(MSU Collections)

- 24-classes of Peruvian woods
- 167 specimens sanded at 7 grits
- 75 specimens knife cut

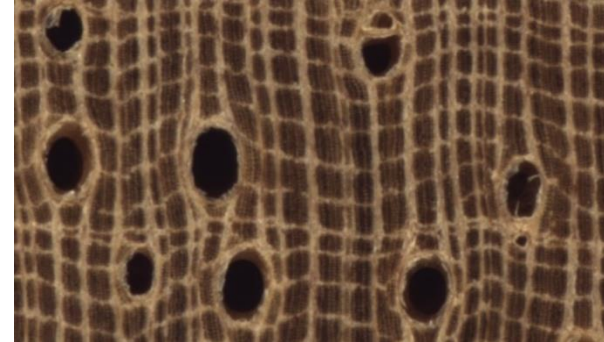
Surface Quality at Each Grit or Cut



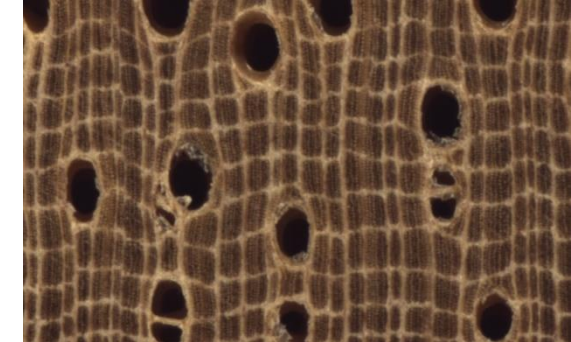
1500



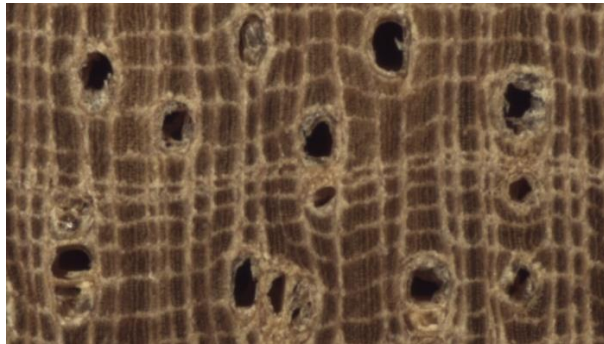
800



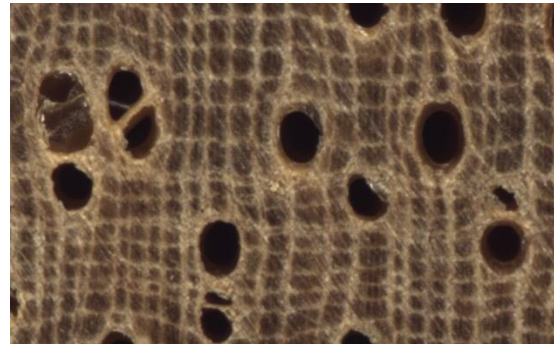
600



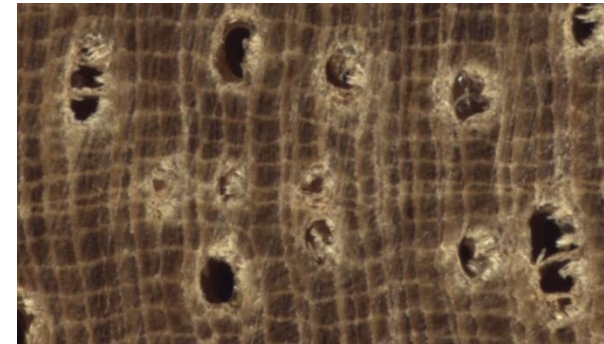
400



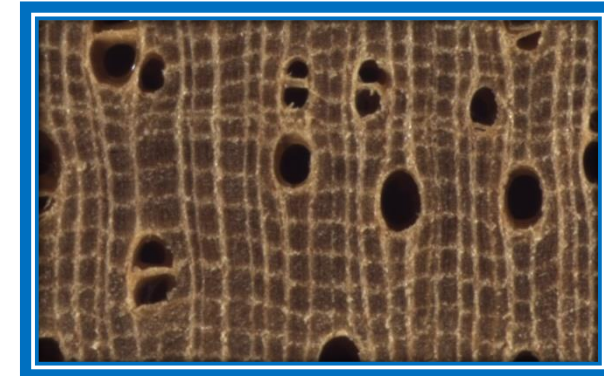
240



180



80



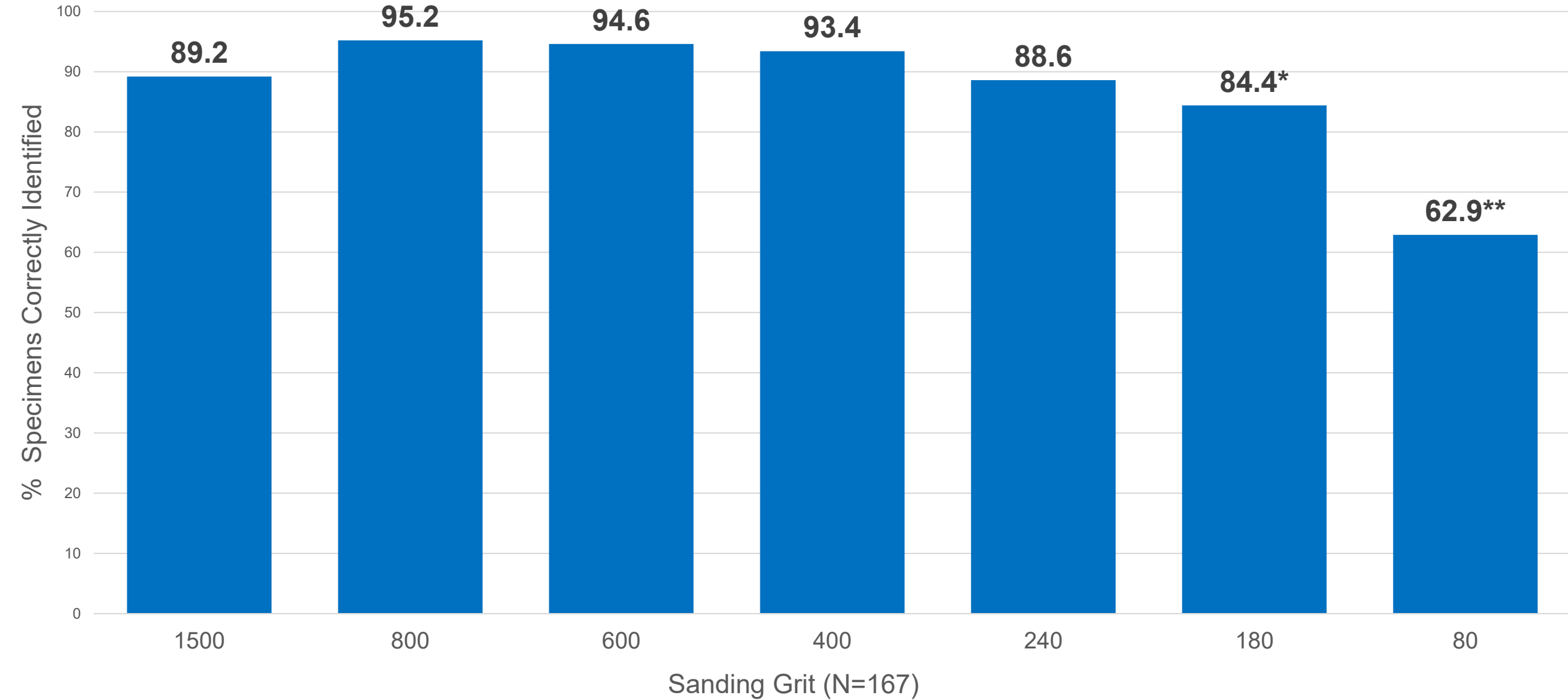
Knife Cut

Same specimen of Cariniana sp.

