

Characterising Superwood for Lutherie

Workshop-Scale Superwood Fabrication and Characterisation for Electric Guitar necks

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Preface

This thesis started way before it had a title, with a deep interest in how a guitar is put together and, even more so, what happens when you take one apart and build it differently. Ever since I started playing, I have been tinkering, swapping necks and bodies, mixing and matching woods to see what each does to the sound, rewiring pickups, changing hardware, and fixing anything that came my way. To me, a guitar is never really finished; it's just a collection of choices, and the question that always stuck with me was a simple one: what happens if you make a different choice?



A journey through tinkering with guitars: a collection of bodies, necks, and part-built instruments from the author's workshop. Necks and bodies swapped between guitars, woods mixed and matched by ear, electronics rewired, hardware changed, and whatever came along repaired.

One of those experiments became a guitar I called Scratch Paul,^[1] an electric built entirely from reclaimed wood, assembled from offcuts and salvaged timber - pine drawing boards sandwiched together for the body and laterally laminated marine plywood for a neck, freshly bought timber.



Scratch Paul, the author's reclaimed-wood electric: a body laminated from pine drawing-board offcuts and a laterally laminated marine plywood neck.[1]

It taught me, with a chisel and a soldering iron rather than a testing machine, that the wood a guitar is made from is not sacred, and that a good instrument can come from humble material if you understand what that material is doing. Years of building this way, matching woods by ear and by feel, trying to make inexpensive guitars feel and sound like premium ones, left me with a question I could not answer by intuition alone: what is it, measurably, that makes one wood sound and behave the way it does, and could an abundant, otherwise seen as unglamorous species be made to do the work of a prized one?

This thesis is my way of trying to answer that question correctly. It combines the workshop's feel with the lab's precision. Instead of just feeling and hearing a neck, I now measure it and use standard tests adapted for the workshop. I've always tried to keep what I can prove separate from what I can only guess. The tinkerer's curiosity still drives the work, and I have always aimed to make the investigation thorough, honest, and scientific. This way, a hunch developed over years of building guitars can become something a reader can trust and build upon.

Abstract

Guitar making depends on a set of 'tonewoods'. The increasing regulations on traditional tonewoods motivates the development of sustainable alternatives for musical instrument manufacture. These woods are slow growing and increasingly limited by cost, supply, and conservation restrictions, which raises a practical question: can an abundant, fast-growing species be processed to stand-in as a drop-in replacement? A credible substitute would ease the pressure on scarce timbers and make instrument building more sustainable, without asking players to accept an engineered composite in place of real wood.

To address this, as a proof of concept, yellow poplar (a common fast-growing hardwood) was delignified and densified, with equipment available at a laboratory, transferable to a workshop scale. The material was then characterised against hard maple across the properties that matter for a guitar neck - its density, surface hardness, bending stiffness, and tap tone, using adapted mechanical and acoustic testing standards.

The densified poplar met the bending stiffness of maple and exceeded its surface hardness, showing that the mechanical demands of a neck can be met by a processed abundant species. Its acoustic behaviour was more subtle: the compression needed to reach maple level hardness lowered the material's specific stiffness (the ratio of stiffness to density), which emerged as one of several properties affecting tonal character, and it showed that the acoustic and mechanical optima need not coincide. For a given species there is likely an ideal degree of densification for tone, lighter than the compression that maximises hardness.

The study concludes that superwood properties can be tuned, and discusses the design drivers that should guide how far it is densified, because it sets the wave speed and with it the tap tone frequency. It is not, however, a standalone predictor of perceived tonal character: density, impedance, the radiation ratio and damping must be read together. Its durability in service is established in principle and scoped for validation. More broadly, the work reframes densification as a property to be tuned rather than maximised, and points to sustainable tonewoods that behave as natural wood rather than engineered substitutes.

Keywords: superwood, wood densification, delignification, guitar manufacturing, lutherie, tonewood alternatives, acoustic characterisation of wood

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Artificial intelligence tools were used during the preparation of this document as writing aids. Their use was limited to spell-checking, grammar and language refinement, summarising sections for clarity, and assisting with formatting and layout of the document. All research, experimental design, data collection, analysis, interpretation, and conclusions are the author's own work. AI was not used to generate original technical content, test plans, results, insights or arguments.

Data reading, parsing, and plotting were carried out with standard tools, namely Python with the matplotlib library, with the help of tools like Microsoft Excel and Claude Code. Their use was limited to reading and organising the recorded measurements and to curve fitting: for example, fitting and extrapolating the Janka load against depth curve beyond the machine's force limit to estimate the value at full ball penetration. No measured value was generated, replaced, or altered by these tools; every measurement reported is the instrument reading, and any fitted or extrapolated value is labelled as such.

Nomenclature

This section defines the specialised vocabulary, symbols, and abbreviations used in this thesis, covering the guitar and lutherie terms, the wood chemistry and anatomy, the densification process, and the mechanical and acoustic testing. Terms that a general science reader would already know are omitted. Definitions are concise and refer to the sense in which each term is used here.

Symbols and Notation

Symbol	Meaning	Unit
E	Modulus of elasticity (Young's modulus); bending stiffness of the material	GPa
MOE	Modulus of elasticity, as above	GPa
MOR	Modulus of rupture; bending stress carried at failure	MPa
ρ	Density	g/cm ³
E/ρ	Specific stiffness; stiffness carried per unit weight. Sets the wave speed and tap frequency; one of several descriptors linked to the warm to bright character, not a direct predictor of it on its own (Section 6.3, Appendix F)	-
$\sqrt{(E/\rho^3)}$	Acoustic radiation coefficient (radiation ratio); how efficiently a material radiates sound	-
c	Sound velocity; speed of a stress wave along the grain, $c = \sqrt{(E/\rho)}$	m/s
f₁	First flexural resonant frequency of a tapped beam	Hz
η	Loss factor (damping); fraction of vibrational energy dissipated per cycle	-
Q	Quality factor; sharpness of a resonance and reciprocal of damping, higher Q meaning longer sustain	-
T₆₀	Decay time; time for the tap response to fall by 60 decibels	s
T_g	Glass transition temperature of lignin	°C
μ	String mass per unit length	kg/m
T	String tension (context dependent; T also denotes the tangential axis where stated)	N
M	Bending moment applied to the neck by the strings	N·mm
e	Offset of the strings from the neutral axis of the neck	mm
δ	Midspan deflection in the bending test	mm
k	Stiffness; load per unit deflection	N/mm
F, F_{max}	Applied load and peak load	N
H₂/H₁	Harmonic content ratio; second overtone amplitude relative to the fundamental	-

L, R, T	Longitudinal, radial, tangential; the three natural axes of wood (L also denotes span where stated)	-
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Abbreviations

ABX	A three sample listening test in which a listener decides whether an unknown sample X matches reference A or reference B.
ASTM	American Society for Testing and Materials; the source of the test standards adapted in this work.
CITES	Convention on International Trade in Endangered Species; the treaty restricting trade in many tonewoods.
EMC	Equilibrium moisture content; the moisture level a wood settles at in a given environment.
FPL	Forest Products Laboratory (USDA); source of reference wood property data.
G type, S type, GS type	Lignin classes: guaiacyl, syringyl, and mixed guaiacyl syringyl.
JND	Just noticeable difference; the smallest change a listener can reliably detect.
MOE	Modulus of elasticity.
MOR	Modulus of rupture.
NSSC	Neutral sulphite semi chemical; a sodium sulphite-based solution trialled in the screening step.
RQ, SRQ	Research question and sub research question.
USDA	United States Department of Agriculture.

Glossary of Terms

Guitar and Lutherie

Lutherie, luthier	The craft of building and repairing stringed instruments, and the person who practises it.
Tonewood	A wood chosen for a musical instrument on account of its acoustic and mechanical properties.
Solid body, semi hollow, hollow body	Electric guitar constructions with, respectively, a solid timber body, a partly chambered body, and a fully hollow resonating body.
Soundboard	The thin resonating top plate of an acoustic instrument that radiates most of its sound.
Fretboard (fingerboard)	The thin hard wood surface on the front of the neck against which the strings are pressed.
Fret	A metal strip set across the fretboard that fixes the vibrating length, and hence the pitch, when a string is pressed behind it.
Fret wire, fret tang, fret slot	The stock a fret is made from, the ridged base that grips the wood, and the sawn groove it seats in.
Nut	The slotted strip at the top of the neck that spaces and seats the strings as they pass to the headstock.
Bridge, saddle	The assembly anchoring the strings at the body, and the small movable supports on it that set string height and intonation.
Tuner (machine head, tuning peg)	The geared mechanism on the headstock that winds a string to set its tension and pitch.
Bushings	The fittings that seat the tuners in the headstock.
Truss rod	The adjustable steel rod inside the neck that opposes string tension and sets the neck curvature.
Relief (bow)	The slight deliberate forward curve of the neck under string tension.
Action (action height)	The height of the strings above the frets.
Intonation	The accuracy of pitch along the length of the neck.
Scale length	The vibrating string length from nut to bridge saddle, which sets the pitch relationships and the tension required.
Pickups	Coils wound around magnets that sense the steel strings' motion and convert it into an electrical signal.
Pickup selector, potentiometers (pots)	The switch that selects pickups, and the variable resistors behind the volume and tone controls.
Output jack	The socket through which the signal leaves the guitar.
String gauge	The thickness of a string or a set of strings.

Neck joint	The junction where the neck meets the body.
Setup	The periodic adjustment of truss rod, action, and intonation that keeps a guitar playing correctly.
Sustain	How long a note continues to sound after it is struck.
Tap tone	The sound a piece of wood makes when struck, used to judge its stiffness and damping.

Tonewood and Tonal Vocabulary

Warm	A fuller, darker tone with softer high frequencies.
Bright	A tone with pronounced, cutting high frequencies.
Crisp	A sharp attack with clean separation between notes.
Muddy	A soft onset with notes that blur into one another.
Attack	How quickly a note reaches full volume after it is struck.
Clarity	How distinctly successive notes stay separated rather than overlapping.
Presence	The forward, cutting quality of a tone in the upper register.
Voice (sonic or tonal signature)	The characteristic sound associated with a given wood or instrument.
Overtone rich	Producing strong harmonics above the fundamental, heard as a lively, complex tone.
Harmonic content (H_2/H_1)	The strength of the overtones relative to the fundamental, used here as a measure of timbre.

Materials and Species

Roasted maple (torrefied maple), torrefaction	Maple heat treated at high temperature in low oxygen to reduce moisture and improve stability; and the process itself.
Laminated maple	Maple built up from bonded layers rather than a single solid piece.
Richlite	A dense resin and paper composite used commercially as a fretboard material.
Korina, swamp ash, basswood, koa, paulownia	Less common tonewoods referred to for comparison.
Acer saccharum	Botanical name for North American hard maple.
Picea abies	Botanical name for Norway spruce.
Liriodendron tulipifera	Botanical name for yellow poplar.
Swietenia macrophylla	Botanical name for Honduran mahogany.

Wood Chemistry and Anatomy

Delignification	The partial chemical removal of lignin from wood to soften the cell walls.
Densification	Compressing the softened wood to collapse its cell cavities and raise its density.
Lignin	The natural polymer that binds the cellulose framework of wood and gives it rigidity.
Guaiacyl (G type), syringyl (S type), guaiacyl syringyl (GS type) lignin	Lignin classes differing in their building blocks; softwoods are mainly G type and more resistant to chemical breakdown, while hardwoods also contain S type.
Monolignol; coniferyl, sinapyl, p coumaryl alcohol	The alcohol building blocks from which lignin is assembled.
β O 4 aryl ether linkage	The most common chemical bond linking lignin units, and the main target of the alkaline treatment.
Sulphonation	A reaction that attaches sulphonate groups to lignin, keeping the dissolved fragments soluble.
Klason lignin	A standard laboratory method for measuring the lignin content of wood by mass.
Microfibrils	The fine crystalline cellulose fibres that give the cell wall its tensile strength.
Cell lumen (lumina)	The hollow central cavity of a wood cell, which collapses during densification.
Earlywood	The lower density wood formed early in a growing season, with thin walled cells.
Ray structure	The bands of cells running radially across the grain, which affect workability and appearance.
Growth rings	The annual rings visible in a cross section; a face may meet them normal (across) or parallel (along).
Orthotropic	Having distinct properties along three mutually perpendicular axes, as wood does.
Longitudinal, radial, tangential	The three natural directions of wood: along the grain, across the rings, and along the rings.
Equilibrium moisture content	The moisture level a wood settles at in a given temperature and humidity.
Vacuum pre impregnation	Drawing the treatment solution into the wood under reduced pressure before boiling.

Densification Process

Spring back	The partial recovery of a compressed sample toward its original thickness after the press is released.
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Hot pressing, cold pressing	Compressing wood with or without heat; only hot pressing softens the lignin enough to lock the compressed shape.
Cooling under load	Holding the press closed while the sample cools, so the lignin resolidifies in its compressed geometry.
Constraining jig	The steel fixture that prevents the sample spreading sideways during pressing.
Compression ratio	The percentage reduction in thickness achieved by pressing.
Glass transition (of lignin)	The temperature range over which lignin softens from rigid to pliable; the mechanism that makes hot pressing permanent.
Workshop scale	Achievable with accessible equipment rather than industrial or specialist laboratory apparatus.

Testing Terms and Standards

Janka hardness	The force needed to press a steel ball halfway into the wood; a measure of surface indentation resistance.
Normal, parallel to the rings	Indentation on the flat face across the rings, or on the edge face along them.
Blank, coupon	A prepared piece of wood for processing or testing; the coupon is the smaller cut down piece used for bending.
Density graded (density gradient)	Having density that varies through the thickness, denser near the pressed faces.
Version A, Version B	This study's labels for the conservative measured lower bound and the extrapolated estimate of Poplar 50% hardness.
Truncation force	The force recorded at the instant the testing machine reached its limit before full penetration.
Machine load ceiling	The maximum force the testing machine can apply.
ASTM D143, E1876, D6874	The test standards adapted for hardness, bending, and acoustic testing respectively.
USDA Wood Handbook	The reference source of certified wood property data used for benchmarking.

Acoustic and Material Tonal Terms

First flexural frequency (f_1)	The lowest bending resonance of a freely supported beam, set by its stiffness and density.
Dynamic modulus (dynamic MOE)	Stiffness inferred from a vibration rather than a slow bend; usually slightly higher than the static value.
Specific stiffness (E/ρ)	Stiffness per unit weight
Acoustic radiation coefficient	A measure of how efficiently a material radiates sound; light, stiff woods score high.

(radiation ratio, $\sqrt{(E/\rho^3)}$)	
Loss factor (η)	The fraction of vibrational energy dissipated per cycle; high damping shortens sustain.
Decay time (T_{60})	The time for a struck note to fall by 60 decibels; a direct measure of sustain.
Just noticeable difference (JND)	The smallest change in a sound a listener can reliably detect.
ABX discrimination test	A blind listening test in which a listener judges whether an unknown sample matches one of two references.
Piezo contact disc	A small sensor that picks up vibration directly from the surface of the sample.
Ashby chart (stiffness against density)	A materials selection chart plotting modulus against density for all material families.
ANSYS Granta EduPack	The materials database and charting software used to generate the Ashby chart.
Valorisation, upcycling	Turning low value or waste wood into a higher value material.
Speed of sound in wood ($c = \sqrt{(E/\rho)}$)	The wave speed along a bar, set by modulus and density; it fixes the pitch of the wood's own resonances.
Acoustic impedance ($Z = \rho c$)	A measure of how stiffly a material resists being driven; for a solid body it describes how firmly the wood anchors and loads the string.
Quality factor (Q)	The reciprocal of the loss factor; a high Q indicates a lightly damped sample that rings for longer.
Loss tangent ($\tan \delta$)	The tangent of the phase angle by which strain lags stress in a viscoelastic material; equal to the loss factor for light damping.
Complex modulus ($E^* = E' + iE''$)	The storage modulus E' , the energy returned each cycle, together with the loss modulus E'' , the energy dissipated; their ratio gives $\tan \delta$.
Half power bandwidth (-3 dB width, $\Delta f / f_0$)	The width of a resonance peak three decibels below its maximum, normalised by the peak frequency; the route used to read damping from a tap.
Acoustic conversion efficiency ($ACE = R / \tan \delta$)	The radiation ratio divided by the damping; a combined figure of merit that rewards light, stiff, low damping wood.
Acoustic constant (A)	An alternative name for the radiation coefficient c / ρ , used in the recent densification literature.
Longitudinal mode ($c = 2Lf$)	A compression wave resonance along the length of a bar; the mode required if the speed of sound is to be read from a tap frequency.

Nodal suspension	Supporting a specimen at the nodes of the mode of interest so that the supports remove as little vibrational energy as possible.
Viscoelastic hysteresis	The lag between loading and unloading in the cell wall polymers; the enclosed area is the energy converted to heat each cycle, the origin of internal damping.
Harmonic content ratio	The relative strength of the overtones above the fundamental, used as a descriptor of overtone richness.

Design Framing

Material driven design (material experience)	A design approach that treats how a material looks, feels, and sounds as legitimate design variables, not only its measured properties.
Perceptual mapping	Placing materials on axes defined by how people perceive them, such as warm to bright.
Player perception, player acceptance	How musicians experience a material and whether they will accept it as a substitute for a traditional tonewood.

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Chapter 1 - Introduction

1.1 Background and Context

Lutherie is the craft of building stringed instruments such as guitars, violins and cellos, and a craftsman is known as a luthier. This project focuses specifically on electric guitars. An electric guitar is built from a small number of principal wood components: the body (usually bean shaped, houses the electronics and bridge mainly and the part where the strings are strummed/plucked) ; the neck, which is the part where the notes are played. This project is concerned specifically with the neck, the component that must combine sufficient stiffness to resist bowing under string tension with sufficient surface hardness to resist wear at the frets and nut.

The guitar manufacturing industry has relied on specific wood species for construction for centuries, each contributing to a certain sonic character, with maple and mahogany being the predominant materials for electric guitar necks. These specific wood species, often called ‘tonewoods’, are selected for their acoustic and mechanical properties. While the overall sound of an instrument is also dictated by its construction, joineries, adhesives, and electronics, but the wood itself is a major part of what defines the sound. Lately, these species are increasingly scarce due to overexploitation, habitat loss, and international trade restrictions.^[2,3]

1.1.1 The Tonewood Crisis

Since 2017, the Convention on International Trade in Endangered Species (CITES) has regulated the trade of certain rosewood and mahogany species, significantly impacting guitar manufacturers.^[2] While rosewood primarily affects fretboards rather than necks, It is only a matter of time before other species are also subject to these regulations.

Maple and mahogany, the primary neck woods for electric guitars, face similar pressures. As Guitar World reports, manufacturers are facing the reality that the woods they have relied on for decades are no longer guaranteed.^[3] This scarcity drives up costs and threatens the viability of small-to-medium guitar manufacturers, however larger companies still rely on their wood reserves, they are finite.

Ebony (another wood that is used in fretboards) presents a parallel case, with stricter export controls and traceability requirements. Although ebony has not been restricted as broadly as rosewood, these regulations have increased costs and administrative complexity across the supply chain, limiting its use to high-end instruments.

1.1.2 Effects of the Tonewood Crisis

The increasing scarcity and regulation of traditional tonewoods have introduced structural challenges to consistency, material reliability, and manufacturing reproducibility within the guitar industry.

A primary consequence is the growing variability between instruments that are identical (same model). For instance, the same model produced by Fender across different manufacturing locations (like USA, Indonesia, Korea, Japan) may use different wood species due to regional availability, cost constraints, and supply chain considerations. Even within a single production context, the substitution of species leads to measurable differences in density, stiffness, and acoustic response, affecting the perceived tonal characteristics of the instrument.

Beyond inter-species variation, wood as a natural material introduces inherent intra-species variability. Differences in growth conditions, grain orientation, moisture content, and ageing result in heterogeneous material properties across batches. Collectively, these factors challenge the principle of replicability that underpins industrial manufacturing and represent a fundamental disruption to established manufacturing practices in the guitar industry.

1.1.3 Current Industry Response

The guitar industry has responded with several strategies:

- **Alternative species exploration:** Manufacturers experiment with less traditional woods, though these often lack the established performance characteristics of maple or mahogany.
- **Certified sustainable sourcing:** While important, this approach does not address fundamental scarcity.
- **Synthetic alternatives:** Carbon fibre, Richlite (a composite material for fretboards made from paper pulp)^[4] and other composites offer consistency but face aesthetic and cultural resistance from players and builders.

None of these approaches fully addresses the dual challenges of sourcing/sustainability and performance equivalence to traditional tonewoods.

1.1.4 Superwood as a Solution

Superwood is wood engineered through chemical delignification and mechanical densification, offers a potential paradigm shift. Pioneered by researchers at the University of Maryland,^[5] superwood demonstrates mechanical properties that can exceed steel while remaining fully bio-based and sustainable. However, superwood is not to be confused with MDF/particle board or other wood based composites, as it is the closest to natural wood, using a natural binder.

The fundamental principle is straightforward: by partially removing lignin(the natural polymer that binds cellulose fibres) and subsequently compressing the wood structure, low-density abundant softwoods can achieve the density and mechanical properties of scarce hardwoods. Recent work states that low-value wood can be transformed into high performance structural materials suitable for various applications.^[6]

1.1.5 Research Gap

While superwood research has advanced rapidly in materials science laboratories, translation to specialised applications like musical instrument manufacturing remains unexplored. Specific gaps include:

- **Workshop-scale feasibility:** Published superwood methods require industrial equipment not available to small manufacturers.
- **Application-specific characterization and validation:** Guitar necks demand specific combinations of mechanical strength, dimensional stability, and subjective tonal characteristics that have not been characterised in superwood.
- **Player acceptance:** Beyond measurable properties, guitar necks must satisfy aesthetic and perceptual criteria that define player experience.

This thesis addresses these gaps by developing a workshop-scale superwood process and validating performance through technical characterisation.

1.2 Problem Statement

How can an abundant, fast grown wood be delignified and densified, using equipment accessible to a small or medium workshop, to meet the mechanical and acoustic demands that a traditional tonewood such as hard maple meets in an electric guitar neck?

This question is approached along two dimensions that this thesis addresses empirically, and two further dimensions that it identifies and frames but leaves for validation beyond its scope.

Addressed in this thesis:

- Technical feasibility. Can a densified abundant species meet or exceed the bending stiffness and surface hardness a neck requires, and does its acoustic behaviour place it credibly among the woods luthiers already use?
- Manufacturing accessibility. Can the process run on workshop accessible equipment, without a fume hood, an industrial press, or a climate chamber, and does the resulting material enter an ordinary lutherie workflow?

Identified and framed, and set out as named future work:

- Dimensional stability in service. The treatment is expected on chemical grounds to improve humidity stability, but this is established here as a reasoned hypothesis rather than measured. The validation programme is set out in Section 7.2.
- Perceptual acceptance and economic viability. Whether players accept the material as a tonewood, and whether it is cost competitive, are recognised as decisive for adoption but fall outside the empirical scope of this thesis. The perceptual question is framed in Chapter 5 and scoped for a listener study; economic modelling is left to future work.

1.3 Research Objectives and Questions

1.3.1 Project Goal

To develop a workshop-scale process for producing densified wood, or superwood, and to characterise it against hard maple as a candidate guitar neck material: its mechanical and acoustic performance, its manufacturing feasibility, and how closely it behaves as a natural tonewood, for small to medium guitar manufacturers.