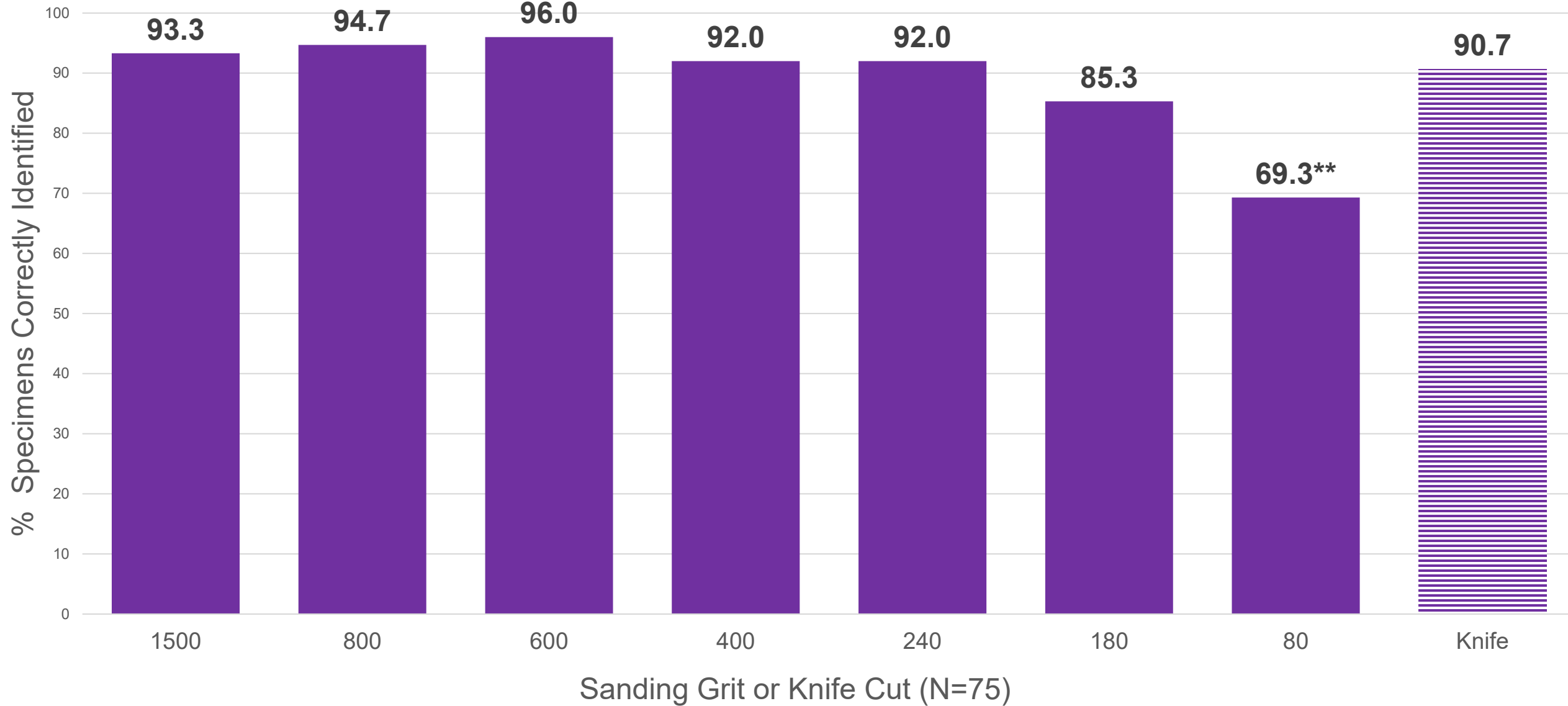
Results



Field Model Predictive Accuracy by Test Specimen Sanding Grit



Field Model Predictive Accuracy by Test Specimen Sanding Grit or Knife Cut



Discussion



Evidence Suggesting...

- Badly obscuring anatomical detail and/or the increase in surface preparation artifacts can result in reduced model performance.
- Minor differences between higher levels of surface preparation quality might have little-to-no practical effect.
- More datasets/study needed to offer general guidance.



Next Steps

- Expand the datasets to include training and testing images at each sanding grit and knife cut.
- Train and test on each combination of grit/cut.
- Apply results to estimate the minimum surface quality needed for testing in the field.
- Propose best practices for surface preparation.



How Surface Preparation Quality Affects the Performance of a Computer Vision Wood Identification Model

Frank C. Owens
Assistant Professor
Mississippi State University

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25. "Checklist," Animated Heaven (2016), Accessed 29 Apr 2021: <https://www.flickr.com/photos/71195909@N03/28955874330>
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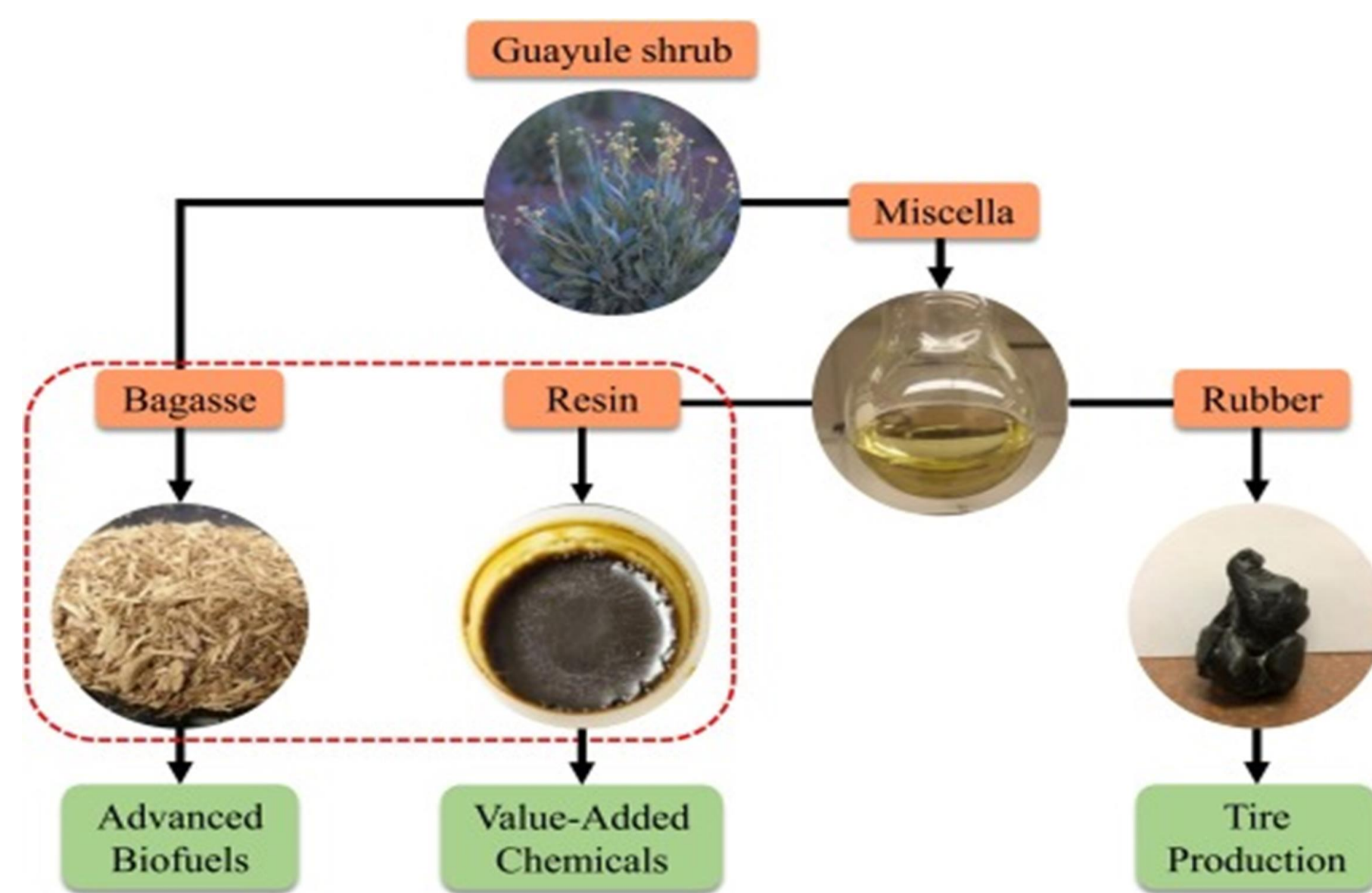
Utilizing Guayule Resin in Wood Products