1.3.2 Research Questions

This goal is addressed through two primary research questions (RQs) and six sub-research questions (SRQs):

RQ1: Technical Feasibility

To what extent can workshop-scale superwood production deliver the mechanical and acoustic properties that a traditional neck tonewood, benchmarked against hard maple, provides, and what can be established about its dimensional stability?

- **SRQ1.1:** What are the baseline mechanical, acoustic, and dimensional stability properties to be matched, benchmarked from traditional tonewoods?

- **SRQ1.2:** What is the relation between densification/compression parameters and mechanical/acoustic properties?
- **SRQ1.3:** Can superwood be integrated into traditional neck manufacturing workflows without specialised equipment and tools?

RQ2: Behaviour as a Natural Tonewood

How closely does superwood, as an engineered wood, behave like a natural tonewood: in how it looks, how it responds to standard woodworking processes and finishes, and how its measurable properties map onto the tonal vocabulary used for tonewoods?

- **SRQ2.1:** How do the measurable properties of superwood, specific stiffness among them, relate to the warm to bright tonal descriptors used for tonewoods, and which of them track that axis?
- **SRQ2.2:** How does superwood behave under standard lutherie practice, cutting, shaping, gluing, and finishing, compared with natural wood?
- **SRQ2.3:** In what way does superwood, as a delignified and densified natural wood, differ from engineered woods such as MDF, particle board, and plywood, and what does that imply for its acceptance as a tonewood?

1.4 Scope and Limitations

1.4.1 In Scope

- **Material:** Electric guitar necks (not bodies or acoustic instruments)
- **Process:** Partial delignification (20-40% lignin removal) and moderate densification (30-50% compression)
- **Scale:** Workshop-accessible equipment (laboratory hot press, vacuum oven)
- **Validation:** Mechanical and acoustic testing through workshop-scale process development & mechanical and acoustic characterisation, while framing player acceptance as future validation.

Workshop-scale means producible by a small lutherie workshop or an independent maker using accessible, non-industrial equipment: a benchtop heat source, a benchtop hot press, and a vacuum oven, together with standard woodworking tools, and without a fume hood, an industrial press, or a climate chamber, working one blank at a time rather than in production batches (the equipment used for fabrication is discussed later in chapter 3). The term marks a deliberate move away from equipment that only a laboratory or a factory would have. Defined this way, the process is not only a route for lutherie: it reads as a recipe that a small workshop in any field could follow to make densified wood for itself.

Demonstrated versus to be validated

Demonstrated at workshop scale	Still to be validated
Delignification and densification on benchtop equipment	Repeatability across many blanks
Mechanical and acoustic properties of the blank	Long term stability under load and humidity
Machining and finishing with standard tools	Behaviour as a finished, strung instrument

1.4.2 Out of Scope

- Guitar / instruments soundboards
- Complete delignification or extreme densification
- Industrial-scale production optimisation
- Economic cost modelling beyond feasibility assessment
- Long-term ageing and weathering studies (>6 months)
- Sustainability assessment

Chapter 2 - Literature Review

This chapter reviews the scientific and technical literature supporting the development of superwood for guitar neck applications.

2.1 The Electric Guitar and the Loads It Places on the Neck

This section introduces the instrument itself and the mechanical demands it places on its materials. It is included because the material requirements developed later in this work, stiffness, surface hardness, dimensional stability, and acoustic behaviour, follow directly from how a guitar is built and how it is loaded. It also introduces some of the the vocabulary used throughout the thesis defined here.

2.1.1 Anatomy of a solid body electric guitar

A solid body electric guitar has three structural elements: a body, a neck joined to it, and six strings stretched over both under tension. Unlike an acoustic guitar, the body may or may not be a hollow or semi-hollow resonating chamber; the sound is captured electromagnetically from the vibrating steel strings and sent to an amplifier. The main components are labelled in Figure 2.1 and described below.

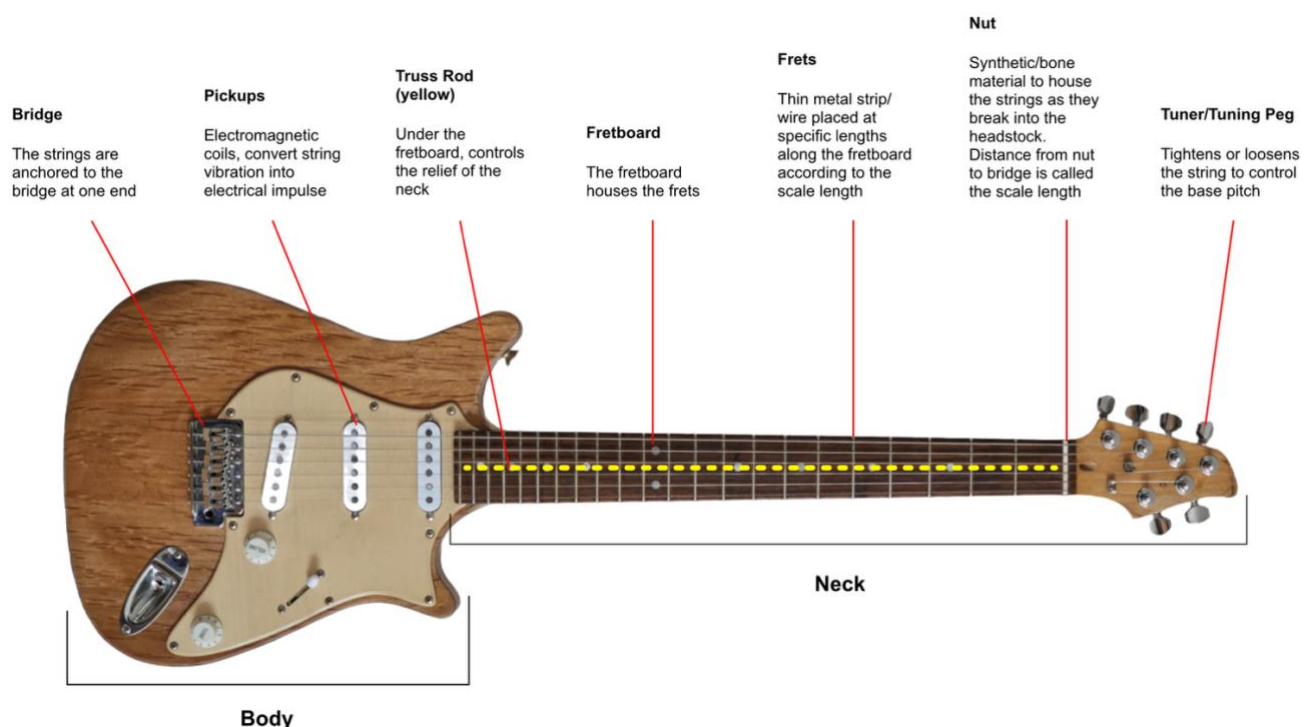


Figure 2.1. The principal parts of a solid body electric guitar. The truss rod, shown dashed, is buried inside the neck beneath the fretboard. Image: author's own build.

The string path: from tuner to bridge

Each string is anchored at the bridge, runs the length of the instrument, passes over the **nut** at the top of the neck, and terminates at a **tuner**, also called a machine head or tuning peg. Turning the tuner winds the string and raises its tension, and therefore its pitch. The tuners are mounted on the **headstock**, the paddle at the end of the neck.

The **nut** is a slotted strip of bone, synthetic material, or metal that seats the strings as they transition from the fretboard to the headstock. At the other end, the **bridge** carries the strings on individual **saddles**, small movable supports whose position can be shifted to fine tune the intonation of each string. The distance from the nut to the bridge saddle is the **scale length**, typically about 628 mm (24.75 in) or 648 mm (25.5 in) on a standard electric, and it governs both the pitch relationships along the neck and the tension required to reach a given pitch. The placement of frets is also determined on the scale length.

The neck assembly

The **neck** is the long member that holds the **fretboard**, or fingerboard, a thin slab of hard wood carrying the **frets**: metal strips seated in narrow slots sawn across the board. Pressing a string down behind a fret shortens its vibrating length against that fret, which is what sets the pitch. The neck is therefore not a passive handle. It must stay straight enough for the strings to clear the frets cleanly, and its surface must hold the fret slots tightly for years.

Buried inside the neck, beneath the fretboard, is the **truss rod** (see Figure 2.2): a steel rod, usually adjustable by a nut at one end, that runs the length of the neck. Its purpose is to oppose the pull of the strings and to let the curvature of the neck be adjusted. The idea is long established; the first truss rod patent was filed in 1921 by Thaddeus McHugh at Gibson, and related concepts appear in patents from as early as 1908^[7]. The truss rod can be tightened or loosened to control the relief of the neck (to control the bow of the neck). This can also affect player comfort and playability of the instrument.

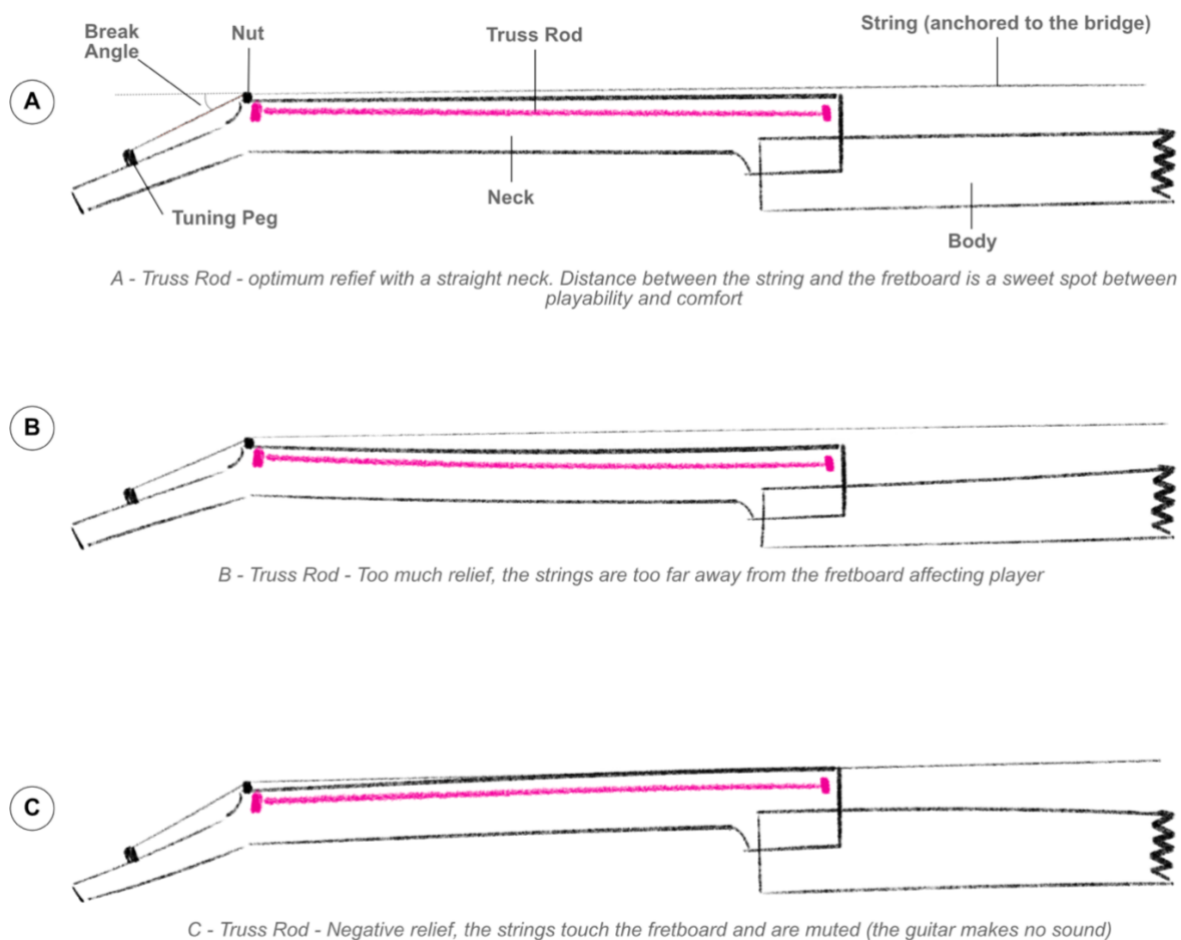


Figure 2.2. The truss rod controls the neck relief/bow

Body, electronics, and hardware

The **body** anchors the bridge and houses the electronics. Mounted beneath the strings are the **pickups**, coils of wire wound around magnets that sense the motion of the steel strings and convert it into an electrical signal. That signal passes through the **controls**, normally volume and tone potentiometers and a pickup selector switch, and leaves through the **output jack** to the amplifier.

Why the neck material is chosen for benchmarking - The neck is the more mechanically demanding component of a guitar, the part that carries the sustained structural load, sets and holds the playing geometry, and is in continuous contact with the player's hand. This is why the neck is the component targeted in this work, and why its stiffness and surface hardness are the properties characterised.

2.1.2 Forces acting on an electric guitar

Once a guitar is strung and tuned, it is a structure in permanent, static equilibrium under load. The strings pull continuously for as long as the instrument is kept in playing condition, which may be decades. The 2 main loads are summarised in Figure 2.3 - A compression along the neck caused by the string tension and a bending moment acting at the nut, as the string tension is slightly offset from the neck center line.

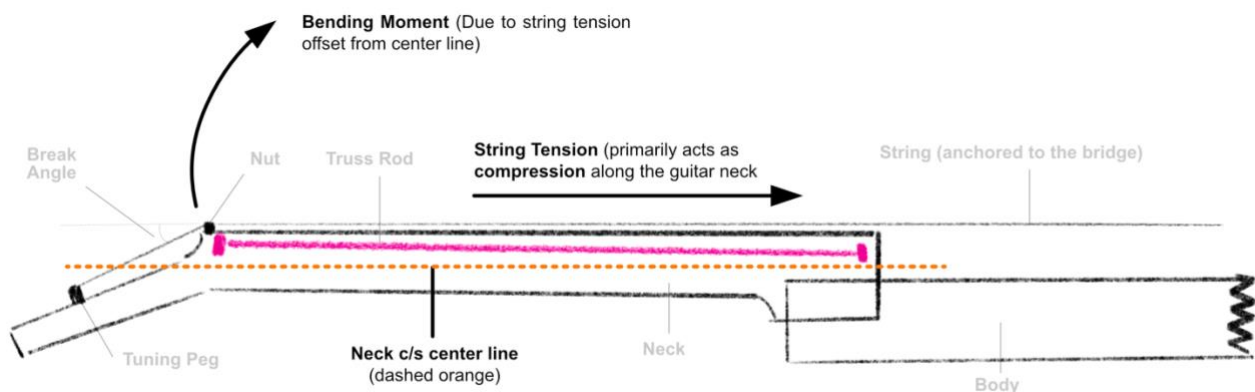


Figure 2.3. Above, the mechanics of the neck under string tension, with the resulting bending moment and compression along the grain; below, the six categories of load a neck must carry.

String tension, the primary load

Each string has a tension determined by its material, mass per unit length, scale length, and pitch, as per the standard relation for a vibrating string. For a string of unit weight μ tuned to frequency f over a vibrating length L , the tension can be calculated using the formula:

$$T = 4 \mu L^2 f^2$$

A guitar in standard tuning (E-A-D-G-B-E) typically carries roughly of 400 to 580 N of tension, depending on string gauge, scale length, and tuning^{[8][9]}. Moving from a light gauge set to a heavier one can be enough to change the neck curvature noticeably and to require readjustment^[8]. While electric guitar strings are made of steel, other instruments such as classical guitars and ukuleles may use nylon strings and are less mechanically demanding.

The bending moment on the neck

String tension acts along the strings, but the strings sit above the centre line of the neck, at an offset from its neutral axis. The tension therefore does not merely compress the neck; it applies a bending moment of approximately $M = T \times e$, where e is that offset. This moment bows the neck forward, lifting its middle away from the strings, this curvature is called *relief*. Resisting this bending is the single most important structural duty of the neck wood, and it is governed by the modulus of elasticity of the material and by the second moment of area of the neck cross section. This is the direct reason that bending stiffness is one of the properties characterised in this work.

Warping

The string tension on a guitar neck is not consistent across all strings. This is because the strings are tuned to different frequencies and have varying thicknesses (from thick to thin, from top to bottom). Consequently, the tension is also not uniform. Additionally, fluctuations in weather conditions, such as humidity, can add to this issue, potentially causing the neck to twist and warp under load.

The truss rod

The truss rod exists precisely because to counter effects of the wood bowing/bending under load with weather changes. Tightening the rod applies an opposing moment that pulls the neck backwards against the strings, and adjusting it sets how much relief remains^{[10][11]}. In practice a neck is not set perfectly straight: a small amount of forward relief is deliberately left, so that strings ring cleanly in the lower positions while the action stays low higher up the neck^{[7][10]}.

Bridge down force and body loads

Where the strings break over the saddles they change direction slightly, so the tension resolves into a vertical component pressing down into the bridge and, through it, into the body. On a solid body instrument this load is carried comfortably by the body timber and the bridge mounting. It is noted here for completeness rather than as a design constraint, since it is not the limiting case for a neck material.

Local surface and contact loads

Alongside the global bending, the neck carries concentrated local loads. Frets are pressed or hammered into slots cut in the fretboard and are retained by the grip of the wood on the fret tang, a purely local bearing action (see Figure 2.4). Untreated, uncured, or unsealed wood can swell due to prolonged moisture exposure, resulting in pinching of the slots. This can cause the fret wire to lose its level seat, causing the instrument to lose its calibration and playability. The playing surface is also subject to continuous abrasion from strings and from the player's hand. These are surface phenomena, governed by hardness rather than by bulk stiffness, and they are the reason indentation hardness is characterised in this work alongside the bending modulus.

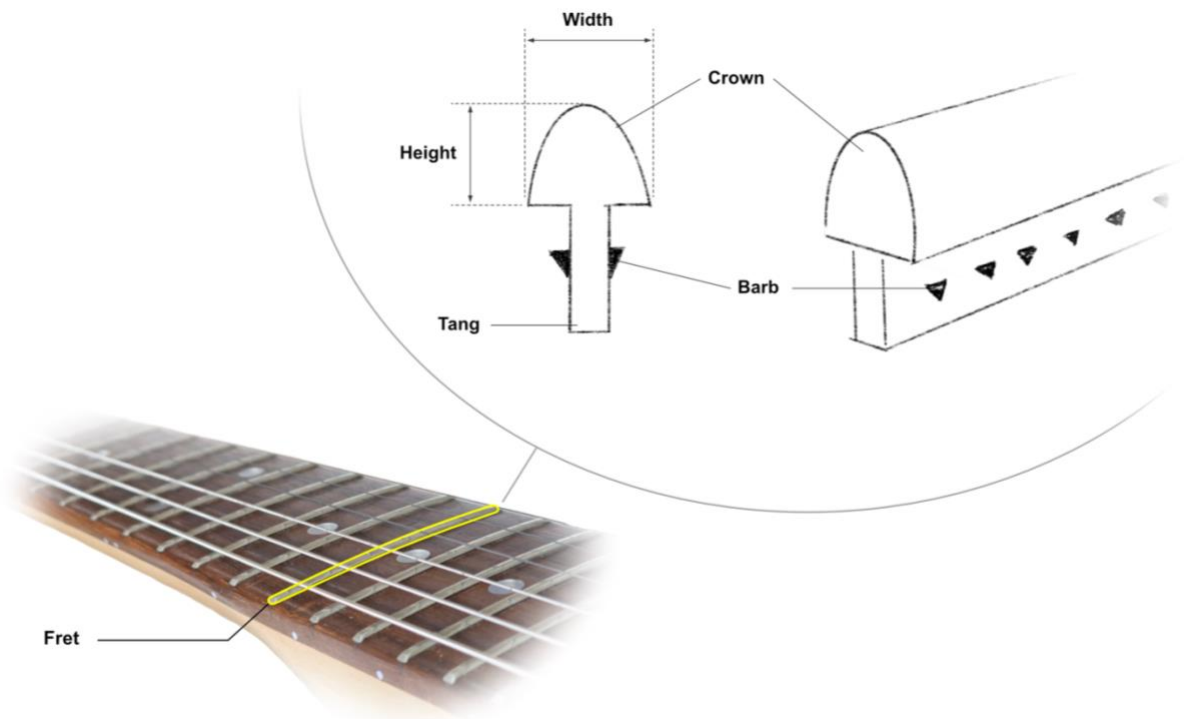


Figure 2.4. Anatomy of a fret wire

Environmental and time dependent effects

Two further effects act over the life of the instrument. Wood is hygroscopic, so it takes up and gives off moisture as ambient humidity changes, swelling and shrinking as it does, which alters neck relief and can loosen fret seating; this is why players adjust the truss rod seasonally. Separately, because the string load is sustained rather than momentary, the neck is subject to creep, the slow accumulation of deformation under a constant load. Neither effect is captured by a short term stiffness or hardness test, which is why both are identified in the recommendations of this work as necessary validation before a densified material could be trusted in service.

2.1.3 Implications for the neck material

Taken together, the load case defines what a candidate neck material must deliver, and it explains the structure of the experimental programme that follows.

Load	What it demands of the material	How it is addressed here
Sustained bending from string tension	Bending stiffness, so relief stays within the truss rod adjustment range	Three point bending, modulus of elasticity
Fret seating and surface wear	Surface hardness on the fret bearing face	Janka indentation, normal face
Vibration transmission and tone	Predictable acoustic behaviour, comparable to established tonewoods	Acoustic tap tone, first flexural frequency
Humidity change and sustained load over time	Dimensional stability and creep resistance	Informed hypothesis, not tested here; identified as required future validation

Table 2.1. The mechanical demands placed on a guitar neck and the tests used in this work to address them.

North American hard maple is the established benchmark for electric guitar necks precisely because it satisfies the first three rows well: it is stiff enough to hold relief, hard enough to retain frets and

resist wear, and acoustically well understood. The objective of this thesis is therefore not to outperform maple in any absolute sense, but to determine whether a densified, abundantly grown alternative can meet the same set of demands.

2.2 Wood Structure and Properties

2.2.1 Chemical Composition

Wood can be considered as a natural composite, and the mechanical behaviour is dictated (just like in any other composite), the interaction of the fiber matrix and binders. Cellulose (40-50% of dry wood mass) forms crystalline microfibrils providing tensile strength. Hemicellulose (15-30%) acts as a matrix connecting cellulose microfibrils like a grid, contributing to moisture uptake and cell wall visco-elasticity. Lignin (18-35%) binds cellulose and hemicellulose, providing rigidity, hydrophobicity, and resistance to biological degradation.^{[5], [12]} See Figure 2.5.

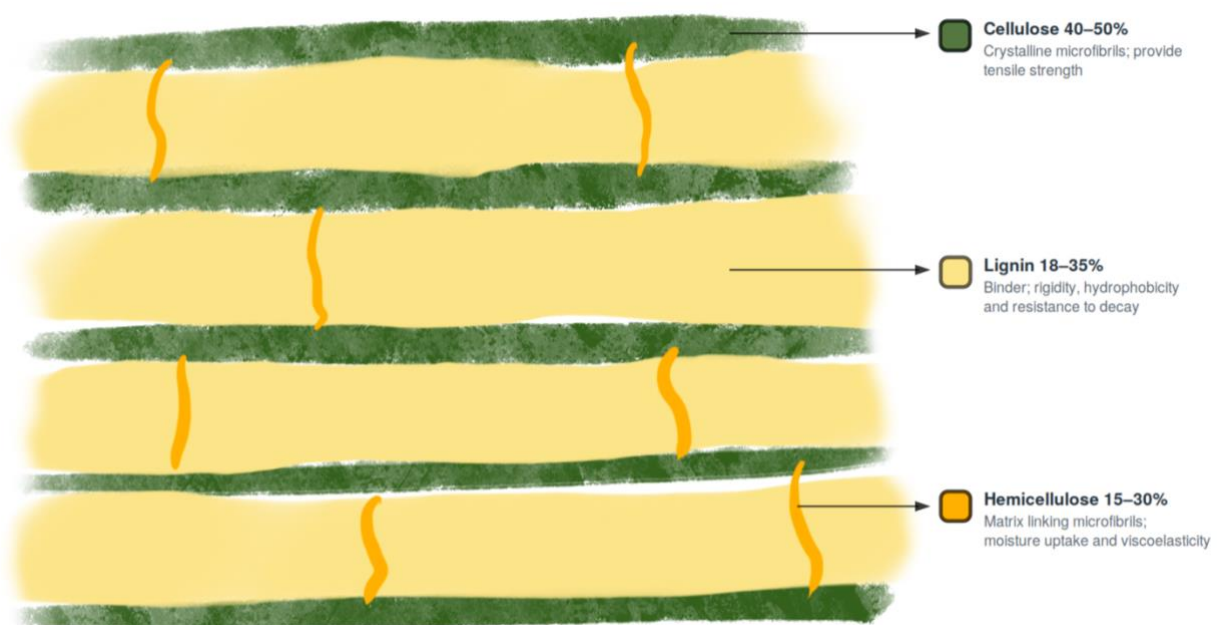


Figure 2.5. Schematic of the wood cell wall as a three-component composite

Softwoods and hardwoods differ fundamentally in lignin composition, impacting the delignification strategy. Softwoods contain guaiacyl (G-type) lignin, formed from coniferyl alcohol monomers, while hardwoods contain a guaiacyl-syringyl (GS-type) copolymer with both coniferyl and sinapyl alcohols. Hardwoods generally respond better to the established delignification processes due to the solutions catering to specific types of lignin. This difference has direct implications for the delignification protocol adopted in this project, as discussed in Section 2.4.

2.2.2 Mechanical Properties

Wood being an orthotropic material, its mechanical properties differ along three axes - longitudinal (L, along the grain), radial (R, along the rings), and tangential (T). In the longitudinal direction, because of the cellulose orientation, stiffness and strength are highest. Because of the matrix structure, mechanical properties such as modulus of elasticity (MOE), modulus of rupture (MOR), and compressive strength all scale positively with density at equivalent moisture content. This relationship informs the densification strategy in this project: increasing the density of a low-density

softwood by compressing its cellular structure is expected to produce a proportional increase in mechanical performance.

For guitar neck applications, the most relevant mechanical properties are flexural stiffness (MOE), which governs resistance to bow under string tension, and surface hardness, which governs resistance to denting at fret positions, nut slots, and tuning machine bushings. Hoadley^[12] provides a craftsman's account of how density, grain angle, and ray structure interact to determine the workability and surface quality of wood under machining conditions, all of which are directly relevant to the neck fabrication phase of this project.

2.2.3 Acoustic Properties of Wood

The acoustic properties of wood are also a result of a combination of its mechanical properties. The foundational reference in this area is Wegst^[13] who developed material property charts plotting acoustic parameters for several hundred wood species, enabling systematic comparison for instrument making applications. Wegst notes that for wood, stiffness and damping are largely independent of one another, which is what makes it possible to engineer an acoustic comparable to a traditional tonewood rather than having to match every property at once.

2.3 Traditional Tonewoods for Guitar Necks

2.3.1 The Tonewood Crisis

As discussed, the supply of certain species of woods is under increasing pressure. Gill^[3] documents the environmental and regulatory challenges facing guitar manufacturers, noting that over 36 species used in instrument construction are now subject to international trade controls. For example, since 2017, CITES regulations have placed all rosewood species (*Dalbergia* spp.) requiring documentation for any commercial trade regardless of origin.^[9,10] Whilst maple itself is not currently CITES-listed, its premium grades are increasingly scarce, and the broader pattern of tonewood restriction predicts a systemic sustainability and supply challenge that the guitar manufacturing industry must address proactively, and a lot of manufacturers are already looking towards alternative materials. The methodologies and procedures employed in this study are adaptable for replicating other scarce wood species. However, this is not the scope of this study.

2.3.2 Material Selection Criteria for Guitar Necks

A guitar neck is a structurally demanding component. The USDA Wood Handbook^[14] identifies the principal mechanical requirements for structural wood applications: adequate modulus of elasticity and rupture for resistance to long-term creep under static string load, and sufficient surface hardness for durability in service. For lutherie specifically, Hoadley^[12] adds dimensional stability under humidity cycling as a critical requirement: If a neck shrinks, swells or warps with the seasons, it can cause the fret ends to stick out or make the neck feel different, which can affect playability, intonation and what notes sound right. This dimensional stability requirement should also be considered for the assessment criteria applied to superwood specimens in this project.

Beyond mechanical requirements, Wegst^[13] notes that the acoustic contribution of the neck in a solid-body electric guitar is a secondary factor but cannot be ignored. The neck-body joint transmits string vibration into the body, and the damping characteristics of the neck material affect how much of the energy of the string is retained, transmitted/radiated or lost. Harder, denser neck materials with low internal damping are associated with brighter, more sustain-rich instruments, a perceptual effect that is well established in luthiers' practice, even if the precise cause of tonewoods affecting the sound of a solid-body structure remains debated.

2.3.3 State of the Art Neck Woods

Table 2.2 compares 3 most commonly used woods in electric guitar necks- Hard Maple, Mahogany and Roasted (torrefied) maple.

Material	Humidity Stability	Regulations
Hard Maple	Well characterised; moderate movement	Regionally restricted; not CITES listed [8-10]
Roasted (torrefied) maple	Manufacturer and user reported improvement; not independently verified	Same sourcing constraints as maple
Mahogany (Swietenia macrophylla)	Good stability; historically favoured for necks	CITES Appendix II listed; heavily trade-restricted

Table 2.2 Some popular guitar neck materials used in manufacturing today.

Roasted (torrefied) maple is considered a distinct material and product specification in guitars. Torrefication involves heating wood to approximately 160 to 230°C in an inert or low-oxygen environment. This process removes moisture and partially breaks down hemicellulose, the most hygroscopic of the three wood constituents and is responsible for water absorption and release, contributing to the neck's stability in response to weather changes and warping.

2.3.4 Player Perception and Material Acceptance

Positioning superwood within Industrial Design Engineering requires looking beyond mechanical equivalence to how players actually experience and evaluate neck materials. Karana et al.'s material driven design framework treats a material's meaning to a user as jointly produced by the material, the product, and the user, rather than as a fixed physical property, and argues that aesthetic, sensorial, and emotional experience are legitimate design variables alongside technical performance.^[15] Under this framing, superwood's acceptance as a tonewood substitute depends not only on matching maple's measured stiffness and hardness, but on how it looks and feels.

Studies from Carcagno et al.^[16] and Jasinski et al.^[17] on tonewood perception show mixed results. While some studies find no significant differences in sound quality between tonewoods, others detect measurable differences, suggesting tonewood may influence sound but not necessarily be perceptually decisive. These tests include informal listening as well as formal ABX testing.

The wider Leonardo Guitar Research Project^[18] reports a related and arguably more consequential finding: sighted listening tests show a strong preference shift toward guitars built from prestige tropical woods that disappears under blind conditions, indicating that a meaningful part of tonewood preference is driven by visual identification and pre-existing material associations rather than sound alone. In a lot of cases, players associate with the novelty associated with exotic materials, and the value they hold (For instance, a preference for a particular instrument or material due to its association with a favored artist).

2.4 Delignification Chemistry

2.4.1 Lignin Structure and Its Role as a Structural Binder

Lignin is a complex, three-dimensional aromatic polymer formed by the combination of monolignol building blocks: p-coumaryl alcohol (H-type units), coniferyl alcohol (G-type units), and sinapyl alcohol (S-type units). The ratios and proportions of these affect the response of the wood to the chemical treatments. In softwoods, lignin is predominantly G-type, forming a highly cross-linked, resistant network. This makes them harder to break down as compared to hardwoods, where the S-type units limit cross-linking, making the lignin structure more linear.

Within the wood cell wall, lignin acts as the binding agent that holds the cellulose and hemicellulose framework together and adds mechanical rigidity and hydrophobicity. Song et al.^[5] demonstrate that partial removal of lignin (20-45% by mass) It's enough to soften the inter-cellular matrix just enough to let the cell walls bend and stretch when heated and pressed, but still have enough lignin left over to bind everything back together when it cools down. When lignin is completely removed, the cell wall separates when pressed, which shows that lignin plays a double role: It is the substance we are attempting to remove but it also contributes to maintaining the structural integrity of the cell wall after it has been densely packed.

2.4.2 Alkaline Delignification: The NaOH/Na₂SO₃ System

One of the more recognised works in the field of superwood by Song et al.,^[5] has popularly established the two-reagent system used in this project (and consistent with other resources/research) - NaOH and Na₂SO₃ in aqueous solution. This is regarded as the optimal combination for producing partial delignification across a range of wood species including basswood, oak, poplar, western red cedar, and eastern white pine.

The process unfolds in two separate directions. NaOH starts by attacking and breaking the bonds in G-type lignin, creating soluble phenolic fragments that dissolve into the alkaline solution. This can be seen as the solution boils, it changes from clear to amber to dark brown, showing how much lignin is breaking down. Na₂SO₃ keeps the lignin from re-binding and helps make the fragments easier to dissolve. It also helps break down the more tightly packed G-type bonds that NaOH cannot reach on its own.

2.4.3 Vacuum Pre-impregnation

One of the limiting steps in alkaline delignification of wood specimens is penetration: the alkaline solution must penetrate throughout the cross-section of the blank before the chemical reactions can proceed uniformly. Due to logistical constraints in this project, vacuum pre-impregnation was explored as a way to catalyse the densification process.

A study in Forests^[19] from 2021 looked into using vacuum and ultrasound to speed up how poplar samples soak up solution, using the same NaOH/Na₂SO₃ mix. It concluded that an hour of vacuum treatment at about 950 mbar could get lignin into the wood as well as boiling for a longer time. Moreover, mixing 30 minutes of ultrasound with 30 minutes of vacuum worked best. This idea led to the vacuum pre-impregnation step in the method for later experiments in this project, which is explained in Chapter 3 however the ultrasonic method was not used.

2.5 Wood Densification Mechanics

2.5.1 Compression Behaviour of the Wood Cell Wall

Wood densification takes advantage of how wood cell walls deform differently when squeezed. When squeezed perpendicular to the grain (as is done in this project), the hollow spaces inside the cells start to shrink. This happens first with the earlywood cells (larger, less dense cells), which have thin walls and don't show as much resistance to squeezing. The densification keeps going until the cell walls touch, and then the load moves into the cell wall material itself, which makes it much harder to squeeze. Song et al.^[5] showed that basswood's hollow spaces completely collapse around 80% of its volume, turning it into a solid material with tightly packed, intertwined cell wall material.

The anisotropic deformation also means that compression in one axis produces lateral expansion in the unconstrained axes. This lateral expansion, and the use of a constraining jig to control it, is addressed directly in the experimental method described in Chapter 3.

2.5.2 The Role of Lignin Glass Transition in Hot Pressing

The key insight that distinguishes hot pressing from cold pressing for densification is the glass transition behaviour of lignin, and the decisive variable is moisture. In the dry state the glass transition temperature (T_g) of lignin is high, around 200 °C^{[20]–[21]}, so at lower temperatures accessible to the workshop, dry lignin remains glassy and the wood resists permanent deformation. Water acts as a plasticiser. When absorbed into the wood, it increases molecular mobility and depresses the transition sharply^[22]. In moist hardwood, the T_g falls to roughly 65 to 85 °C, with the exact value depending on moisture content and loading rate^{[23]–[24]}. Because the solution itself has water and wood is pressed moist, the lignin therefore reaches its softening region at readily attainable press temperatures rather than near 200 °C.

2.5.3 Partial vs. Complete Delignification

Song et al.^[5] systematically varied the degree of lignin removal from 0% to 100% and assessed the resulting mechanical properties. The data suggests that complete removal of lignin (100%) results in a material that is not dimensionally stable. This is because the cellulose structure has no binding agent, and the cell walls start to pull apart when compressed (like plain carbon fibre without the epoxy binder). Conversely, zero lignin removal with hot pressing alone produces only partial densification with large numbers of voids and the cell walls are not fully collapsed. The optimal range - approximately 45% lignin removal, yields the highest tensile strength, work of fracture, and density.

Alqrinawi et al.,^[25] in a parametric study directly extending the Song et al. methodology, further refined these findings by testing boiling durations of three, five, and seven hours under the standard NaOH/Na₂SO₃ protocol and measuring the resulting modulus of rupture (MOR). The results confirm that three hours of boiling is a viable and mechanically effective treatment duration. Prolonged boiling beyond this point degrades the crystalline cellulose structure, reducing MOR below the value achievable at three hours despite achieving higher lignin removal. This finding directly informed the reduction of boiling duration from six hours (Experiment 1) to 3.5 hours (Experiments 2 and 3) in this project.

2.6 Superwood Research

2.6.1 Pioneering Work: Song et al. (2018)

The foundational superwood study was published by Song et al.^[5] in *Nature*, demonstrating that natural wood can be transformed into a high-performance structural material through a two-step process: partial delignification using a boiling alkaline NaOH/Na₂SO₃ solution, followed by hot-pressing. The study was conducted on five species spanning the hardwood-softwood range: basswood, oak, poplar, western red cedar, and eastern white pine.

The results show significant changes in mechanical properties, with a 10-12x increase in tensile strength compared to untreated wood across all species. Basswood achieved 548.8 MPa, higher than most structural metals and alloys by specific strength. Work of fracture increased 10x, and scratch hardness increased by 11.5x, from 740 lbf to 9,455 lbf. Densified wood also showed improved dimensional stability: after 128 hours at 95% relative humidity, it swelled by only 8.4% in thickness, compared to 43.1% for conventionally pressed wood, and a painted sample showed zero swelling. This provides a direction for estimating dimensional stability for the project.

Song et al.^[5] also demonstrate that the process is translatable across species, including some softwoods (cedar and pine), which is directly relevant to this project's use of abundantly available Norway spruce and planned extension to poplar. The specific strength of the densified material exceeds that of lightweight titanium alloys, establishing the basis for the 'superwood' designation widely adopted in subsequent literature.

2.6.2 Recent Developments: Dong et al. (2022)

Dong et al.^[6] published in *Nature Sustainability*, extend the superwood concept to encompass low-value and waste wood streams including damaged, decayed, disposed, and fractured wood, demonstrating that the approach is not restricted to virgin timber. Their process involves delignification combined with partial dissolution and regeneration of cellulose fibrils, producing a 'healed' wood material in which regenerated cellulose forms strong hydrogen-bonding networks at the fracture interface.

The mechanical results are similar to those of Song et al.: the healed basswood reached tensile strengths of 154 MPa along the long axis, compared to its natural starting point of 49 MPa ^[6]. The study also shows that the material is recyclable and does not react well with solvents, which opens up new possibilities for using wood waste in a circular way. The Dong et al. study is a great example of how this project expands the idea: if superwood can be made from waste and leftover wood, it really changes how we think about recycled wood and feedstock. However, this is taken as a scope for future work, and not explored within this project.

2.6.3 Applications and Limitations

Published applications of superwood to date are concentrated in structural and defence contexts: building materials, lightweight armour, ballistic panels, and thermal and acoustic insulation.^[4,5] No published study has characterised superwood in a musical instrument context, nor assessed its acoustic properties, even though they are an extension of its mechanical properties.

Two practical constraints are relevant to this project. First, the original Song et al. protocol^[5] requires extended boiling (approximately one day) and hot pressing at specific pressure and temperature parameters that are difficult to maintain without industrial equipment. Translating this to a workshop-scale process with accessible/available equipment (a hot plate, a vacuum oven, and a laboratory hot

press) is the central engineering challenge of Phase 1 of this project. Second, while the optimised 45% removal process improves stability substantially relative to partially densified wood, the long-term dimensional stability of superwood under the cyclic humidity conditions experienced by a guitar neck in service (and constant load) has not been characterised. This represents a key knowledge gap that this project begins to address.

2.7 Summary and Research Gap

The literature establishes a clear and well-evidenced scientific basis for the superwood approach. Wood is a composite material whose properties are determined by the interaction of its constituents. Partial removal of lignin, followed by hot-pressing densification, produces order-of-magnitude improvements in mechanical performance across a range of wood species, including softwoods.^[5] The process has been extended to low-value and waste wood,^[6] and parametric studies have begun to optimise the boiling duration and lignin removal targets.^[25] Vacuum pre-impregnation has been demonstrated to accelerate and homogenise solution penetration, enabling shorter boiling cycles.^[19]

Against this backdrop, three specific research gaps define the scope of this project:

- **No workshop-scale process exists.** All published superwood research has been conducted with laboratory or industrial equipment operating at parameters that are not accessible to small-to-medium guitar manufacturers.^[5] There is no published methodology for producing superwood at workshop-scale using commercially available reagents and standard laboratory equipment.
- **No acoustic or lutherie characterisation exists.** No published study has measured the acoustic properties of superwood (sound velocity, damping coefficient, or acoustic radiation coefficient) nor compared them against tonewood benchmarks established by Wegst^[13] and subsequent work. It is unknown whether the densification process increases, maintains, or degrades the acoustic radiation efficiency of the feedstock species.
- **No player acceptance data exists.** The guitar manufacturing industry's adoption of alternative materials is constrained not only by technical performance but by player perception. Gill^[3] and Tingen^[26] document the cultural resistance to engineered wood alternatives in lutherie. No study has assessed whether superwood necks are perceptually distinguishable from traditional maple necks by experienced players in blind conditions.

This project addresses all three gaps through a phased programme of workshop-scale process development, mechanical and acoustic characterisation, and player testing.

Chapter 3 - Material Development

3.1 Overview

This chapter sets out the densification process that produced the material characterised in the rest of the thesis, and it is arranged so that the process can be read and followed directly as a recipe. Section 3.2 gives the final, established process in full: the chemistry it relies on, the method step by step, and why it can be run in a workshop rather than in a chemistry laboratory. Section 3.3 places that process alongside the reference protocol of Song et al.,^[5] tracking what was changed, where each change is an improvement and where it is a compromise, and the reduction in processing time that was achieved. Section 3.4 describes the specimen set the process was used to produce, including the yellow poplar compressed to 50% that is carried forward as the primary candidate into the characterisation reported in the following chapter. Only then, in Section 3.5, does the chapter look back at how the process was arrived at: four earlier iterations, the specific way each one failed or fell short, and what that development path can and cannot establish. The full method and results of every early experiment are retained in Appendix A; the account here keeps only the design takeaways that shaped the final process.

3.2 Adapted Delignification and Densification Protocol for Workshops

3.2.1 Process Chemistry

Sodium hydroxide and sodium sulphite play distinct roles in the solution. Sodium hydroxide begins breaking down the cell wall structure without fully dissolving it, producing a more porous cellular structure and assisting the movement of fluid through the wood by capillary action. Sodium sulphite acts through sulphonation, bonding to lignin and blocking its recondensation, which keeps the lignin in a soluble state once it has been mobilised. This mobilisation still requires heat: the lignin must reach its glass transition temperature, 65 to 85°C (see Section 2.5.2), before it plasticises and begins to dissolve into solution.

3.2.2 Method

The central change in the final process is the way heat is delivered to the lignin. In the earlier development iterations (Section 3.5) the wood was boiled directly in the alkaline solution. In the final process the solution is instead drawn into the wood by vacuum beforehand, and the sample is then boiled in plain water. By analogy with sous-vide cooking, where food is heated inside a sealed bag immersed in water rather than in direct contact with the cooking liquid, boiling the impregnated sample in plain water still heats the absorbed solution enough to reach the lignin glass transition, while the surrounding water simultaneously begins washing the sample as the solution diffuses back out.

The prepared samples were vacuum impregnated in the 1 M sodium hydroxide and 1 M sodium sulphite solution (The solution screening sub-experiment that established the final 1 M NaOH / 1 M Na₂SO₃ solution is reported in full in Appendix A.8.2.) for approximately 45 minutes to an hour, to ensure the solution fully penetrated the sample before the boil in water step. Following impregnation, the sample was boiled directly in tap water in cycles of one hour. After each cycle the sample was returned to the vacuum chamber with no solution present, drawing residual alkaline solution and dissolved lignin further out of the wood, and was then returned to a fresh change of boiling water for the next cycle. This alternation of boiling and solution free vacuum extraction combines

delignification and washing into a single repeating cycle rather than treating them as separate stages.

The pH of the boiling water was recorded after each cycle, and cycles were repeated until the water reached a neutral pH of approximately 7. This replaces the fixed rinse count and the solution colour endpoint used in the earlier iterations with a measurable, repeatable stopping criterion, and typically takes about 5 cycles for the given sample size. Once the neutral endpoint was reached, the sample was pressed in the same constraining jig used in Experiments 3 and 4 (see Section 3.5, Appendix A.5), in the heat press at 140°C, held under heat for approximately 1.5 to 2 hours. The heat was then switched off while pressure was maintained, and the sample was allowed to cool naturally under full load until the lignin resolidified in its compressed geometry, following the cooling under load protocol established in Experiment 3^[5]. At the end, the sample was dried in a vacuum oven at 70 degrees Celsius, 950 mBars for 6 hours to remove excess moisture.

3.2.3 Workshop Feasibility

Boiling in plain water rather than in the alkaline solution removes the need for a fume hood, which is the single largest barrier to running this process outside a chemistry laboratory. Delignification and washing both proceed largely in water, so the process can run on a standard stove and saucepan instead of a laboratory hot plate. This also allows a harder, more sustained boil with more vigorous water movement than the laboratory hot plate could sustain, which was found to assist both delignification and washing. The refined process is therefore meaningfully closer to a genuine workshop-scale pipeline than the alkaline boiling method used in Experiments 1 to 4 (see Appendix A), while remaining grounded in the same delignification and glass transition chemistry.

3.3 Comparison with the Reference Protocol

The process developed here is a workshop-scale adaptation of the delignification and densification route established by Song et al.^[5] The underlying mechanism is unchanged: alkaline sulphite chemistry partially removes and mobilises lignin, and hot pressing above the lignin glass transition, with cooling under load, locks the compressed geometry. What changed is how heat and reagents are delivered and how the process is controlled, driven throughout by workshop practicality rather than by any change in the mechanism. Table 3.1 sets the two side by side. A detailed documentation of all experiments can be found in the Appendix A.