Queen Aguma and C. Elizabeth Stokes, PhD
Department of Sustainable Bioproducts
Mississippi State University

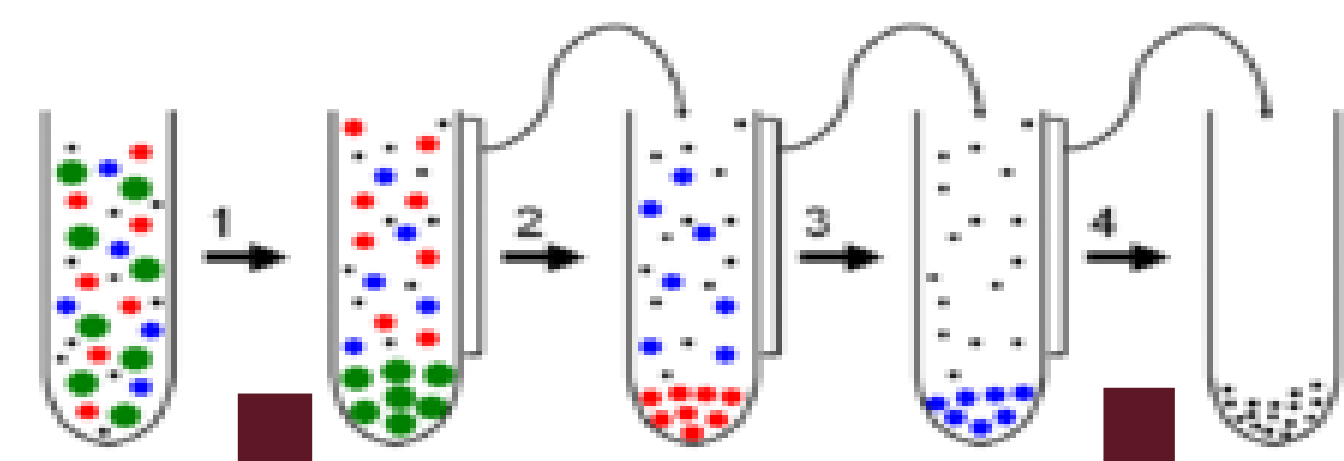
ABSTRACT

Parthenium argentatum, commonly known as guayule, a shrub native to the dry parts of the American southwest and Central America, has been modified for cultivation and large-scale rubber production in recent years. Investigations into uses of guayule by-products have led to potential applications in wood protection and preservation. Some of the complications that arise when trying to utilize guayule as a wood preservative are: 1. The determination of the required treatment and its retention levels, 2. development of the most efficient application technique, and 3. development of the most appropriate carrier system. Previous studies exposed native termites to concentrated solutions of guayule resin to determine the effect of dispersal in the various carrier compounds. Additionally, the possibility for leaching and retention of guayule from wood were also investigated. Fractionation, utilization, and application of guayule fractions are presented in this study.