Stage	Reference protocol (Song et al.) ^[5]	Final workshop process
Solution	2.5 M NaOH + 0.4 M Na ₂ SO ₃	1.0 M NaOH + 1.0 M Na ₂ SO ₃ (selected by screening)
Solution uptake	Diffusion during extended boiling	Vacuum pre impregnation, 45 to 60 minutes
Delignification medium	Boiled directly in the alkaline solution	Boiled in plain water after impregnation
Delignification time	Extended, approximately one day	Cyclic one hour boils to a measured endpoint, completed within one working session
Washing	Separate boiling water rinses, approximately 15 hours	Folded into the boil and vacuum extraction cycle; no separate stage
Endpoint criterion	Fixed time / target removal	Measured neutral pH (≈ 7)

Pressing	Hot pressing at 100°C	Heated pressing at 140°C, load held through cooling
Equipment and environment	Fume hood, laboratory hot plate, industrial press	Domestic stove, laboratory hot press, no fume hood

Table 3.1 The final workshop process compared with the reference protocol of Song et al.^[5]

Three of these changes are clear improvements for the intended setting. Replacing the direct alkaline boil with vacuum impregnation followed by boiling in water removes the fume hood requirement, which is what allows the process to leave the laboratory at all. Vacuum pre impregnation also removes the need for the long, diffusion limited boil of the reference protocol. Folding the wash into the boiling and extraction cycle removes the separate rinsing stage, and defining the endpoint by a measured neutral pH makes the stopping point reproducible where the reference protocol relies on fixed time and the earlier iterations relied on solution colour. Taken together, the active chemical processing, boiling and washing, is reduced from well over a day in the reference protocol to a few hours completed in a single working session. The overnight cooling under load is retained deliberately, because it is the step that eliminates spring back, so total batch turnaround is on the order of two days, most of which is passive cooling rather than active work.

The compromises are equally important to state. The process does not pursue the optimised degree of densification reported by Song et al.: the project targets maple equivalence rather than maximal properties, so the very high densities and strengths of the reference work are neither sought nor achieved. The degree of lignin removal is controlled by pH and colour rather than by a gravimetric measurement, so the actual removal percentage is not quantified against the approximately 20 to 45 per cent optimal range identified in the literature.^[5] The accessible equipment gives less precise control of pressure and temperature than an industrial press, and batches are small. These are acceptable within the aim of a workshop feasible route to a maple equivalent material, but they bound what the process can currently claim, and they point directly to the quantitative characterisation that follows.

3.4 Production of Characterisation Specimens

With the process fixed, it was used to produce the specimen set for characterisation. Fresh Norway spruce and yellow poplar were each processed to two compression ratios, 25 and 50 per cent, giving four processed conditions. Unprocessed spruce and poplar were retained as species baselines, and Hard maple was used as the reference benchmark against which every condition is compared. All processed specimens were made by the single fixed process described in Section 3.2, so that differences between them can be attributed to species and compression ratio rather than to variation in the process itself. The specimen set is listed in Table 3.2.

Material	Condition	Compression	Role
Hard maple	Raw	0%	Reference benchmark
Yellow poplar	Raw	0%	Species baseline
Yellow poplar	Compressed	25%	Processed condition
Yellow poplar	Compressed	50%	Processed condition
Norway spruce	Raw	0%	Species baseline
Norway spruce	Compressed	25%	Processed condition
Norway spruce	Compressed	50%	Processed condition

Table 3.2 Specimen set produced by the final process for mechanical and acoustic characterisation against the hard maple benchmark.

This set holds species and compression ratio as the two deliberate variables against a common maple reference, and isolates the effect of the densification process by including the unprocessed baseline of each species. The mechanical and acoustic characterisation of these specimens is reported in the following chapter.

3.5 Development Path and Its Limitations

The process above was not arrived at directly. It is the outcome of four earlier iterations on laboratory equipment, each of which failed or fell short in a specific way, and it was those shortcomings that determined the three governing variables of the final method. This section records that path, both because it explains why the process takes the form it does and because it bounds what the development phase itself can claim.

3.5.1 The Four Early Iterations

Three of the four iterations were run on Norway spruce; the fourth transferred the result to yellow poplar. Each iteration changed the process in response to the shortcomings of the one before it.

Experiment 1 served as a baseline study. Norway spruce was boiled in a 2.5M sodium hydroxide solution for six hours and pressed without lateral constraint. The sample densified from 0.447 to 0.760 g/cm³, an increase of 69.6 per cent that placed it within the maple equivalent density range,^[14] but it cracked extensively along the grain and was unusable for machining. The cracking was attributed principally to the omission of sodium sulphite from the solution: spruce contains predominantly G type lignin, which requires sulphonation to break down, so the cell walls were insufficiently plasticised before compression. The six hour boil, which can degrade crystalline cellulose,^[25] and the absence of a jig to constrain the sample laterally were secondary contributors.

Experiment 2 corrected the chemistry and the constraint. Sodium sulphite was added to the solution, a vacuum pre impregnation step was introduced to drive the solution into the wood,^[19] the boil was shortened to 3.5 hours,^[25] and a steel constraining jig was used during pressing. The sample was structurally sound with no cracking. It was, however, cold pressed for reasons of equipment access, and on release it recovered from the compressed height of 30 mm to approximately 38 mm, a springback of about 26.7 per cent, settling at a density of 0.630 g/cm³. Without heat the lignin does not pass through its glass transition and cannot lock the compressed geometry in place, so the compressed state was only metastable.

Experiment 3 introduced heat during pressing and held the load through cooling. The jig and steel plates were preheated, the sample was pressed at 130°C, and the load was maintained until the sample had cooled to room temperature. Springback was eliminated. The sample reached a density of 0.690 g/cm³, a 53 per cent increase from 0.451 g/cm³, within the target maple equivalent range,^[14] with a mass loss of 6.1 per cent and a near neutral surface pH of 7 to 8 after an acid wash. This is the point at which the three governing variables, sulphite chemistry, lateral constraint, and heated pressing with cooling under load, were all present together and the process first produced a usable densified blank.

Experiment 4 transferred the Experiment 3 protocol from spruce to yellow poplar. The same two reagent solution and heated pressing were applied to poplar blanks at a larger cross section. However, the blanks showed a dark coloured border attributed to inconsistent washing (removal of

solution) after boiling. Table 3.3 summarises the four iterations, their principal changes and their outcomes.

Iteration	Species	Principal change(s)	Outcome	Density	Limiting issue
Experiment 1	Norway spruce	NaOH only; six hour boil; no lateral constraint; hot pressed	Densified but cracked along the grain; unusable	0.447 → 0.760 g/cm ³ (+69.6%)	No Na ₂ SO ₃ ; unconstrained; long boil
Experiment 2	Norway spruce	Added Na ₂ SO ₃ ; vacuum step; constraining jig; 3.5 h boil; cold pressed	Intact but sprang back ~26.7%	0.630 g/cm ³ (after springback)	Cold press; no lignin glass transition
Experiment 3	Norway spruce	Heated press at 130°C; load held through cooling; preheated tooling; acid wash	Intact; no springback; first usable blank	0.451 → 0.690 g/cm ³ (+53%)	(working process reached)
Experiment 4	Yellow poplar	Experiment 3 protocol transferred to poplar	Intact; no springback (feasibility only)	Not recorded (25% compression)	Supports species transfer

Table 3.3 Summary of the four early development iterations, their principal changes, and outcomes. Full detail for each is given in Appendix A.

3.5.2 What the Early Iterations Can and Cannot Establish

Read as a sequence, these four iterations identify the variables that govern the process and the direction in which each one acts, and that is their purpose here. They do not isolate the individual effect of any single variable. Between Experiment 1 and Experiment 3 the solution chemistry, the boiling time, the presence of vacuum pre impregnation, the use and design of the constraining jig, the pressing temperature, and the presence of heat during pressing were all changed, in several cases more than one at a time. When a later iteration produced a better sample than an earlier one, the improvement therefore cannot be attributed to a single cause with confidence; it reflects the combined effect of several changes made together.

The iterations are best understood as a directed search for a working process, not as a controlled study of cause and effect. This is a deliberate limitation of the development phase, and it is the reason the quantitative comparison in this thesis rests on the characterisation specimens described in Section 3.4, which were all produced by one fixed process, rather than on the early iterations themselves. The one point in the development where a single variable was isolated is the solution screening described in Appendix A.8.2, where three candidate solutions were compared under otherwise identical conditions. A formal design of experiments, varying one processing parameter at

a time across a defined range, is the natural next step for establishing quantitative relationships between individual parameters and material properties, and is identified as future work.

3.6 Key takeaways

- Sodium sulphite is required in the delignification solution for reliable lignin breakdown.
- The sample must be laterally constrained during pressing, to prevent cracking and control the geometry.
- Pressing must be done under heat with the load held throughout cooling, to eliminate springback.
- The early iterations changed several variables at once, so they form a directed search for a working process rather than a controlled study.

Chapter 4 - Material Characterisation and Testing

This part reports the experimental characterisation of the densified samples as a candidate neck material for electric guitars, benchmarked against North American hard maple. It opens with a shared description of the materials, processing, sample hierarchy, and methods common to all three tests, then presents each test in turn, and closes with a synthesis, a general discussion, and recommendations for the validation still required. Full numerical detail is collected in the Appendix C.

Throughout this chapter and the supporting appendices, compression is expressed as a fraction of original thickness: a blank described as being at x% compression or compressed by x% means x% of its original thickness has been pressed, so Poplar 50% is half its original thickness and the excluded poplar at 25% compression is three-quarters of it. The figure refers to thickness reduction only, and not to a change in density, mass or any other quantity.

4.1 Shared Materials and Methods

4.1.1 Materials and candidate selection

Three material conditions are carried through the full comparison:

- **Hard maple, raw.** North American hard maple, uncompressed. The reference tonewood and benchmark against which the candidates are judged.
- **Yellow poplar, raw.** Uncompressed yellow poplar. The unprocessed baseline that shows what the densification adds.
- **Poplar 50%.** Yellow poplar delignified and compressed by 50% in thickness. The primary candidate.

Two further conditions were processed and tested but are not carried forward, and appear here only as excluded, with the full data given in the Appendix. Norway spruce, in raw, 25% and 50% forms, was set aside because it fractured and cracked under Janka indentation, which proved the process would have to be further optimized for spruce (or other specific woods, based on the lignin content). Poplar at 25% compression was set aside because its hardness came out very close to raw poplar (4,215 N against 4,025 N), showing hardly any meaningful densification, so 25% compression does not usefully change the material. This leaves maple, raw poplar, and Poplar 50% as the working set.

4.1.2 Sample hierarchy and the single specimen design

A total of six blanks were processed across the study, three of yellow poplar and three of Norway spruce, at raw, 25% and 50% compression, alongside the unprocessed maple reference. After the exclusions in Section 4.1.1, only raw maple, raw poplar and poplar 50% were considered.

For each material there was a **single blank**, and that one blank was carried through all three tests in sequence. The blank was first used, non destructively, for the acoustic tap tone test. The same blank was then indented for Janka hardness. Finally it was cut down into the coupon used for the three point bending MOE test. So the acoustic result, the hardness result, and the stiffness result for a given material all come from the same physical piece of wood, tested in that order.

Independent specimens versus technical repetitions. The multiple indentations in the Janka test, and any repeated taps in the acoustic test, are repeated measurements on the same single blank. They are technical repetitions, which show how reproducible a measurement is on that piece, not independent specimens that would show how the material varies from piece to piece. Every standard deviation reported here should be read as measurement scatter within one blank. Determining whether these values are representative of the material as a whole requires replicated testing on independently processed blanks, which is listed under future work.

4.1.3 Specimen preparation, geometry, and sizing caveats

Every blank was machined to the same nominal dimensions before testing, listed in Table 4.1. Matching the geometry is what allows the acoustic frequency ratio to be read as a stiffness ratio in the synthesis, since geometry can be cancelled between materials. A brief visual overview of the grain direction and face orientations relative to the grain are shown in fig 4.1.

Parameter	Value	Note
Length	150 mm	Identical for all blanks
Width	46 mm	
Thickness (as tested acoustically and for Janka)	20 mm	Full blank thickness
Volume	138.0 cm ³	Used for density
MOE bending coupon	cut thinner from the same blank	See sizing caveat below

Table 4.1. Common specimen geometry. The bending coupon was cut down from the same 20 mm blank for the MOE test.

A rectangular wood beam presents three distinct kinds of face, and how each behaves follows directly from the grain direction. The surface (or face) is the tangential plane, along the direction of the wood. It is the largest surface in a beam. The edge faces are normal to the faces, along the direction of the grain (radial plane) and the end faces are where the exposed rings can be observed (transverse grain). The three faces are illustrated in Figure 4.1.

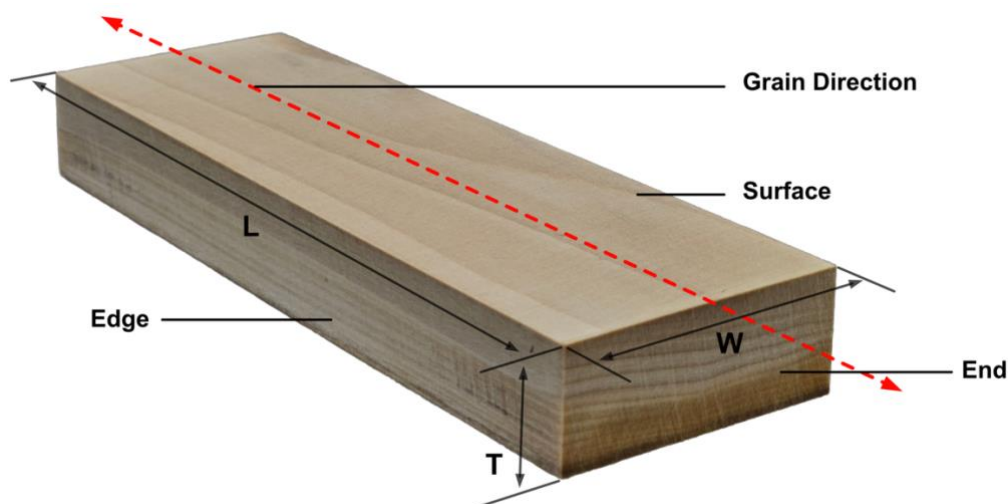


Figure 4.1. The three faces of a rectangular wood specimen. Surface, edge and end faces are defined relative to the grain direction (red dashed arrow), with length L , width W and thickness T as marked.

Two sizing caveats matter. First, the bending coupon was cut thinner from the 20 mm blank, so the MOE test used the same material but a different, test specific cross section. Since it is now a technically different blank, there might be a slightly different average density from the full blank, which is noted where relevant. Second, the coupon depth relative to its span sits below the minimum length to depth ratio of 14 recommended in ASTM D143, so shear deformation is not negligible and the absolute bending modulus should be read as indicative rather than exact.

Two outliers arose during testing and are treated as such throughout. The Poplar 50% normal face Janka indentations reached the machine load ceiling before full penetration, so those forces are conservative lower bounds rather than true hardness values. The Norway spruce specimens fractured under indentation, producing a fracture load rather than a hardness value, which is the basis for excluding spruce.

4.1.4 Density

Density was measured directly, by weighing each blank and dividing by the 138.0 cm³ volume. These are measured values, not literature estimates, and they are used consistently across all three tests and in the synthesis. The densities obtained are listed in Table 4.2.

Material	Mass (g)	Density (kg/m ³)	Note
Hard maple, raw	98	710	Benchmark
Yellow poplar, raw	82	594	Baseline
Yellow poplar, 50%	130	942	1.59 × raw poplar

Table 4.2. Measured densities (measured result), from mass over volume on the full blank.

4.1.5 Moisture conditioning

The two raw materials, hard maple and yellow poplar, were both at 8% moisture content (written specification from vendor) and procured 2 weeks before the densification or testing procedure. During this time, the wood /samples were kept in the ambient lab environment (same as testing environment) till the time of testing, so the comparison between them is not distorted by a moisture difference. The Poplar 50% blank followed a different path: after processing it was vacuum oven dried, then left at ambient laboratory conditions for a week before testing. Its exact moisture content at test was not measured. The moisture conditioning for the blanks is not fully compliant with the respective ASTM standards.

4.1.6 Deviations from standard compliance

All tests were informed by, but not in full compliance with its standard, for reasons of workshop-scale and specimen supply. The deviations are condensed below, so the reader is made aware of them once. They do not invalidate the comparisons, which are made at matched geometry against an in study benchmark, but absolute values should be read with care.

- **Janka hardness.** Adapted from ASTM D143^{[27][28]}. Indentations were driven at 2 mm/min rather than the 6 mm/min specified by the standard; the slower rate was applied identically to every material, so the comparison is unaffected, although the lower loading rate may

marginally reduce the absolute hardness recorded. The Poplar 50% normal face indentations reached the machine load limit, so those are reported as a conservative lower bound (labelled Version A) rather than as full penetration hardness.

- **MOE, three point bending.** Adapted from ASTM D143. Loading was applied at a constant 1.5 mm/min rather than the rate specified by the standard/sample size; as with hardness, the same rate was used for every material, so the comparison is unaffected. The length to depth ratio is slightly below the recommended minimum, so shear may be a factor, and deflection was taken from crosshead travel rather than a midspan transducer, which tends to make the absolute modulus a slight underestimate because of machine indentation.
- **Acoustic tap tone.** An adapted comparative test informed by ASTM E1876^[29] and ASTM D6874^[30] rather than a compliant one. The support position, the support material (elastic band cradles at the nodal points), and the impact (a soft mallet) while fit enough for testing within the sample set for comparison, all differ from the standard method, and a single representative tap was used per blank.

4.1.7 How to read the evidence in this part

To keep the claims honest, results are distinguished throughout by how they were obtained:

- **Measured** results come directly from an instrument reading, for example the peak load, the indentation force, the first resonant frequency, and the densities.
- **Calculated** results are derived from measured values through a standard formula, for example the modulus of elasticity from the fitted stiffness, or the acoustic loss factor from the peak width.
- **Extrapolated** results estimate a value beyond what was directly reached, for example the Janka forces beyond the machine ceiling, by curve fitting.
- **Interpretation** is the reading placed on the numbers, and hypothesis marks a proposed explanation that this study does not itself test. These labels are used where the distinction matters.

A note on constraints. The single specimen basis of this study, and the deferral of the long term durability and perceptual evaluations, are consequences of external constraint rather than of choice. Access to the densification and testing facilities was limited and intermittent, a single blank takes on the order of two days to process to completion, and specimen material and machine time were rationed accordingly. The programme was therefore designed to extract the most defensible comparison possible from one blank per condition: each blank was carried through all three tests at matched geometry so that the results triangulate, and every value is reported with its provenance and its caveat. Where a claim would require replication or long term testing to settle, it is marked as provisional and carried into the recommendations (Chapter 7) rather than overstated here.

4.2 Janka Hardness

4.2.1 Context and Test Rationale

Project context and motivation for hardness testing

This report documents Janka hardness testing carried out as part of a workshop-scale superwood development study for electric guitar lutherie. Hardness matters at this stage because it relates directly to the main ways a guitar neck wears in service: resistance to fret slot wear, denting from strings and hardware, and surface durability under repeated playing.

What the Janka hardness test measures

The Janka hardness test measures how well a wood surface resists localised indentation. It records the peak force needed to press a hardened steel ball to half its diameter into the wood. The result is expressed in newtons (N) and represents the material's resistance to permanent surface deformation. It is not a measure of overall stiffness (modulus of elasticity), fracture toughness, or compressive strength. It is specifically a surface indentation hardness index.^[13]

A neck blank has two kinds of long face. The flat faces are the broad top and bottom, that is the surface the fretboard sits on and the back of the neck the hand slides along. The edge faces are the two narrow sides. Both are tested here, because they meet the growth rings at different angles and may harden differently. The growth rings are the annual rings seen in the cross section of a tree trunk. Relative to those rings, the flat faces are described as normal to the rings and the edge faces as parallel to the rings. Both faces are reported separately.

How to read the results in this report

Results are presented in three ways:

- **By direction.** Normal to rings (flat faces) and parallel to rings (edge faces) are reported separately, because they are mechanically distinct. A combined average across all indentations per specimen is also given, weighted so that a direction with more indentations counts proportionally more.
- **As a percentage of maple.** In the ranking figure below, every condition is shown as a percentage of the single maple combined benchmark (7,106 N), so that all conditions can be ordered on one scale. In the results table and in the conclusions, the Poplar 50% comparison is instead made like for like, each grain direction against the maple value in the same direction, since comparing a directional value against the combined benchmark would mix two different references. A value of 100% is parity with maple; above 100% is harder than maple in that direction.
- **With quality flags.** Results that carry a caveat are shaded in the results table and labelled. They should not be used as primary design data without the noted caveats.

4.2.2 Method in brief

Janka indentations were made with a 11.3 mm ball on the single blank of each material, in both the normal (face) and parallel (edge) directions. The comparison against maple uses the normal face only, because:

- It is normal to the pressing (densification) direction.
- It is the fret bearing surface and the direction in which the bending test loads the material.
- The edge indentations were taken on the thin 20 mm dimension, where the indenter sits close to the far surface and the reading is less reliable.

All readings in both directions were taken and are given in full in Appendix C. Because the Poplar 50% normal face reached the machine load ceiling, its normal face figure is reported as Version A, the force at the moment the machine stopped, an un-extrapolated lower bound.

4.2.3 Results

The combined Janka hardness of each material is shown in Figure 4.2, with the Poplar 50% directional range marked. Poplar 50% is harder than maple, raw poplar is much softer, and the size of the difference depends on which face is compared.

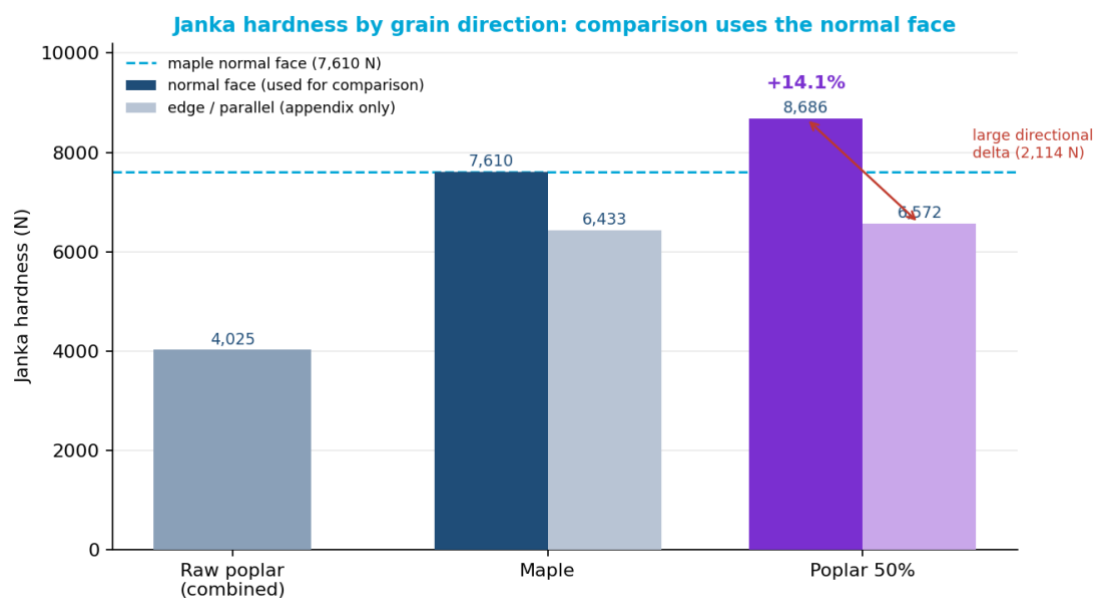


Figure 4.2. Janka hardness by grain direction (measured). The maple comparison uses the normal face (dark); the edge readings (light) sit on the thin 20 mm dimension and are less reliable. Note the large Poplar 50% directional delta. The normal face value is a machine limited lower bound.

On the normal face, Poplar 50% is at least 14.1% harder than maple, as shown in Table 4.3. Raw poplar is far softer, which reinforces that the hardness is created by the densification and is not inherent to poplar. Poplar 50% is also strongly anisotropic: 8,686 N on the face against 6,572 N on the edge, a delta of more than 2,000 N, and larger still once the machine limit on the face value is considered. This is expected for a material densified through its thickness, which consolidates the face far more than the edge.

Direction	Poplar 50% (N)	Maple (N)	Poplar 50% vs maple
Normal face (comparison basis, Version A lower bound)	8,686	7,610	at least +14.1%

Edge / parallel (thin face, appendix only)	6,572	6,433	near parity
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Table 4.3. Janka comparison of Poplar 50% against maple. The normal face is the comparison basis (the fret bearing surface, and the direction the bending test loads); the edge readings sit on the thin 20 mm dimension, are less reliable, and are kept for completeness and given in full in Appendix C.1. Normal face values are Version A machine limited lower bounds, hence “at least”. Raw poplar combined hardness is 4,025 N, far below maple.

The choice of the normal face is both application based and methodological. A neck is loaded on its face: frets are pressed into slots cut in that face, and the face takes string and handling wear, so the face hardness is the property that matters. The bending test also loads the material through the face, so the normal face is the like for like partner to the stiffness result. On that measure the densified poplar clearly meets and exceeds maple, and because the value is a machine limited lower bound the true margin is at least the figure quoted (interpretation).

4.2.4 Test specific limitations

- **Machine limited normal face (extrapolated boundary).** The Poplar 50% normal face is a lower bound; the true hardness is higher but was not reached.
- **Single blank, technical repetitions.** All indentations are on one blank per material, so the scatter is within specimen repeatability, not material variability.

4.3 Modulus of Elasticity (Three Point Bending)

4.3.1 Context and Test Rationale

Context for MOE testing

MOE is a key benchmark for this phase because it governs the stiffness of the guitar neck under string tension and under the hands of the player. A neck that is too flexible will deflect under load, causing intonation instability and imprecise action height. MOE, together with density, also governs how vibration travels along the neck and into the body, so it bears on both playability and the sonic character of the instrument. Matching maple MOE is therefore a prerequisite for a credible maple substitute.

What the three point bending MOE test measures

The three point bending MOE test quantifies the bulk bending stiffness of a wood specimen by measuring the midspan deflection under a known load applied at the centre of a simply supported beam. The result is expressed in gigapascals (GPa) and represents the material's resistance to elastic deformation in bending.

The test was run in three point bending with the load applied at midspan at a constant displacement rate of 1.5 mm/min, and deflection recorded continuously. The MOE was calculated as:

$$E = FL^3 / (4bt^3\delta)$$

where F is the applied load (N), L is the span (mm), b is the specimen width (mm), t is the specimen thickness (mm), and δ is the midspan deflection (mm). The stiffness $k = F/\delta$ was taken from a linear regression over the elastic region, up to 40% of $F_{\max}$, and used with the known geometry to compute MOE.

Deflection was recorded as crosshead displacement rather than from a transducer placed at midspan. Crosshead displacement includes a compliance and from local indentation at the loading nose and supports, which can slightly increase the measured deflection and lower the absolute MOE. Because both specimens were tested on the same rig with the same setup, this contribution is common to both and cancels in the maple to poplar comparison.

How to read the results in this report

Results are presented in two ways:

- As an absolute MOE value in GPa, alongside the measured stiffness k in N/mm and the peak load $F_{\max}$.
- As a percentage of published benchmarks. Two certified literature sources for hard maple are used, the USDA Wood Handbook^[14] and Hernandez et al. 2020 in the Forest Products Journal^[31]. The maple reference specimen from this study is also compared against these benchmarks as a setup validation step.

The Poplar 50% result is additionally compared against two supporting lines from this study, acoustic tap tone resonant frequency and Janka hardness, neither of which requires extra specimens (see

Appendix D.5). These are supporting checks rather than independent confirmations of the MOE value.

4.3.2 Method in brief

Each coupon, cut down from the same blank used for the earlier tests, was loaded in three point bending. The elastic stiffness k was taken from a least squares fit over the initial linear region (to 40% of peak load), with a fit quality above 0.999 for both specimens, and the modulus of elasticity was calculated from k and the known geometry. Deflection was taken from crosshead travel, which includes machine compliance and local indentation and therefore tends to make the absolute modulus a slight underestimate.

4.3.3 Results

Quantity	Maple	Poplar 50%	Note
Stiffness k (N/mm), measured	474.0	438.2	Poplar 50% is 7.6% below maple
MOE (GPa), calculated	13.23	12.23	Poplar 50% is 96.9% of USDA maple
Peak load F_{max} (N), measured	$\approx 1,407$	$\approx 1,407$	Near identical; see failure note

Table 4.4. Bending results. MOE is a calculated value derived from the measured stiffness and geometry. The load and deflection curves are in Figure 4.3.

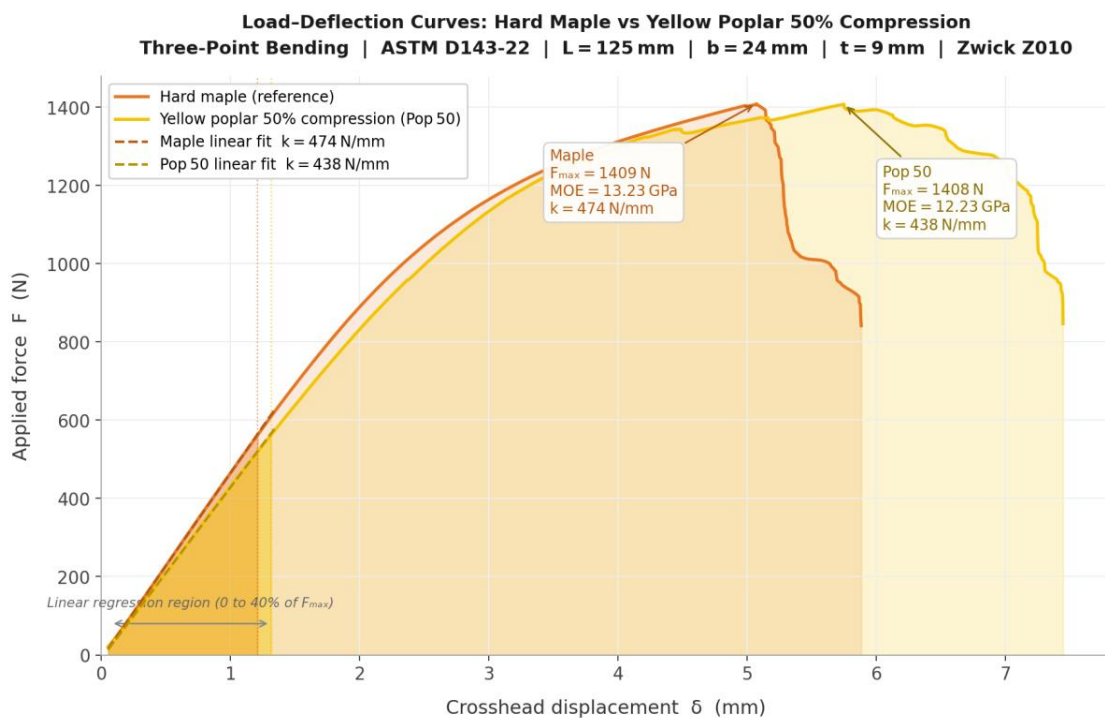


Figure 4.3. Load and crosshead displacement curves for the maple reference and Poplar 50% (measured), with the fitted stiffness and calculated MOE for each.

The Poplar 50% coupon reached a modulus of 12.23 GPa, which is 96.9% of the USDA Wood Handbook^[14] hard maple value (12.62 GPa) and 98.5% of the Hernandez et al. peer reviewed value (12.42 GPa). Its stiffness is 7.6% below the maple reference tested on the same rig. So the densified

poplar is close to maple in bending stiffness, a little below on this single coupon and within a percent or two of the published maple values.

On the near identical peak loads

Both coupons reached almost the same peak load, about 1,407 N. This figure is the force applied at failure, a load in newtons, and not a material strength. Strength would not depend on the size of the coupon while a peak load does. A true flexural strength, the modulus of rupture, was not extracted, because the failure was not a clean rupture but a progressive splintering and splitting. The 1,407 N is therefore reported only as a peak load, or load carrying capacity, of these particular coupons.

4.3.4 Test specific limitations

- **Single specimen, no equivalence claim.** With one coupon per material there is no within condition variance. The result shows that the tested Poplar 50% coupon had an MOE close to the tested maple coupon and to the selected literature values; whether this is representative requires replicated testing on independent blanks.
- **Crosshead deflection and shear.** Absolute MOE is likely a slight underestimate. Using the same geometry for both materials reduces these systematic effects in the maple to poplar comparison, but does not necessarily eliminate them, since the two materials may differ in shear and local indentation behaviour.

4.4 Acoustic Tap Tone

4.4.1 Context and Test Rationale

Acoustic tap tone testing is a non destructive way to characterise the vibrational behaviour of wood. A freely suspended beam (sample) is struck once, its response is recorded, and the frequency spectrum reveals the natural resonances of the material. The first flexural resonance is set by the specimen's stiffness and density, so it provides an independent, quick check on the modulus of the material, and it relates to the tonal behaviour of an electric guitar neck.

The acoustic behaviour of the neck does not directly set playability, since the vibrating length of each string is fixed by the frets rather than by the neck wood. The neck still matters indirectly, through how vibration is transmitted and absorbed, and through fret slot durability. However, this study would suggest some pointers towards whether the material could be a good fit for body woods or soundboards or not. The purpose of this test is to characterise the resonant behaviour of the candidate materials.

What the acoustic tap tone test measures

The primary measured quantity is the first flexural resonant frequency, f_1 . For a beam of fixed geometry, f_1 scales with the square root of the specific stiffness:

$$f_1 \propto \sqrt{(E/\rho)}$$

where E is the modulus of elasticity and ρ is density. Because all specimens in this study share identical dimensions, the ratio of f_1 between two materials reflects the ratio of their specific stiffness directly, which is what makes the cross check with the bending modulus possible.

Two further quantities are examined, but only as a preliminary, exploratory analysis for the reasons given in Appendix E.8. The damping loss factor η , and its reciprocal the quality factor Q , describe how quickly the vibration decays: a lower η , or higher Q , means a longer sustain. The harmonic content ratio H_2/H_1 describes the strength of the first flexural overtone relative to the fundamental. These are reported as indicative but not as settled measurements.

How to read the results in this report

Results are presented for three materials: raw hard maple as the benchmark, raw yellow poplar, and yellow poplar compressed by 50%. The first flexural frequency is the firm result. The density and the modulus cross check follow from it. The damping and harmonic values are given separately as a preliminary exploration, clearly flagged, because the current recordings limit how reliably they can be extracted.

4.4.2 Method in brief

Each blank was suspended on elastic band cradles at the first flexural nodal points, struck once on the end face with a soft mallet, and recorded through a piezo contact disc (See Figure 4.4). This is an adapted comparative test informed by ASTM E1876 and ASTM D6874, not a compliant one, because the support position, the elastic band support material, and the mallet impact all differ from the standard method. A single representative tap was used per blank. The first flexural frequency is a physical property of the blank, so repeated taps on the same blank reproduce the same modal

frequency to within measurement noise, and averaging them adds nothing. The variation worth capturing is the variation between independently processed blanks, which requires several blanks rather than several taps. With a single blank per condition this between blank scatter could not be sampled, and it is carried as a limitation in section 4.4.5.

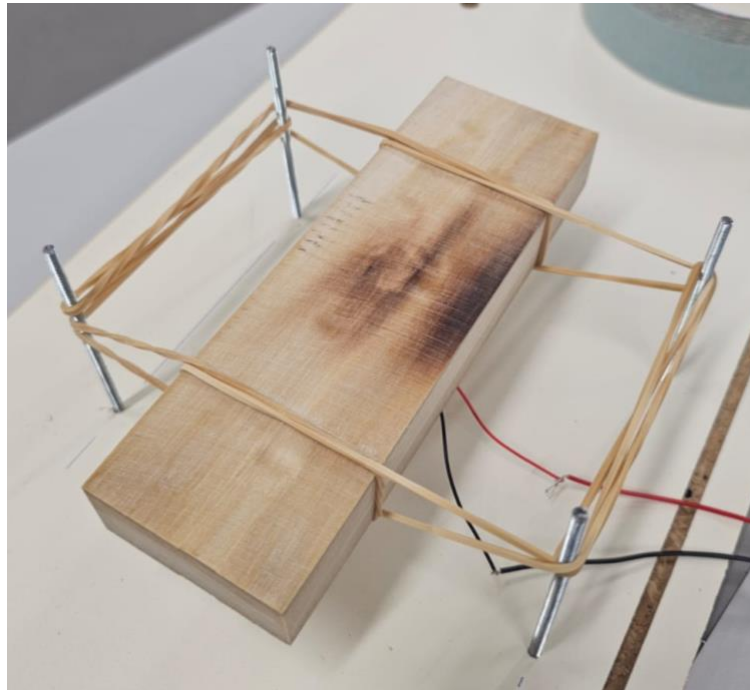


Figure 4.4. The finalised acoustic setup (measured configuration): elastic band cradles at the nodal points, 33.6 mm from each end, with the piezo contact disc.

For reproducibility, the signal analysis was: a 4th order Butterworth high pass at 80 Hz; a one second analysis window^[32] with a Hanning taper, giving a frequency resolution of about 1 Hz; a Savitzky Golay smoothing of the magnitude spectrum (window 31, order 3); and identification of the first flexural resonance as the dominant peak in the physically predicted band, near 3.5 to 5 kHz for these blanks, which distinguishes it from the lower suspension and contact peaks. Damping was estimated two ways, from the half power bandwidth of the peak and from the band limited decay time. The measured results are collected in Table 4.5 and Figure 4.5

4.4.3 Results: first flexural frequency

Material	f_1 (Hz), measured	Note
Hard maple, raw	4,299	Benchmark
Yellow poplar, raw	4,635	Highest f_1 , lowest density
Yellow poplar, 50%	3,792	Lowest f_1 , highest density

Table 4.5. Measured first flexural frequency (one representative tap per blank).

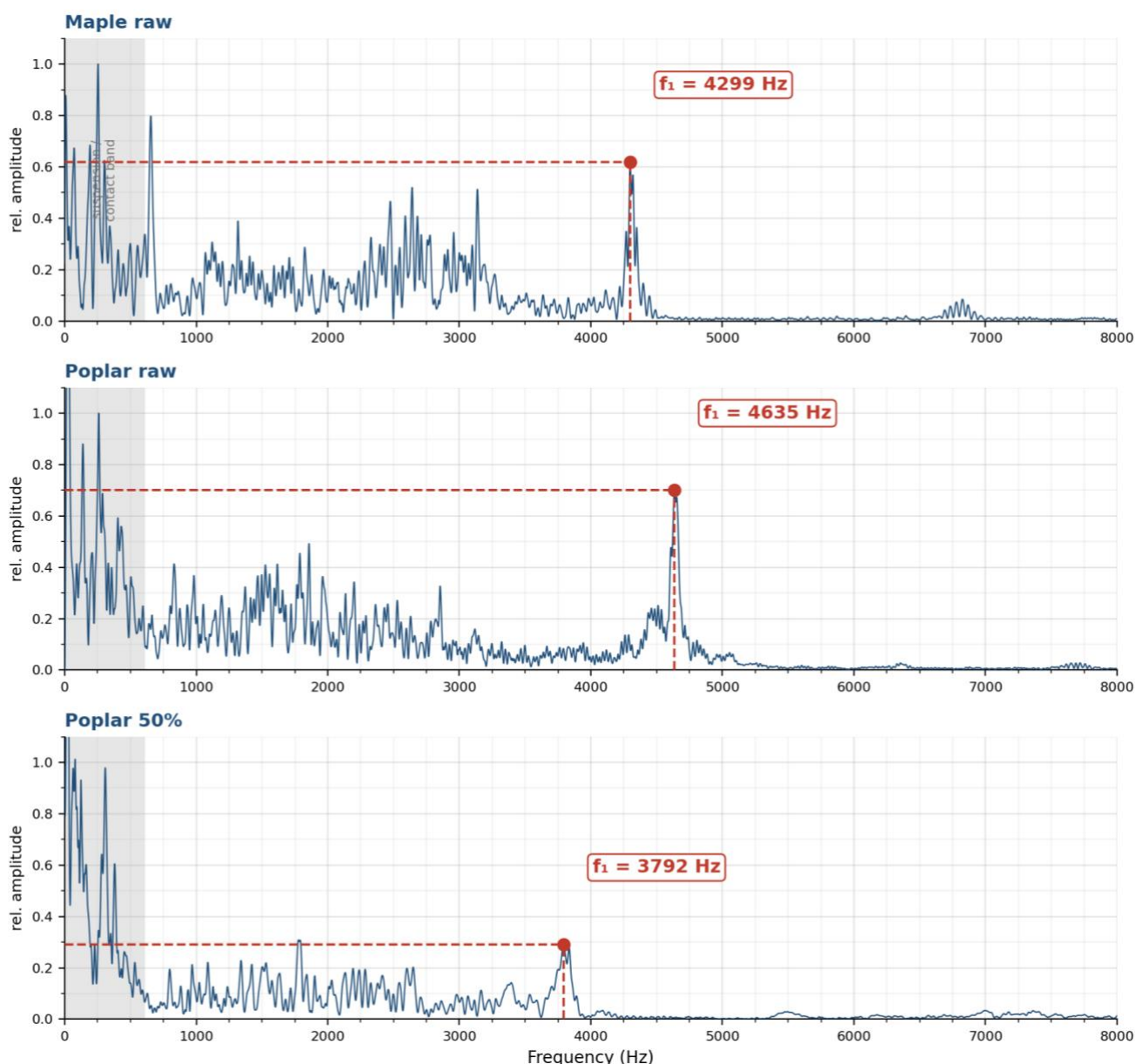


Figure 4.5. Tap tone spectra of the three materials on identical axes, with the first flexural resonance marked. The shaded band below about 600 Hz is suspension and contact noise, not a bending mode.

Raw poplar has the highest first frequency despite being the softest wood, because f_1 tracks specific stiffness, stiffness divided by density, and raw poplar is very light. Poplar 50% has the lowest first frequency, because compression raises its density faster than its stiffness. The stiffness reading these frequencies imply is developed in the synthesis (Section 4.5).

4.4.4 Exploratory damping and harmonic content

Damping and harmonic content are reported as a preliminary, exploratory analysis, not as settled results, for two reasons. The taps ring only briefly, so the two damping methods disagree by roughly twofold to threefold, and a soft mallet barely excites the first overtone, so the harmonic ratios sit near the noise floor. The comparative summary is shown in Figure 4.6.

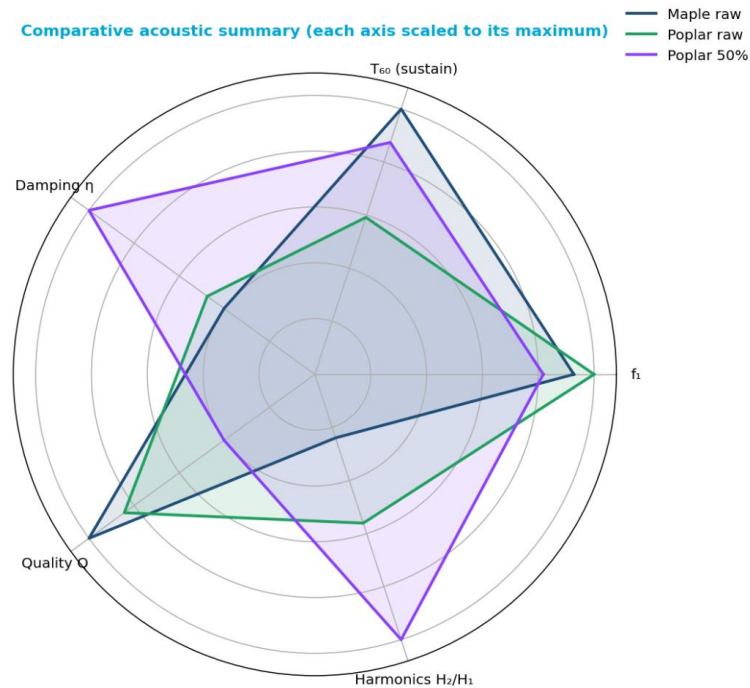


Figure 4.6. Comparative summary of the three materials across first frequency, sustain, damping, quality factor, and harmonic content. The damping related axes use preliminary values and should be read as indicative.

One qualitative signal is consistent across both damping methods: raw maple is the least damped and longest ringing of the three, which matches its reputation as a sustaining tonewood. The relative damping of the two poplars is not resolved by these recordings, and the effect of densification on damping cannot be settled here. No perceptual or instrument level evaluation was made, so the results are best stated as measured differences in first frequency, damping, and harmonic content between the materials under this setup, with the perceptual significance, whether a listener would hear one as warmer or brighter, remaining to be investigated.

4.4.5 Test specific limitations

- **Single tap, adapted setup.** One representative tap per blank on an adapted, non standard rig; f_1 is repeatable but carries no spread.
- **Preliminary damping and harmonics.** Short recordings and a soft mallet mean the damping and overtone values are indicative only; longer recordings and a firmer, calibrated striker are needed to measure them properly.

4.5 Synthesis

The three tests are brought together here, so the cross checks between them are made once rather than repeated in each chapter. Table 4.6 collects the headline results.

Property	Maple	Poplar 50%	Poplar 50% vs maple
Density (kg/m ³)	710	942	+33%
Janka, normal face (N)	7,610	8,686	at least +14.1%
MOE (GPa)	13.23	12.23	-7.6%
First frequency f_1 (Hz)	4,299	3,792	-12%

Table 4.6. Headline comparison of Poplar 50% against maple across the three tests.

4.5.1 Acoustic and bending stiffness agree

Because all blanks share the same geometry, the ratio of first frequencies gives an independent estimate of stiffness that can be checked against the directly measured bending modulus. From $f_1 \propto \sqrt{E/\rho}$, anchored on the measured maple modulus and the measured densities:

$$E_{\text{Poplar 50\%}} = 13.23 \times (3792 / 4299)^2 \times (942 / 710) = 13.66 \text{ GPa}$$

This acoustic estimate (calculated) sits about 12% above the directly measured static value of 12.23 GPa. That is the expected direction: a modulus measured dynamically, from a fast vibration, is consistently higher than one from a slow static bend, because the static test includes a little time dependent give that the tap does not. The two methods therefore agree in ranking and sit in the expected relationship, which supports the bending result. The absolute dynamic figure is indicative only, because a bar this thick relative to its length needs a shear correction; the frequency ratio itself, at matched geometry, is more robust than the absolute value.

4.5.2 Hardness and stiffness are decoupled, coherently

The most informative pattern across the tests is that hardness and stiffness move in opposite directions. On the normal face, Poplar 50% is at least 14.1% harder than maple, while its bending modulus sits 7.6% below. This is not a contradiction. Janka hardness is set by the small, highly compressed zone directly beneath the indenter at the surface, which densification consolidates strongly. Bending modulus is set by the average stiffness of the whole cross section, which still carries any residual density gradient or lumen space left after pressing. Surface consolidation outrunning bulk stiffness is exactly what a density graded pressed material should show (interpretation).