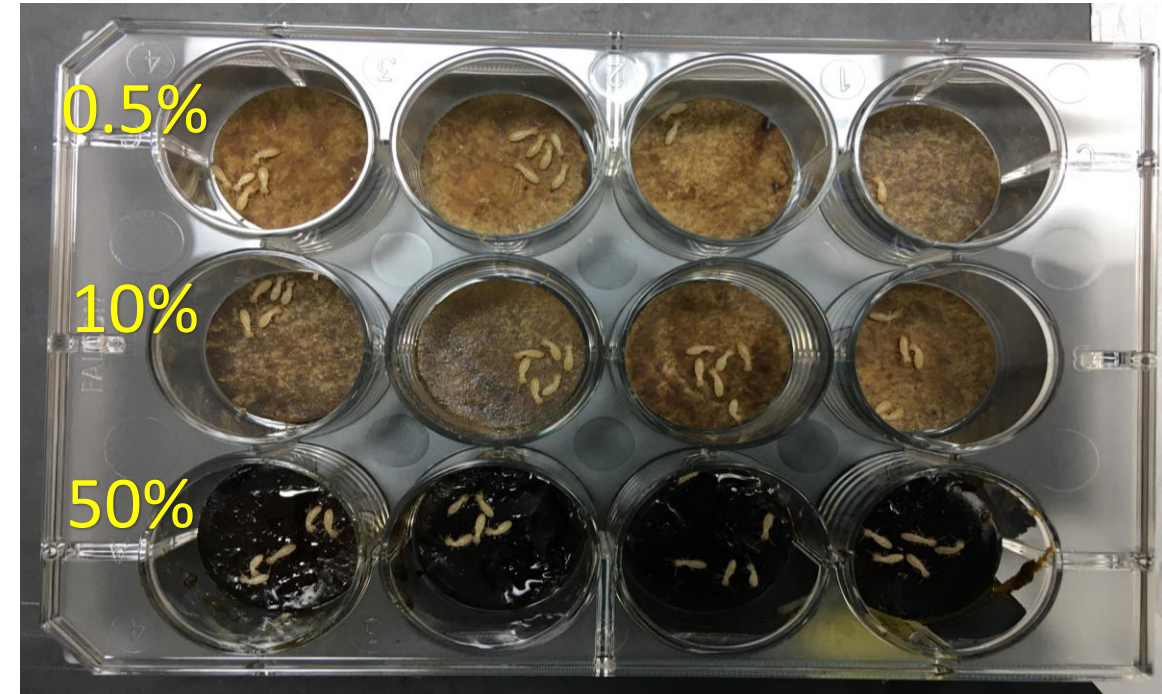
PRODUCTION OF GUAYULE PRODUCTS



FRACTIONATION



TERMITICIDES



ADHESIVES



Figure 1. Multiple product streams and waste streams may be generated during rubber production from guayule. Byproducts and waste streams may be used to create additional products such as termiticides and adhesives. Termiticide image shows 0.5, 10, and 50% guayule resin in toluene solutions applied to cellulose discs for termite feeding studies.