4.5.3 Against the guitar neck requirements

Read against what a neck needs, the picture is encouraging but bounded. The bending stiffness of the densified poplar is close to maple and well within the natural spread of maple modulus, so it should resist string tension and relief comparably. Its surface, on the face that carries frets and wear, is at least as hard as maple and probably harder. Acoustically it behaves as a distinct but plausible tonewood, ringing a little lower than maple and somewhat more damped, with no evidence that it is unsuitable. Taken together, the three tests support building a prototype neck from the densified poplar, while leaving the durability questions in Section 4.7 open.

4.6 Key takeaways

- On this pilot, densified poplar is a credible stand-in for maple: it reaches maple level bending stiffness, exceeds maple in surface hardness, and its acoustic behaviour differs from maple but is not obviously worse.
- The aim was a tonewood stand-in, not the steel like hardness of the original superwood literature, and on that narrower target the results are positive.
- **Single blank per material:** the results characterise particular specimens rather than the materials in general.
- **Moisture not matched:** the processed poplar could not be conditioned to the same moisture as the raw references, so comparisons involving it are suggestive and may be modestly flattered.
- **Measurement limits:** some absolute values, the bending and dynamic acoustic modulus in particular, are affected by known limits, so matched geometry comparisons are more trustworthy than the absolute figures.

4.7 Recommendations and Future Validation

The future work falls into two parts. The first is statistical: repeat the hardness, stiffness, and acoustic tests on several independently processed blanks per condition, so that variability between blanks can be separated from measurement scatter and the pilot values can be confirmed or revised. The second, and just as important, is that hardness, stiffness, and tap tone do not by themselves qualify a neck: a real neck sees sustained loading, humidity change, machining, and years of use. That long term durability and viability programme, covering creep, humidity movement, recovery, fatigue, fracture, machining, and adhesive and coating durability, is set out in full as the viability roadmap in Section 7.2 and is not repeated here.

Addressing the statistical replication here, together with the viability programme in Section 7.2, is the path from a promising pilot to a qualified neck material.

Chapter 5 - From Sound to Stiffness: Placing Densified Poplar in the Tonewood Landscape

5.1 Sonic character in woods

In an acoustic guitar, the wood clearly matters, because the body radiates the sound. In a solid body electric guitar (wherein the body is made from a solid blank of wood, as opposed to hollow box-like construction from veneers) the case is less clear-cut, and it remains debated. The pickup senses the string's motion directly rather than the body, so one common argument holds that the wood contributes little to the amplified tone and that pickups, strings, and electronics account for most of it. Against this, players and luthiers report that otherwise identical guitars built from different woods sound and feel different. This report does not attempt to resolve that debate.

However, every piece of wood has its own vibrational characteristics, audible when tapped and measurable directly. These characteristics affect how the string's energy is absorbed and returned at the points where the wood contacts the string - the nut, the frets, and the neck joint - which is why a maple neck sounds and feels different from a mahogany one. Whether this effect reaches the amplified signal is debated; that the material has these characteristics is not. For a valid substitute, the relevant question is therefore not whether wood determines the tone of an electric guitar, but where densified poplar sits, as a material, among the woods luthiers already use. That is the question this section addresses.

5.2 The tonewood map

Players and luthiers organise tonewoods on a two dimensional map (see *Figure 5.1*). The horizontal axis runs from warm to bright and describes where the tonal energy sits, low and full against high and present. The vertical axis runs from crisp to muddy and describes clarity, whether each note stays defined or blurs into the next. Maple sits in the bright and crisp corner, mahogany in the warm corner, and plain poplar in the bland, muddy centre. The map is compiled from published player and luthier descriptions rather than from measurement,^{[33][34][35]} so it records collective experience, not physics. It is the starting point precisely because it is the language the material must ultimately answer to. The version reproduced as Figure 5.1 is not one of those published charts: it was redrawn for this thesis, traced from and informed by the map in the Andertons Music Co. electric guitar tonewood guide^[33], which cannot be used directly here.

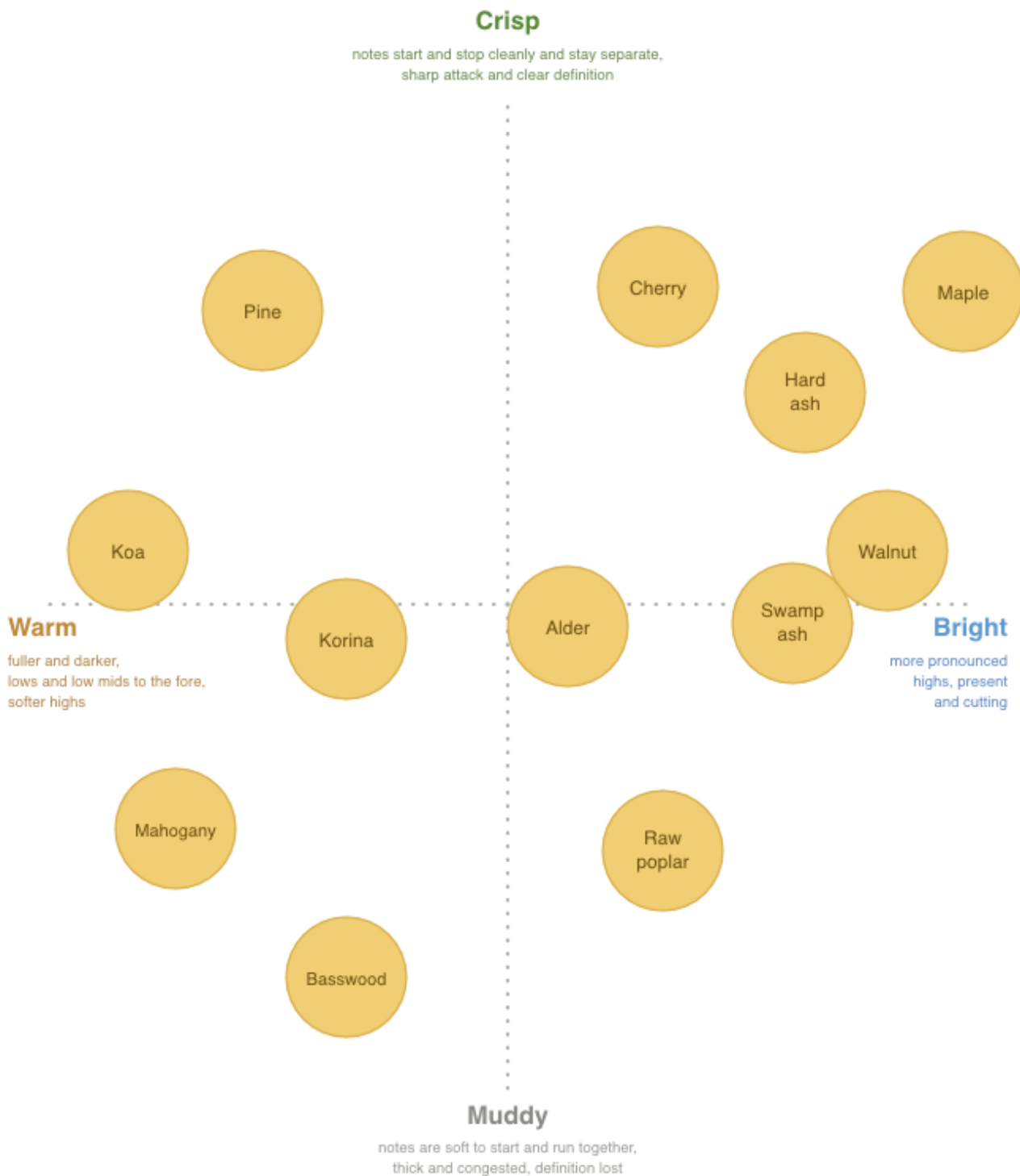


Figure 5.1. The perceptual tonewood map, warm to bright across and crisp to muddy up the side, with common electric guitar woods placed from player and luthier descriptions.^{[33] [34] [35]} The map shown here is not a reproduction of a published chart: it was redrawn by the author, traced from and informed by the tonewood map in the Andertons Music Co. electric guitar tonewood guide^[33], which cannot be used directly in this thesis.

5.3 What the axes indicators mean

The four terms reduce to a small set of things the ear tracks or perceives, and each can be drawn as a shape in the note itself (see Figure 5.2). Attack is how fast the note speaks, the steepness of its onset: a sharp attack snaps in, a mellow one swells slowly. Sustain is how long the note rings before it dies. Brightness is the amount of high frequency content, the sparkle sitting on top of the

fundamental. Clarity is note separation, whether two notes struck in succession stay distinct or overlap into a congested wash. In these terms warm means fuller and darker with softer highs, bright means more pronounced, present, cutting highs, crisp means a sharp attack with clean separation, and muddy means a soft onset with notes that run together.

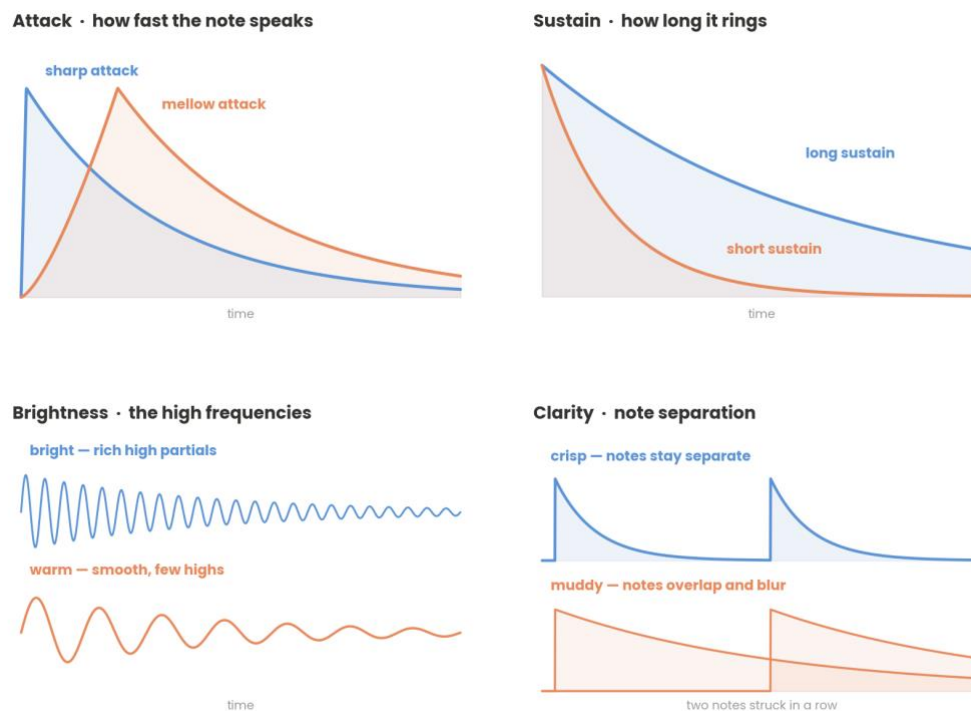


Figure 5.2. The perceptual terms drawn as the shape of the note. Attack is the onset speed, sustain the decay time, brightness the high frequency content, clarity the separation of successive notes.

5.4 Placing densified poplar on the tonewood chart by ear

The placement that follows is a hypothesis to be tested by listeners, not a measured result. It is made by the author, from tap tone recordings, and by a single unblinded ear, and the tonewood preference literature reviewed in Section 2.3.4 is a direct warning that a sighted, invested listener is exactly the case in which judgement is least reliable. It is offered on that understanding, as the most likely position on present evidence.

On present evidence, densified poplar's tap tone resembles maple's but carries richer overtones, sounding lively and open, while its fundamental pitch is slightly lower and fuller than maple's, consistent with its lower specific stiffness. That would place it provisionally in the crisp half of the map, near walnut, rather than in the muddy corner where raw poplar sits or in maple's bright corner. (See figure 5.3) This position awaits confirmation by the listener study scoped in Section 7.1.

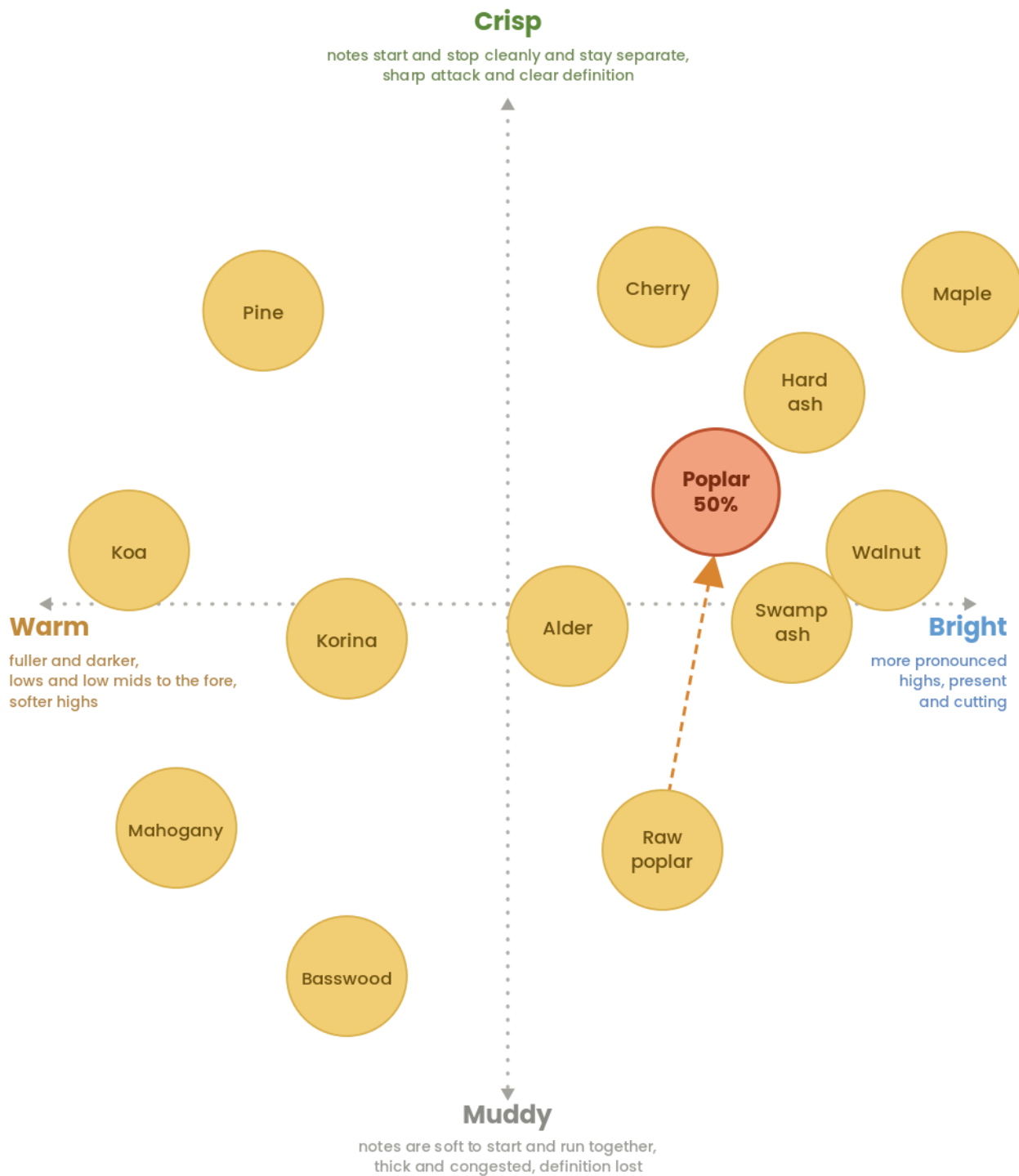


Figure 5.3. Densified poplar placed on the map by ear, from its tap tone character. It rings and sustains like maple and is overtone rich, but its slightly lower, fuller pitch keeps it warm of maple.

5.5 Placing the densified poplar on the tonewood chart based on measurements

When compared to raw poplar, Poplar 50 exhibits a shift in pitch due to its lower fundamental frequency (~3.7kHz compared to ~4.6kHz) and higher damping. This is expected to give an improved note separation that moves it slightly higher on the Y axis (crisp-muddy); see Figure 5.4 The arrow shows the shift from placing by ear versus by measurements.

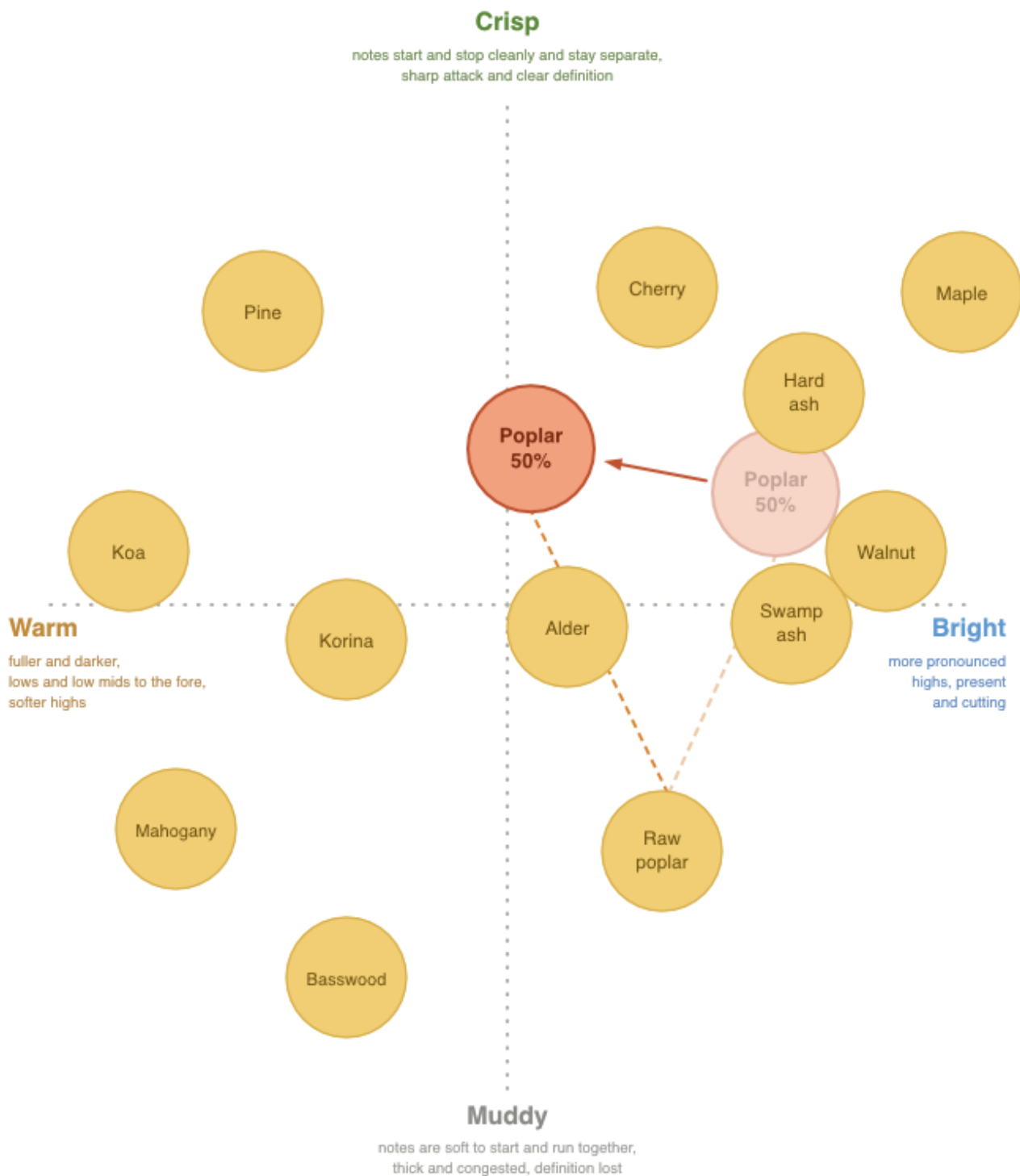


Figure 5.4. Poplar 50 placed on the perceptual tonewood map alongside common electric guitar woods using the mathematical/measured data. The dashed lines trace its shift from raw poplar, and the arrow marks the correction to its final position: warmer and higher on the crisp to muddy axis, reflecting the lower fundamental frequency and higher damping measured in the tap tone tests.

5.6 Addressing the discrepancy; Case study: Alder v/s Paulownia, and the road to specific stiffness

Paulownia, a popular wood used for electric guitar bodies, is about half the weight of alder and considerably softer, yet it is sold and used as an alder substitute and is widely agreed to sound much like it (and in some cases also used as an alternative). If density or hardness set the voice, two

woods so far apart in both could not possibly sound alike. The example begs the question: what actually makes two woods sound the same, or different?

The answer is a ratio, not the raw numbers, and the simplest resonator shows why (see Figure 5.5). A mass on a spring has a pitch set by the square root of the stiffness divided by the mass, $f \propto \sqrt{(k / m)}$, a ratio in which scaling both quantities together leaves the pitch unchanged.

A vibrating piece of wood is a distributed version of the same system, with the modulus E as the spring and the density ρ as the mass, so a wave travels through it at $c = \sqrt{(E / \rho)}$ and its resonant pitch scales with that speed.^[36] This ratio of stiffness to density is the specific stiffness (E / ρ)- the stiffness carried per unit weight (*i.e. how stiff it is for how heavy it is*). A stiffer material has less damping and thus radiates vibrational energy better. But in woods, the stiffness often comes at a cost of density, especially when the loads applied to a guitar neck are considered (The ideal candidate for a sound radiator is a wood with high stiffness and low weight). In simple terms, high specific stiffness means brighter sound (this analogy is usually taken from soundboard woods from acoustic instruments, where a vibrating string transfers energy to the wood, which radiates it as sound waves)

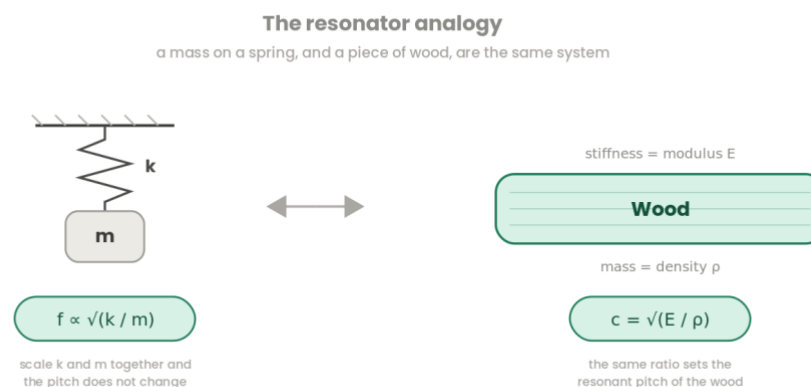


Figure 5.5. The resonator analogy. A mass on a spring and a piece of wood are the same system, and in both the pitch is set by the ratio of stiffness to mass, not by either alone.

A second, largely independent quantity, the damping, sets the other axis, crisp to muddy, and with it the sharpness of the attack and the length of the sustain. Positioning woods by these two properties, sound velocity and damping, rather than by weight, makes the pattern clear: paulownia and alder sit together at very different weights, while dense woods spread apart by their damping. Each axis of the perceptual map now has a physical partner, summarised in Table 5.1: warm to bright follows the specific stiffness, and crisp to muddy follows the damping, both of them decoupled from the density and hardness the placement first reached for.