METHODOLOGY

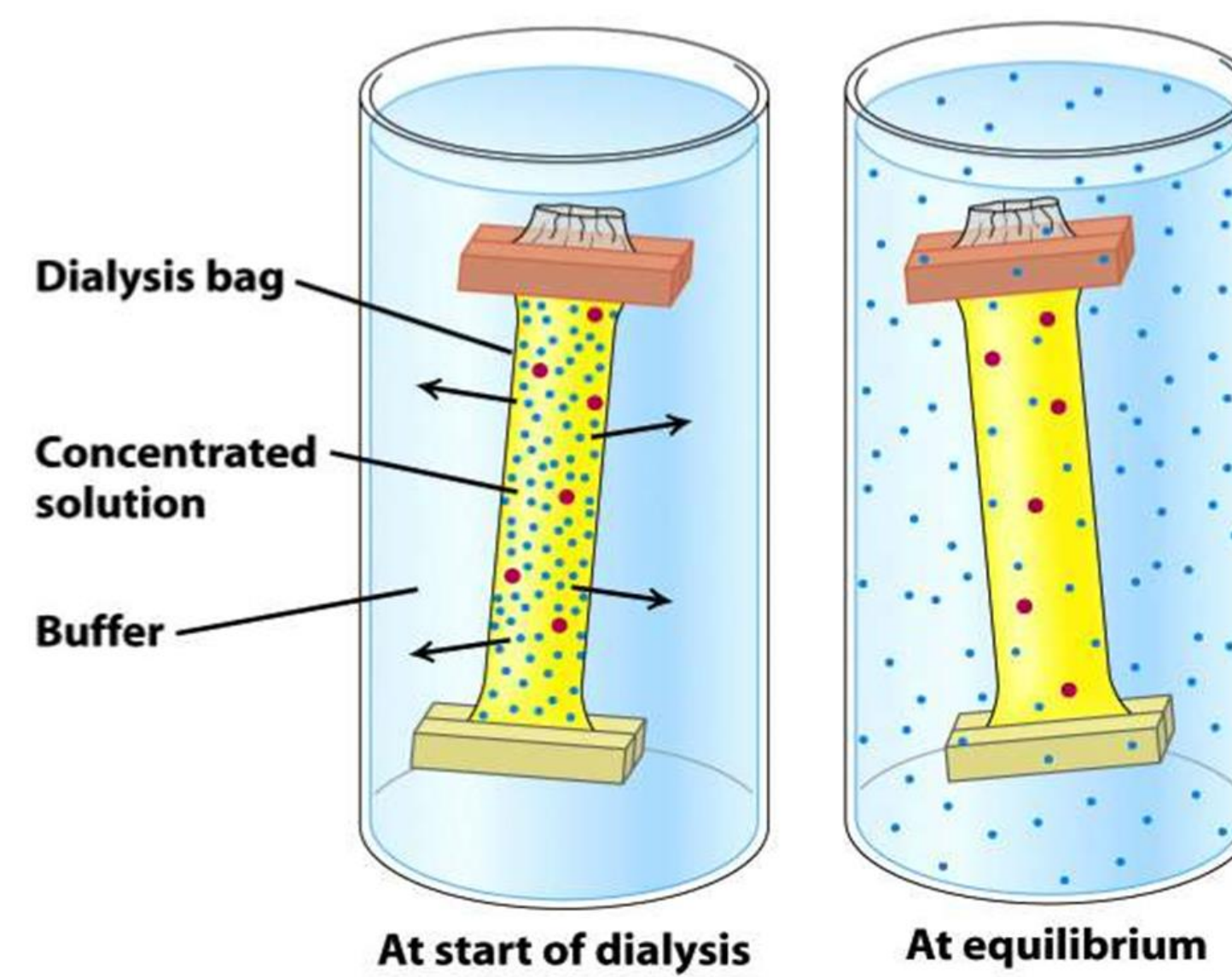


Figure 2. Dialyzing concentrated solutions allows separation based on molecular weight.

Dialysis is a method used to separate and purify molecules based on their size or molecular weight by selectively diffusing them across a semipermeable membrane.

Steps

- Resin preparation (swell the resin in an appropriate solvent or buffer solution)
- Apparatus set up and membrane preparation
- Resin loading into dialysis tubing
- Dialysis by placing resin into an external chamber of dialysis buffer
- Diffusion through the dialysis membrane
- Periodic changing of buffer solution
- Monitoring
- Collection of small and large fractions
- Post-fractionation workflow (concentration, buffer exchange, or further purification)