Perceptual term	What the ear registers	Plausible physical property
Warm to bright	low and full against high and present	specific stiffness E/ρ , the sound velocity; higher is brighter
Crisp to muddy	note separation and clarity	damping, the loss coefficient $\tan \delta$; lower is crisper
Attack, sharp to soft	speed of the note's onset	stiffness and hardness; stiffer is sharper

Sustain, long to short	how long the note rings	damping $\tan \delta$; lower damping rings longer
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Table 5.1. What each perceptual term corresponds to physically, arrived at after the paulownia example. Warm to bright follows the specific stiffness, crisp to muddy follows the damping.

This placement is a considered estimate, not a measurement. It is made by ear from tap tone recordings, the damping figures behind it carry the boundary effects noted in the acoustic report, and the perceptual reading has not yet been confirmed by listeners. It is offered as the most likely position on present evidence, to be tested by user perception study.

5.7 Summary of Mathematical Expressions

The report draws on a small number of physical relations to connect the perceptual map to measurable material properties. They are collected here for reference.

Expression	What it represents
$f \propto \sqrt{(k / m)}$	Resonant frequency of a mass-spring oscillator: pitch scales with the square root of stiffness over mass.
$c = \sqrt{(E / \rho)}$	Wave (sound) velocity through a solid, with modulus E as the spring and density ρ as the mass.
E / ρ	Specific stiffness (specific modulus): stiffness carried per unit weight; sets the warm to bright axis. Higher is brighter.
$\sqrt{(E / \rho^3)}$	Radiation ratio: a more complete measure of the warm to bright direction, combining modulus and density.
$\tan \delta$	Loss coefficient (damping): sets the crisp to muddy axis. Lower damping is crisper and sustains longer.

Table 5.2. Physical expressions used in this report and what each represents.

Note. The findings of this chapter are to be read in supplement with Appendix F, as specific stiffness cannot be considered as the sole governing factor for tonal character. This was pointed out by a caveat in Section 6.7- Mahogany and Maple. Mahogany is found to have a higher specific stiffness than maple, but is commonly described as a warm, dark sounding wood. Other factors like density, damping, radiation ratio and acoustic impedance also play a role.

Chapter 6 - Conclusions

This chapter concludes the thesis. It first summarises what the work established, then sets out the resulting profile of superwood as a design material and the criteria that follow from it, and finally answers the two research questions.

6.1 A faster and more accessible route to a usable material

Two comparisons frame the process contribution of this work: one against the laboratory protocol the densification is adapted from, and one against the way tonewood is conventionally prepared for instrument making.

6.1.1 Against the reference densification protocol

The first outcome concerns the process itself. The densification route developed here reaches a usable densified blank far more quickly, and with less energy, than the reference protocol of Song et al.^[5] Where the reference delignifies by boiling directly in a strong alkaline solution for approximately a day and then washes over some fifteen hours, the workshop process draws a milder solution in by vacuum, delignifies in short cyclic one hour boils to a measured neutral pH endpoint, and folds the washing into the same cycle, completing the whole wet stage within a single working session (Table 3.1). The thermal budget shrinks accordingly: the day long boil and the long rinse, the two most energy hungry steps, are removed, and the heated pressing is the only sustained heating that remains.

The significance is not only convenience. A route that runs on a domestic stove and a small hot press, without a fume hood or a day of boiling, is one that a small workshop or an independent luthier could realistically operate, which is the setting this thesis targets. The trade off, stated in Chapter 3, is that the process does not pursue the maximal densification of the reference work; it aims instead for a controlled, repeatable result at a fraction of the time and energy.

6.1.2 Against the conventional tonewood preparation pipeline

The comparison can also be drawn against the way tonewood reaches an instrument today, which is anything but quick. Before a board can be built into a guitar it must be seasoned and stabilised: air dried over an extended period, then conditioned in climate controlled chambers, and in some cases torrefied, that is thermally roasted to drive off moisture and settle the wood. In current practice a batch can take on the order of eight months to pass through this preparation before it is ready to use^[37]. The densification route developed here reaches a densified, oven dried blank in a small fraction of that time, the wet stage within a single working session, followed by pressing and drying, so on process time alone the contrast is stark.

Two cautions keep this in proportion. First, this is a comparison of process time only. Nothing can be said here about the relative energy use of the two routes, since the energy demanded by the conventional seasoning pipeline, much of it low grade heat spread over months, was not measured and cannot be compared like for like with the concentrated heat of pressing. Second, a fair comparison would ultimately rest on a full cost analysis covering materials, labour, equipment, yield, and energy, which is beyond the scope of this project. The traditional pipeline also delivers fully seasoned, stable stock, whereas the long term conditioning and stability of the densified blank still depend on the validation set out in Section 7.2 The time advantage is therefore real and notable, but the energy, cost, and equivalence questions remain open.

6.2 What the study establishes

6.2.1 The material comfortably satisfies the mechanical demands of a neck

On the mechanical side the case is clear and, if anything, generous. The densified poplar is on par with hard maple in bending stiffness, 12.23 GPa against the maple reference of 13.23 GPa on the same rig, and 96.9% of the USDA maple figure, and exceeds maple in surface hardness on the fret bearing face, by at least 14.1%. Set against the loads a neck actually carries, and remembering that the truss rod carries a large share of the sustained string tension so that the wood need not resist it unaided, this is more mechanical capability than the application strictly demands. The material is, in that sense, over specified for the structural job: as hard as or harder than the benchmark, as stiff, and considerably denser. The density is the one figure that is not purely an advantage, since a heavier neck shifts the balance of the instrument, and it is one reason the optimal degree of densification, discussed in Section 6.4, is worth revisiting.

6.2.2 Acoustic behaviour is plausible but shows outliers

The acoustic results are the least clean part of the study, and honesty requires that they be treated as indicative rather than settled. These are limits of a single tap, coupon scale, workshop measurement more than they are properties of the material, as Section 6.5.1 sets out. The fair reading is that the densified poplar behaves as a distinct but plausible tonewood, near maple in the properties that matter, with acoustic outliers the current data cannot fully resolve.

6.2.3 A plausible stability advantage from the treatment

A third finding is a hypothesis rather than a measurement, but a well-motivated one. Both the alkaline delignification and the press heat attack hemicellulose, the most hygroscopic of the wood polymers, and wood that loses hemicellulose takes up and releases far less moisture, as the thermal modification literature shows^[38]. The effect is measured directly in densified wood: Song et al. report only 8.4 per cent thickness swelling after 128 hours at 95 per cent relative humidity, against 43.1 per cent for conventionally pressed wood^[5]; and in poplar specifically, Wang et al. found that delignification and densification lowered the equilibrium moisture content and raised cellulose crystallinity so the cell walls bound less water, the benefit being greatest at partial rather than extensive delignification^[39]. It is therefore plausible that the densified poplar is considerably more dimensionally stable against humidity than untreated wood, which for a neck, where movement means a lost setup and buzzing strings, would be a genuine advantage. This remains a hypothesis, following from the chemistry and the literature but not measured on the present samples; Section 6.5.2 sets out the humidity testing that would confirm or refute it.

6.2.4 The material fabricates and finishes like conventional wood

Finally, and importantly for a material meant to be used rather than only studied, the densified blanks behave well under normal workshop fabrication. They cut, saw, and shape with ordinary workshop tools, chop saws, jigsaws, sanders, and files, with no special handling, and they machine more like a dense, closed pore hardwood than an open grained softwood, which suits the crisp edges and tight fret slots a neck needs. They also accept primers, paints, and spray finishes without difficulty. In practical terms the material drops into an existing lutherie workflow, which removes one of the standing objections to novel materials, that they demand new tooling or new skills. The long term durability of these finishes and glue lines is a separate question, flagged in Section 6.5.2, but the immediate workability is not in doubt.

6.3 A finding beyond superwood: the material properties behind tonal character

The most transferable contribution of this thesis is not, in the end, about densified poplar at all. In placing the material on the tonewood map (Chapter 5), the work shows that a small set of measurable material properties - specific stiffness, the modulus divided by density (E/ρ), together with its close relative the radiation ratio $\sqrt{E/\rho^3}$, and, as Appendix F sets out, density, acoustic impedance and damping - track where a wood sits on the warm to bright tonal axis [13]. This reframes tone selection as a materials problem with a measurable target, rather than a matter of species lore.

The consequence reaches well past this project. If these acoustically decisive parameters are measurable and replicable, then any material, natural or engineered, can in principle be matched to a desired tonal target by matching the parameters. That opens a route to relatively more sustainable tonewood substitutes, not only for guitars but for other instruments, and to acoustic applications beyond instruments entirely. It is especially suggestive for additive manufacturing, where parameters can be tuned almost independently through infill fraction and lattice design, so that a printed part could be engineered toward a target parameter set, and therefore a target tonal character, by design rather than by trial.

6.4 A hypothesis: an optimal degree of densification

The finding leads to a specific, testable hypothesis about densification itself. Densification also raises the stiffness (not just density) of a wood, but not necessarily in step. At low compression, the collapse of the cell lumina stiffens the material more than it adds weight, so specific stiffness rises. Beyond some point, however, the cell structure is already largely closed, so further pressing adds mass more readily than it adds stiffness, and specific stiffness begins to fall. If that is so, then for any given species there should be an optimal degree of densification at which the wood is the highest stiffness it can be for the weight.

Considering specific stiffness's relation to tonal character and direct dependence on density, Figure 6.1 sets out the idea. At first the wood stiffens faster than it gains weight, so specific stiffness climbs; this is the rising, green part of the curve, where denser means genuinely stiffer. Beyond a certain point the balance reverses. This is the descending, orange part, where denser simply means heavier (this region is possibly where Poplar 50% lies). Between the two lies a peak, the degree of densification at which specific stiffness, and with it the acoustic performance, is highest.

The curve is drawn as a schematic, to show the shape of the relationship rather than fixed values. Its practical importance is that it turns densification from a single setting into a variable to be tuned and establishing where that peak lies is the measurement that would turn the idea into a design rule.

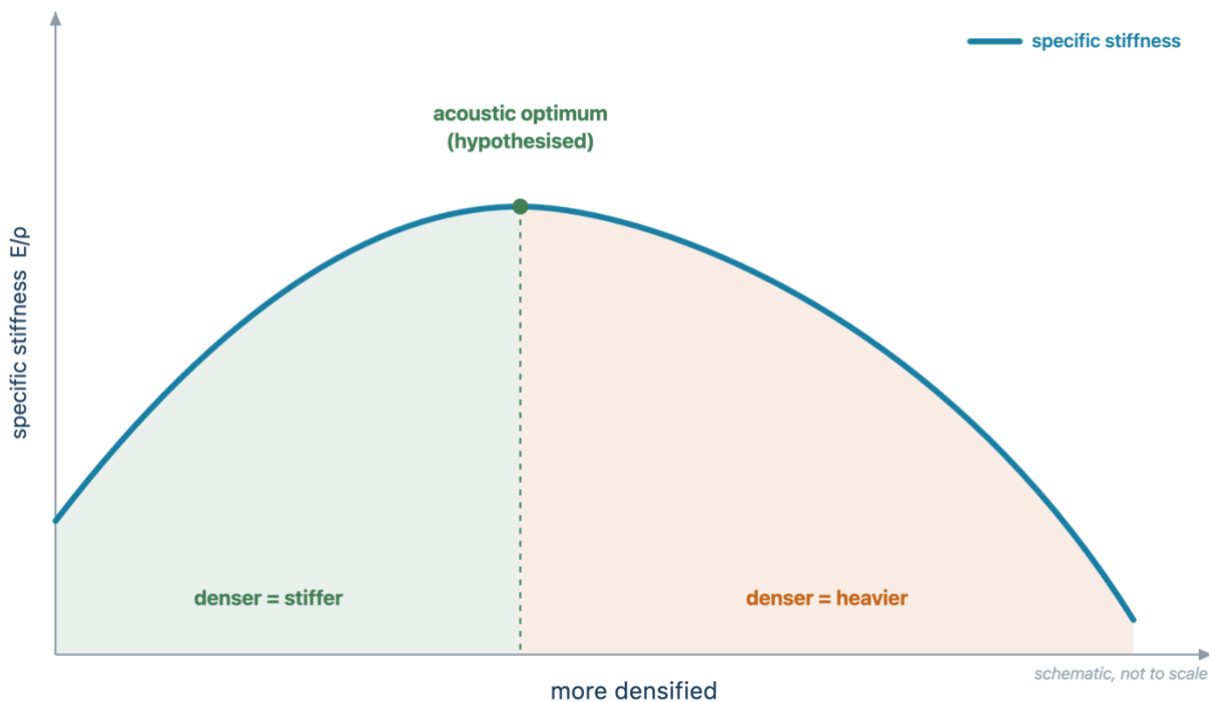


Figure 6.1. Schematic of the hypothesised relationship between degree of densification and specific stiffness. In the rising green region the wood stiffens faster than it adds mass, so specific stiffness climbs; beyond the peak, in the descending orange region, further compression adds mass faster than stiffness and specific stiffness falls.

The consequence is that the acoustic optimum and the mechanical optimum need not coincide. Hardness and density rise steadily with densification, so if the aim is maximum hardness the wood is pressed well up the descending slope, past the acoustic peak, where the added weight has begun to cost more in specific stiffness than the added stiffness returns. If instead the aim is tone, a lighter, less densified blank sitting nearer the peak would be expected to perform better, and for a guitar neck this is affordable, since the truss rod carries much of the structural load and the wood need not be pressed to its hardest to be stiff enough.

This would be worth knowing, because it separates the acoustic optimum from the mechanical one. The present study densified to 50% because that was the compression needed to reach maple level hardness, but the acoustic result, the depressed first frequency, hints that this may already be past the acoustic optimum, where the added density has begun to cost more than the added stiffness returns. A lighter, less densified blank might sound better while still being mechanically sufficient, given the truss rod. Establishing the specific stiffness against compression ratio curve, for poplar and for other candidate species, is a clear and worthwhile next investigation.

Hypothesis. For a given species there exists a compression ratio that maximises specific stiffness E/ρ ; below it stiffness is left on the table, above it density rises faster than stiffness and the acoustic performance as measured by specific stiffness declines. Specific stiffness is, however, only one of the properties that shape acoustic behaviour, alongside density, impedance and damping, which densification also changes. The stiffness to weight optimum is therefore generally lower than the compression needed to maximise hardness, and the two targets should be set independently.

6.5 Superwood as a Design Material

A material is more than the sum of its measured properties. Alongside what it can do, it has qualities that are sensed, meanings it evokes, and values it comes to stand for, and it is inseparable from the way it is made and worked. Choosing a material, and certainly choosing a tonewood, is never done on stiffness and density alone. It is done on how all of these fit the instrument and the people who make and play it. The characterisation so far has given the first of these, the performance. This section places superwood in the holistic picture.

The characteristics of a material are what it is: the qualities it actually possesses. The criteria are what it must be: the targets a candidate is held to. This section describes the characteristics of superwood; the criteria follow from them in the next section (Section 6.6).

From this perspective, a material is experienced on several levels at once.

- What it does, its performance.
- What it is like, the grain, weight, feel, and sound the senses meet.
- What it means, the associations and values it carries for a maker or a player.
- How it is made and worked, which shapes both what can be built from it and who can build it.

On the layers used here. The four layers below combine cues from Material Driven Design^[15] and from the materials experience framework, which reads a material across sensorial, interpretive, affective and performative levels alongside its technical properties. The four level reading, and the performative level in particular, follows Giaccardi and Karana's formulation of materials experience^[40], drawn here from its original interaction design setting into the context of a physical instrument material. They are adapted rather than reproduced: the interpretive and affective levels are merged into a single meaning and values layer for readability, and the making of the material is drawn out as its own layer, since for a workshop-scale process how the material is produced is itself a defining characteristic. The layers are therefore informed by the literature and simplified to suit this material and this argument.

Figure 6.2 sets superwood on these four. They run from the physical material at the base to its meaning at the top, and a material takes its place in an instrument only when they align, not when the numbers alone are right.



Figure 6.2. Superwood read across the dimensions of a material, from the physical material to its meaning and values.

What it stands for: meaning and values

What a material means is carried as much by its values as by its appearance, and here superwood is unusually rich. Its first value is sustainability: it is offered as a candidate answer to the tonewood crisis, standing in for scarce and restricted species with one that is abundant and fast and sustainably grown. Second, it is an honest timber. Unlike the engineered woods it will be set against, MDF, particle board, and plywood, it is not a bonded composite pretending to be timber. It is timber, delignified and densified, and it keeps the grain and the working feel of the real thing. A third value is quieter: the elevation of a humble, common species to a premium use, a reversal of the usual hierarchy in which only rare woods are prized. None of this is incidental to an instrument. A guitar carries heritage, craft, and identity, and whether a material reads as a compromise or as a credible, principled choice is what finally decides its acceptance. This is the substance of the perceptual question in Research Question 2, and it is where the case for superwood is strongest.

What it is like: the sensorial layer

To the senses, superwood remains wood. It keeps a continuous, visible grain, it feels like a dense hardwood in the hand rather than like a board product, and it has its own voice when tapped, distinct from both raw poplar and maple. It machines to a clean edge and takes primer, paint, and spray finish. For an instrument this is not decoration: the sound is part of the material's identity, and the fact that superwood looks, feels, and finishes like a fine tonewood is central to whether it will be received as one.

What it does: the technical layer

On performance, superwood approaches maple where it matters for a neck. Its bending modulus, at 12.23 GPa, is on par with the maple benchmark at pilot scale, and its fret face is harder. The characteristic that matters most, though, is not any single number but that the numbers can be tuned. The degree of densification sets stiffness, density, and hardness together, so the material can be specified rather than merely selected. That is unusual for a natural material, and it is the root of everything that follows.

How it is made: the process layer

Finally, how a material is made is part of what it is, and part of what it invites. Superwood is produced at workshop scale, delignified and densified on benchtop equipment with standard tools, one blank at a time. A material a small maker can produce for themselves carries a different meaning from one only a factory can supply: it invites independent, local making, and it reads as a recipe others can follow, in lutherie and beyond. The way it is made is therefore not only a technical fact but part of its character and its appeal.

From characteristics to criteria

These characteristics become criteria the moment they are turned into targets a candidate material must meet. The next section does exactly that: it fixes the mechanical and acoustic targets against the woods luthiers already trust, and places superwood and its alternatives on a single map of specific stiffness, turning the central finding of this work, that tone can be traced to a small set of measurable material properties rather than to species lore, into a way of choosing and tuning a material rather than only describing one.

6.6 Design criteria

The findings translate into a small set of measurable targets a candidate neck wood should meet. Two properties carry most of the weight: the modulus of elasticity as the mechanical indicator, and the specific stiffness, the modulus divided by density, as the acoustic indicator, since the tonal character of a wood tracks its specific stiffness. Rather than fix arbitrary numbers, the targets are set as the band spanned by the woods luthiers already trust. Hard maple and mahogany, the two dominant electric guitar neck woods, set the range; rosewood and ebony are added because they are the standard fretboard woods, and a neck is rarely a single wood. These reference values and the bands they define are set out in Table 6.1. (Note: values for documented woods including Hard Maple are taken from the USDA Wood Handbook^[14] rather than measured. The measured values in Chapter 4 are taken for relative comparison and testing within the samples)

A note on pairing informs the criteria: a maple neck often carries a maple fretboard, but a mahogany neck never carries a mahogany fretboard, it is paired with maple, rosewood, or ebony (not included in this table, as no data was found). A candidate material can therefore aim at the neck band, the fretboard band, or both.

Reference woods and the target bands

Wood	Role	MOE (GPa)	Density (g/cm ³)	Specific stiffness E/ρ
Hard maple	Neck + fretboard	12.6	0.70	17.8
Mahogany (Swietenia macrophylla)	Neck	10.3	0.50	20.5
Rosewood, Indian (Dalbergia latifolia)	Fretboard	12.3	0.83	14.8
Superwood (Poplar 50%)	Candidate neck/fretboard	12.23	0.94	13.0

Table 6.1. Reference tonewoods and the target bands for a candidate neck material. Modulus and density for hard maple, mahogany, and Indian rosewood are USDA Wood Handbook values at 12% moisture content (Kretschmann 2010)[14]. Superwood values are measured in this study.

The criteria, and where superwood lands

Mechanical: Mechanical parameters land within the neck wood modulus band, which runs from about 10 GPa at the mahogany end to about 12.6 GPa at the hard maple end. Since the design aim is maple equivalence rather than a mid band figure, the target is the upper, maple end of this band, not its middle. Superwood, at 12.23 GPa, sits just inside that upper end, at 96.9% of the maple benchmark, which is exactly where a maple substitute should fall.

Acoustic: With the current compression, Poplar 50% lies slightly short of the specific stiffness band of the reference woods. The neck woods sit at roughly 17.7 to 20.2, the dense fretboard woods lower, at about 14.8. Superwood, at 13.0, sits below even the fretboard woods.

Workability: Machine, glue, and finish with standard woodworking and lutherie tools, which superwood does.

Superwood already satisfies the mechanical and workability criteria, but densifying to 50% has pushed its specific stiffness below the band of the trusted woods. That is exactly the signal behind the optimal densification hypothesis: a lighter, less densified blank would raise specific stiffness back toward the target band while still meeting the mechanical criterion. The design criterion, then, is not maximum densification but the densification that lands specific stiffness inside the reference band.

6.7 The Ashby chart: specific stiffness as a selection driver

The perceptual terms can finally be traced back onto the Ashby stiffness against density chart, the standard map of all material families (see Figure 6.3),^[41] generated using ANSYS Granta EduPack. Because specific stiffness is an important contributor to perceived brightness, described more completely by the radiation ratio $\sqrt{E / \rho^3}$, both built from modulus and density, brightness and warmth have a definite direction on this chart. Brightness rises toward low density and high stiffness, the upper left, where light and stiff woods such as spruce and paulownia radiate efficiently; warmth rises toward high density, the lower right, where dense woods lose radiating efficiency and darken. The dashed yellow line on Figure 6.3 is that direction. It is not a new axis but a reading of the existing one: the same chart that ranks materials by stiffness and weight also, read along this diagonal, ranks woods from bright to warm. The shaded band added to the chart is the neck material belt: it spans

the specific stiffness of maple to mahogany, the two dominant neck woods, and marks where a candidate must lie to serve as a neck. Raw poplar sits within the belt, and densifying to 50% moved the material down and out of it, the same overshoot described in Section 6.4, now read as a selection criterion rather than a tonal one.

In carrying out this comparison, the specific stiffness values of the candidate woods were placed side by side, and an apparent inconsistency surfaced. On specific stiffness alone, some woods did not fall where their tonal reputations would suggest, since a lighter and less stiff wood such as mahogany can carry a higher specific stiffness than a denser and stiffer one such as maple. This mahogany and maple case, and the reconciliation it prompted, is examined in Appendix F.