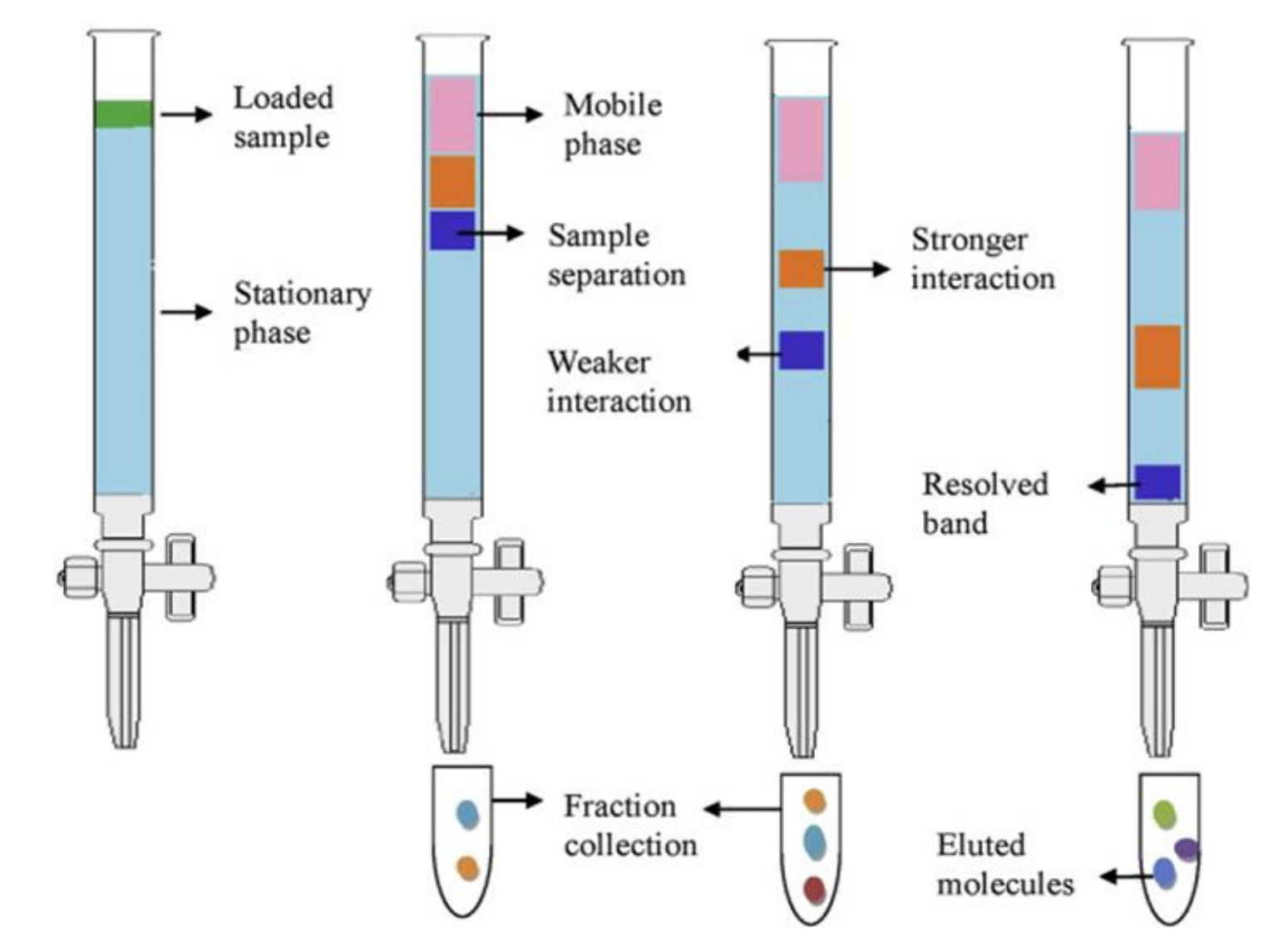


Figure 3. Column chromatography can be used to separate concentrated materials based on molecular weight, polarity, or hydrophobicity.

Separation chromatography uses differential interactions between a stationary phase (solid or liquid) and a mobile phase (liquid or gas) to separate and analyze mixture components.

Steps

- Smallest and shortest column selection that will provide good separation
- Stationary phase pick
- Preparation and preconditioning of the column (packing, required density, uniformity and running equilibration buffer)
- Mobile phase (preparation of eluent)
- Chromatography Column (Load and Run a wash buffer)
- Collection of fractions
- Analysis
- Post-fractionation workflow (concentration, purification)

DATA ANALYSIS

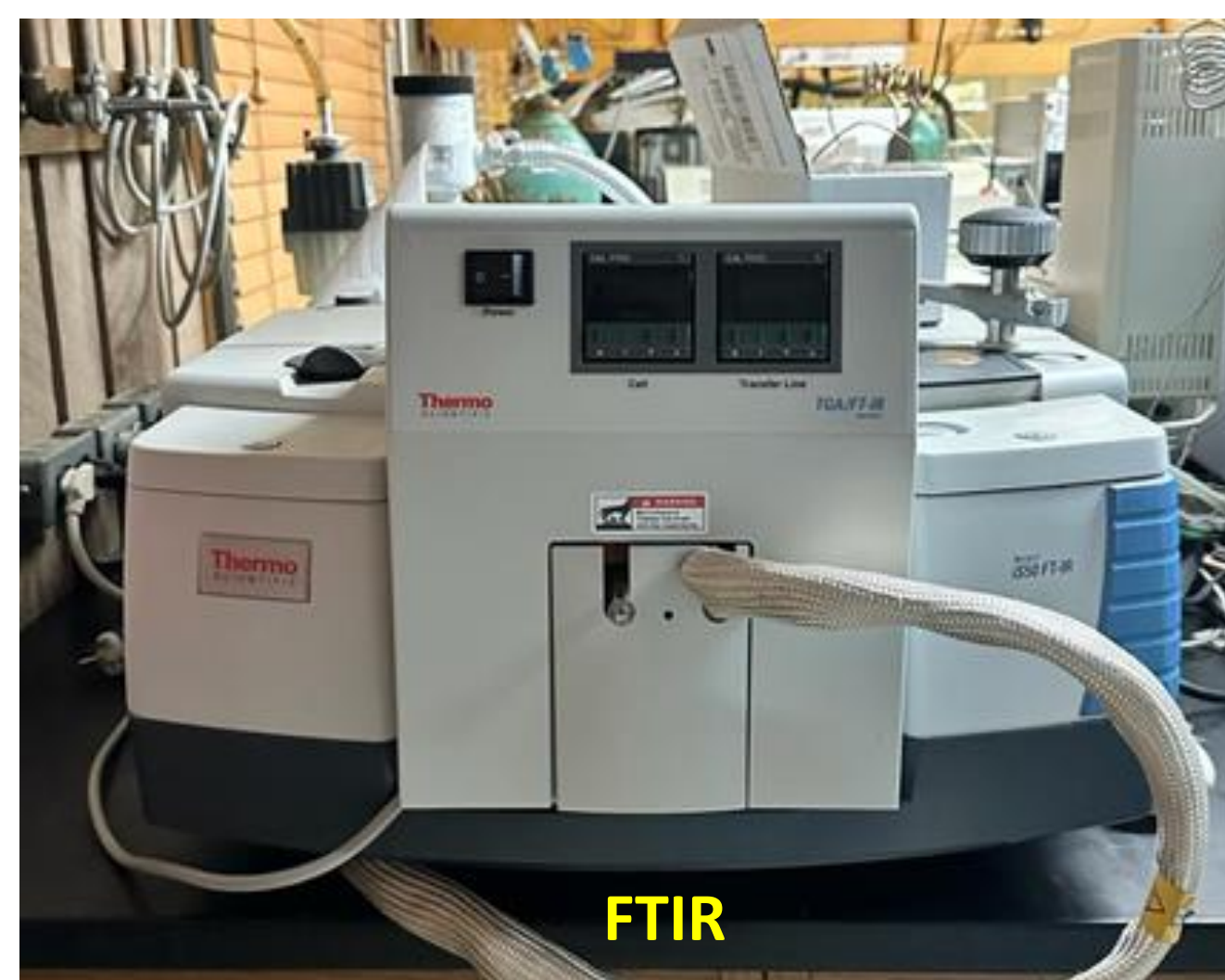


Figure 4. Fourier-transform infrared spectroscopy (FTIR) analyzes a sample's chemical content and molecular structure using infrared light.

Steps

- Placement of samples in a holder
- A detector reads the analog signal
- Detector converts the signal to a spectrum
- Computer (to analyze the signals and identify the peaks)
- The spectrum's peaks match the chemical bonds' vibrational modes, revealing functional groups and molecular structure
- IR beam



Figure 5. High Performance Liquid Chromatography (HPLC) uses a liquid chromatography system's stationary and mobile phases to separate, identify, and quantify mixture components.

Steps

- Preparation of sample and system setup
- Mobile phase preparation
- Column equilibration
- Injection of sample into HPLC
- Mobile phase flow (Chromatographic Separation)
- Monitoring the eluent (Detection and Analysis)
- Data collection and recording
- Interpretation of data

APPLIED TESTS

- Water repellency effectiveness test (WRE)
- Surface analysis
- Water contact angle test
- Color analysis
- Internal bonding test
- Bending strength
- Other tests as needed

TERMITE AND FUNGI TESTS

- Termite repellency test (AWPA E1)
- Decay resistance test (AWPA E10)

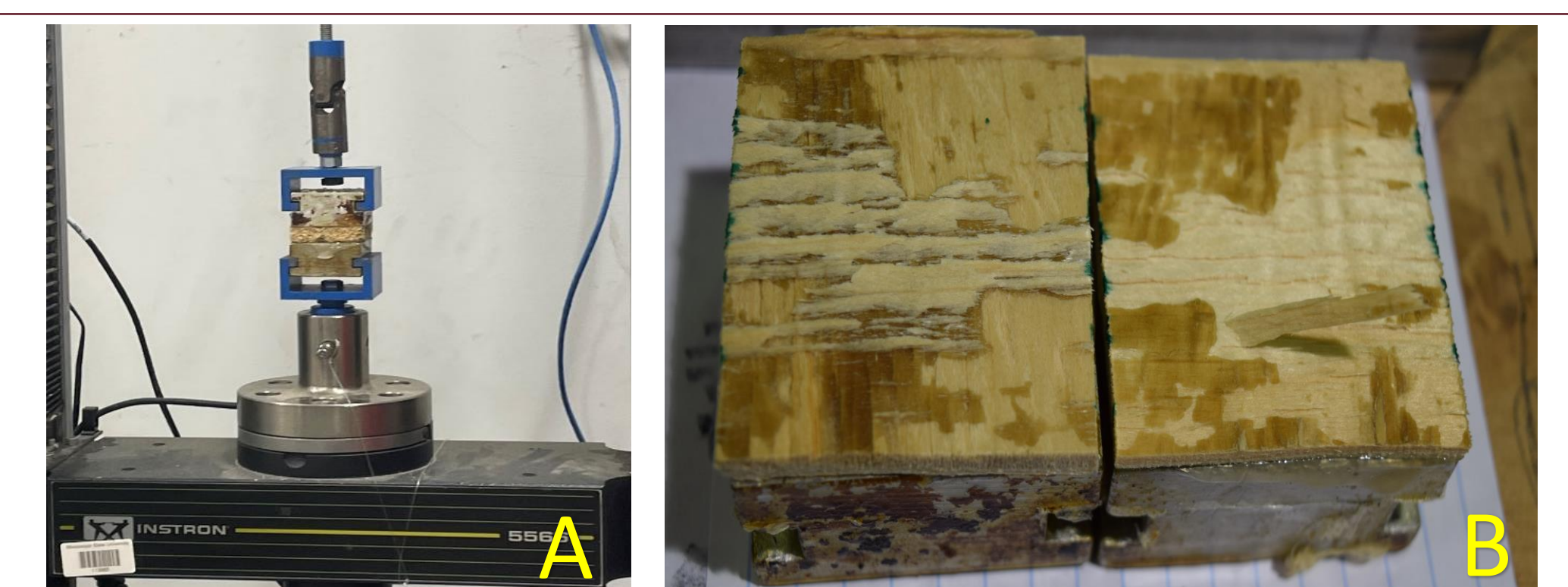


Figure 6. Internal bonding test on Tinius Olsen Universal Testing Machine (A) determines strength of the adhesive bond (B).



Figure 7. Example of decay resistance testing in AWPA E10 soil block study.



Figure 8. Example of termite repellency testing in AWPA E1 study.

EXPECTED OUTCOMES

- Identify guayule resin fractions for most effective adhesive or termiticide.
- Improve application of resin to engineered wood panel products.
- Make changes to the resin to improve the termiticide and adhesives qualities.
- Individual components will provide better treatment for wood, better resistance to decay and termite attacks.