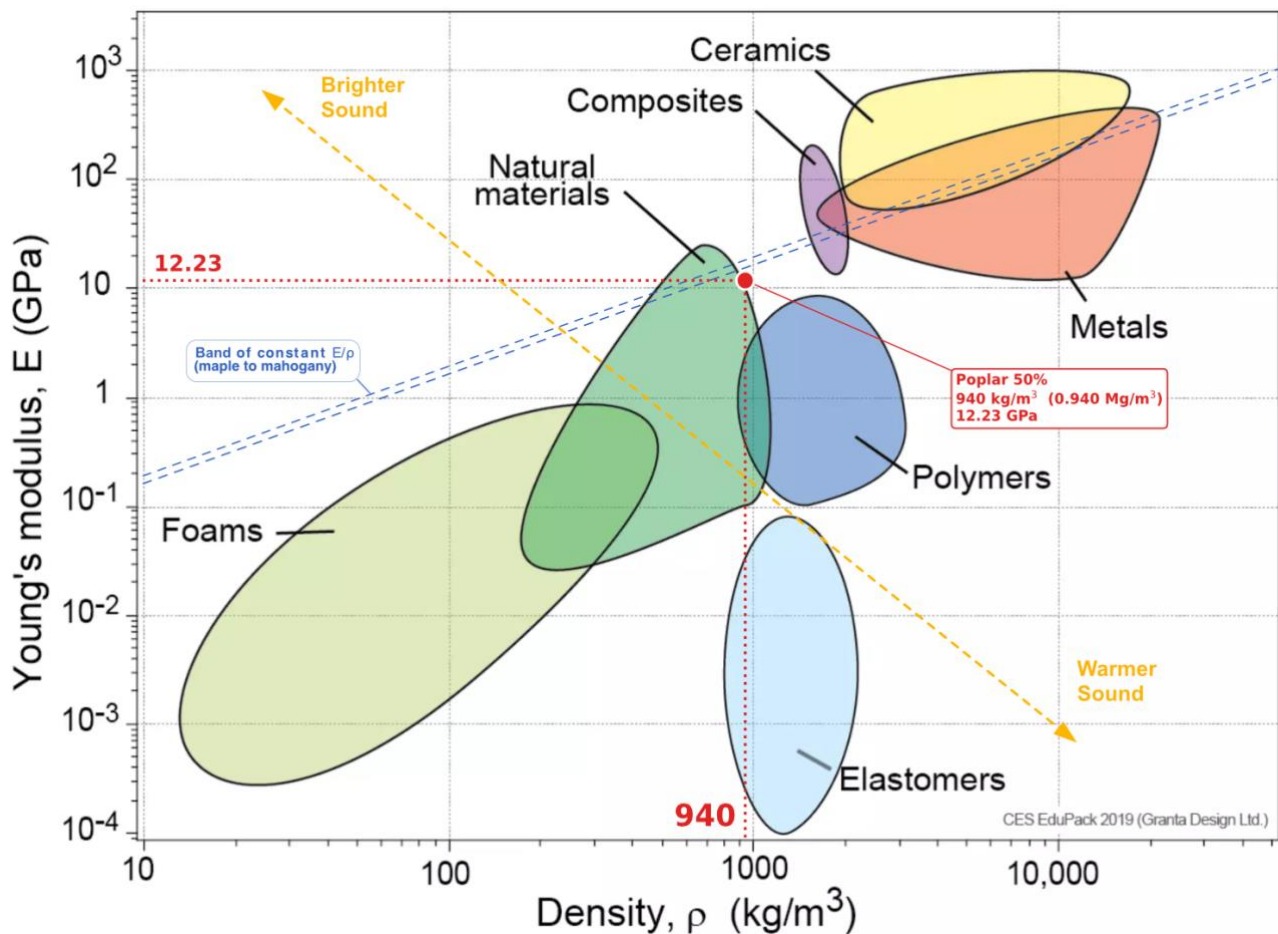


Figure 6.3. The Ashby modulus against density chart for all material families. The dashed yellow line is the tonal direction: brightness increases toward light, stiff woods (upper left), warmth toward dense woods (lower right).

This closes the loop with the material. With the hypothesis that Poplar 50% is on the other end of the optimal specific stiffness curve, it moves down and to the right on this chart, toward the dense, lower ratio corner, towards the warmer side. Its modulus stayed at maple's level, satisfying the mechanical load requirement, while its density rose, lowering the specific stiffness and carrying the voice toward warm (this is also observed in the acoustic test in Section 4.4 - the fundamental frequency of densified poplar is lower than that of raw poplar); the added mass, not any loss of stiffness, is what colours it. The crisp to muddy behaviour is not captured by this chart at all, because it belongs to damping rather than to modulus and density, and that dimension is the one the tap tone damping measurements address separately.

Figure 6.4 shows a zoomed in view of the natural materials region from Figure 6.3, showing the traditional neck wood specific stiffness belt (maple to mahogany) with the measured and reference tone woods mapped. Poplar 50% falls below the belt, denser for its stiffness, in the direction of rosewood. Raw yellow poplar has also been included, with values taken from the USDA wood handbook^[14]

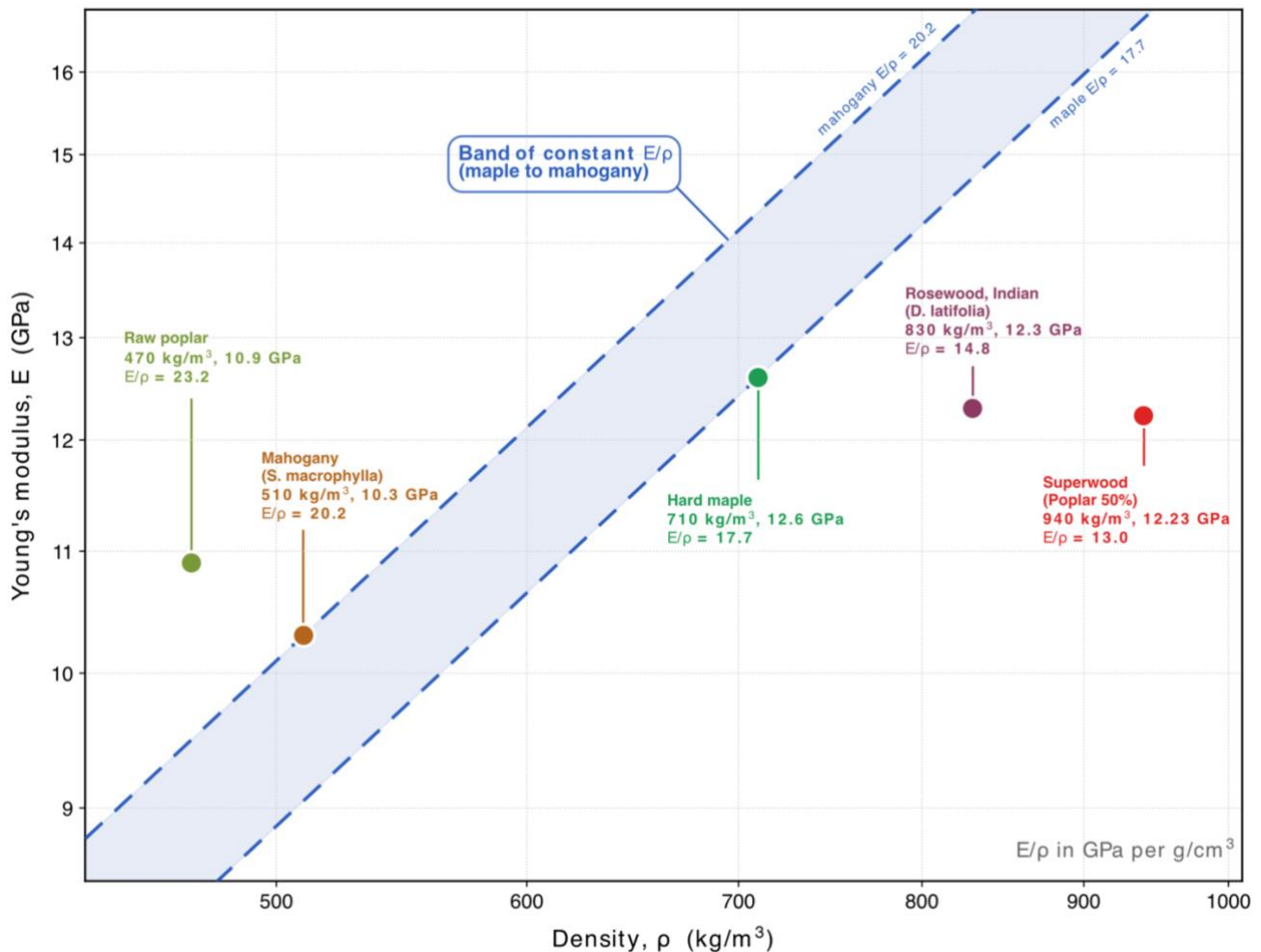


Figure 6.4. Modulus against density for the neck woods, zoomed into the natural materials region of the Ashby chart. The shaded band is the corridor of constant specific stiffness spanned by the two dominant neck woods, mahogany ($E/\rho = 20.2$) and hard maple ($E/\rho = 17.7$). Raw poplar sits above the band at 23.2; densifying to Poplar 50% raises modulus only slightly (10.9 to 12.23 GPa) while density doubles (470 to 940 kg/m³), dropping specific stiffness to 13.0 and placing the material below the band, past Indian rosewood at 14.8. All values except Superwood are taken from the USDA Wood Handbook.

The findings of this study can translate into a simple design tool to find the compression ratio that keeps the material inside the band and calibrate it according to design requirements.

If specific stiffness is measured across a range of compression ratios, for Yellow Poplar or for any candidate species, the resulting points trace a trend across this chart: density rises steadily as the material is pressed while modulus climbs and then saturates, so the trend moves down and to the right, from high specific stiffness at the raw state towards lower specific stiffness as compression increases. Overlaying that trend on the maple to mahogany band turns the chart into a selection tool. Wherever the trend lies inside the band, the material matches the specific stiffness of a traditional neck wood, so the compression ratios that place it there define the usable window. The point at which the trend crosses the lower edge of the band, the maple line, marks the maximum useful compression, beyond which the material leaves neck territory and moves into the denser,

fretboard like region occupied by rosewood. Reading the optimal compression is then simply a matter of finding where the measured trend enters and leaves the band, and if the aim is to combine neck like stiffness with the greatest possible density and surface hardness, the target is the far end of that window, just inside the lower edge. Figure 6.5 illustrates this trend. Within this optimal window lies a design choice, to tweak the sound towards bright or warm.

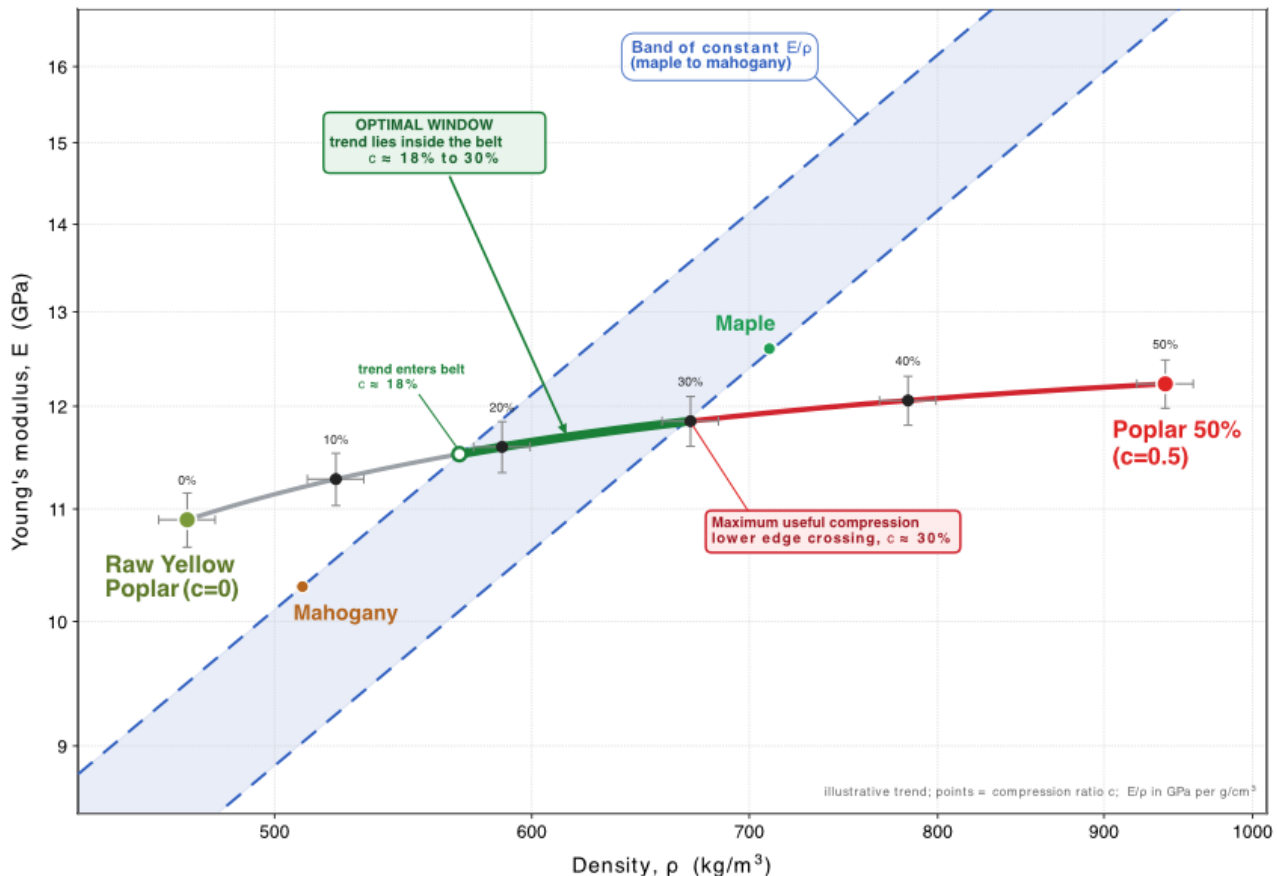


Figure 6.5. Illustration: Young's modulus against density on linear axes for yellow poplar densified from the raw state ($c = 0$) to 50 per cent compression. Modulus climbs and then saturates while density rises steadily, so the trend runs down and to the right across the band: it enters at $c \approx 18$ per cent (green) and crosses the lower edge at $c \approx 30$ per cent (red), the maximum useful compression. The interval between the two crossings is read as the optimal densification window for a maple grade neck.

Note. The trend drawn in the illustration is schematic, to be taken as an example only. It is a saturating curve through the raw and 50 per cent points rather than measured intermediate data, so the window shown, roughly 18 to 30 per cent, is indicative; the same reading performed on real points at several compression ratios, with error bars, would replace it with a calibrated window. And the method is species independent: any wood processed the same way traces its own trend, and its neck suitability is judged by whether, and over what compression range, that trend passes through the band.

A note on the limits of the Ashby selection

The Ashby analysis above ranks the candidate woods by specific stiffness, and by extension the radiation ratio that follows from it. On that single measure the densified poplar is penalised, sitting below maple and mahogany, because densification raises mass faster than it raises stiffness and so lowers the specific quantity. What first drew attention to the problem was the zoomed in view of the

chart, where mahogany sits at a higher specific stiffness than maple. Mahogany is commonly described as a warm, dark sounding wood and maple as a bright one, so if specific stiffness were the quantity that set brightness the two would be ranked the wrong way round. That single contradiction is difficult to reconcile with specific stiffness being the driver of tone, and it is what prompted a closer look.

The wider point is that this measure cannot be treated as the sole descriptor of tone. Specific stiffness and the radiation ratio are figures of merit developed for soundboards, where the plate itself radiates the sound, and they capture only one part of how a wood behaves. They say nothing about acoustic impedance, which governs how firmly the wood anchors the string, nor about damping, which governs how the higher frequencies decay, and both of these are parameters that may contribute at least as much to the perceived brightness and definition of a note. For a solid body electric neck, where the string is sensed directly rather than radiated by the wood, the weighting of these quantities is different again and is genuinely contested in the literature. Specific stiffness is therefore better read as one indicator among several rather than a verdict.

Updated findings on acoustic characterisation of the densified poplar, setting the specific stiffness result alongside measured impedance, damping and tap tone data, and explaining why the maple comparison in particular is misleading when reduced to this one axis, is given in Appendix F.

6.8 Answering the research questions

The thesis set two research questions in Chapter 1. Each is answered here in turn, with the boundaries of the answer stated as plainly as the answer itself.

6.8.1 Research Question 1: technical feasibility

To what extent can workshop-scale superwood production deliver the mechanical and acoustic properties that a traditional neck tonewood, benchmarked against hard maple, provides, and what can be established about its dimensional stability?

The answer, at the pilot scale of this study, is affirmative on the mechanical axis, promising but unresolved on the acoustic axis, and, as yet, only reasoned rather than demonstrated on the dimensional stability axis.

On the three sub questions

The baseline properties of the reference tonewood were established, so that the candidate could be judged against a firm benchmark rather than against species lore (SRQ1.1). The influence of the process variables was resolved to the point of identifying the compression ratio as the single dominant lever, with a strongly nonlinear effect that only reaches maple level hardness near the upper end of the range explored (SRQ1.2). And the material was shown to enter an ordinary lutherie workflow without special equipment, cutting, shaping, and finishing like conventional timber (SRQ1.3). Taken together, these close RQ1 in the affirmative for the property that governs a neck, its stiffness, which the densified poplar matched, and for surface hardness, which it exceeded, while leaving the acoustic equivalence as plausible rather than proven and the dimensional stability as a reasoned expectation awaiting test.

Answer to RQ1. Workshop-scale superwood can be produced with accessible equipment and delivers the mechanical performance a guitar neck requires, matching the reference tonewood

in stiffness and exceeding it in surface hardness. Acoustic equivalence is plausible but not established, and dimensional stability is expected on chemical grounds but untested. The feasibility is therefore demonstrated as a proof of concept on one specimen per material, not as a statistically representative result.

6.8.2 Research Question 2: behaviour as a natural wood

How closely does superwood, as an engineered wood, behave like a natural tonewood: in how it looks, how it responds to standard woodworking processes and finishes, and how its measurable properties map onto the tonal vocabulary used for tonewoods?

Superwood behaves as a natural wood in the ways a luthier would test it. It keeps a continuous grain, and it cuts, shapes, glues, and finishes with standard tools, so it works like wood rather than like a board product (SRQ2.1). The tonal character presents complexities to be measured properly at this scale of samples. By the route the study first assumed, specific stiffness was expected to bridge measurement and the warm to bright axis. Appendix F tested that mapping directly against published data and found it fails the check: for solid body electric woods specific stiffness correlates negatively with brightness, running opposite to the assumed direction, so it cannot be read as a direct driver of perceived tone. It remains a dependable descriptor of wave speed and tap frequency, one contributing material property among several, but density and impedance are the properties that actually order the tonal axis. On the properties that do order the axis, density and impedance, the measured Poplar 50% falls in the bright, crisp region near maple rather than in the warm, muddy region occupied by raw poplar (SRQ2.2).

Crucially, superwood differs from MDF, particle board, and plywood not in degree but in kind: those are bonded composites, whereas superwood is real wood that has been delignified and densified, retaining the grain and workability of timber (SRQ2.3). This is the basis for expecting it to be received as another natural tonewood rather than as an engineered substitute. What the thesis did not do was test that reception directly. No blind listening or playing comparison was carried out, so player perception remains reasoned rather than demonstrated, and the proof of concept strung neck, if built, would be the first such signal.

Answer to RQ2. Superwood behaves, looks, and works like a natural wood, and its tonal position is captured by a set of parameters (specific stiffness, density, impedance and damping), none of which on their own can predict perceived tone. Because it is real wood rather than an engineered composite, it is likely to be accepted as a natural tonewood, though a player study, left as future work, would be needed to confirm this.

6.8.3 Overall conclusion

The thesis set out to determine whether an abundant, fast grown wood could be processed at workshop-scale into a credible substitute for hard maple in a guitar neck. It concludes that it can, within clearly stated bounds. A faster and more accessible densification route was developed and shown to work; the resulting material was characterised and found to meet, and in hardness exceed, the mechanical demands of a neck while fabricating like ordinary wood; and a physically grounded

account of what places a material on the tonal map was established, one that reaches beyond this material and this instrument.

Equally, the thesis is clear about what it has not settled. Every characterisation result rests on a single specimen, the acoustic behaviour carries outliers that the workshop measurement cannot fully resolve, the expected humidity stability is a reasoned hypothesis rather than a measurement, and the perceptual validation has not been carried out. These are not weaknesses concealed but the honest edge of a pilot study, and they define precisely where the work must go next, as the next chapter sets out.

The central conclusion, then, is a qualified but genuine yes. Densified poplar is a technically feasible and mechanically more than sufficient neck material that can be made and worked at workshop scale, and the framework this thesis provides, tone as a function of measurable mechanical and vibrational parameters of wood, turns the search for tonewoods from a matter of tradition into a measurable materials problem. Confirming that promise, on many specimens, on a real neck, and to the ear of a player, is the work that follows.

Chapter 7 - Recommendations and Future Work

This final chapter turns from what the work concluded to what should follow: the validation the material still needs, the durability testing a neck demands, and the wider research directions the findings open.

7.1 From coupons to a neck: proper acoustic validation

The acoustic outliers must not be over read, for reasons that are as much about method as about material. The measurements were made on small coupons, one tap each, on a suspension and excitation rig assembled at workshop-scale rather than to full standard (Chapter 4). Any of these could account for some of the scatter. The single most valuable next step is to move from coupons toward the real object: to process a full size neck blank, and ideally to build a scale guitar neck in the densified material alongside an identical one in maple, for a direct A/B comparison under proper acoustic characterisation, of the kind offered by dedicated tonal characterisation systems such as the Iulius Guitars TPC, or Tonewood Parameters Characterization, system, which analyses a tap test by the free beam method to measure the damping, Q factor, and resonance decay of a sample and to build a comparable acoustic library^[42]. These are precisely the damping and quality factor parameters that this study found hardest to pin down, so such a system would directly address the weakest part of the present acoustic dataset. A simpler and cheaper A/B benchmark, a plain beam of each material strung under tension, would already allow a controlled comparison of the two materials as sounding objects rather than as coupons, and would be a sensible first move before committing to a full instrument.

7.2 Viability: the long term durability roadmap

Everything measured in this thesis is short term, yet viability, whether the material survives years of service, is what finally separates a promising pilot from a usable neck wood. Viability is therefore established here in principle and scoped for validation rather than tested. There is a positive reason to expect it to hold: delignification and the heat of pressing both break down hemicellulose, the most hygroscopic of the wood polymers, so a densified blank should take up less moisture and move less with humidity than natural wood. That is a plausible stability advantage rather than a liability, and it makes the case for viability credible. What remains is to turn the reasoning into measured evidence, against the conditions a neck must meet, set out as the roadmap below.

- **Creep.** Hold a densified specimen under a string tension equivalent bending load for weeks or months and track whether it slowly deforms, since a densified, partially delignified material may relax more than natural wood.
- **Humidity cycling and warping.** Cycle finished blanks through realistic humidity ranges and measure dimensional change, twist, and any loss of neck setup. This is the direct test of the stability hypothesis of Section 6.2.3.
- **Recovery and permanent set.** Check whether the compression is permanent or whether the material slowly springs back or swells, particularly with moisture, which would undo the densification.
- **Fatigue and repeated load.** Beyond steady creep, a neck endures repeated tuning, temperature, and playing cycles; cyclic loading of densified specimens would show whether the compressed structure fatigues, softens, or delaminates over many cycles.

- **Fracture and toughness.** Because the bending specimens splintered rather than breaking cleanly, the material's toughness is unquantified; notched or impact tests would establish how it resists cracking under a sharp load.
- **Machining and fret slot retention.** The neck must cut, rout, and hold fret slots and tuner holes at production tolerances without splitting; machining trials on full blanks would confirm it behaves under tooling as maple does.
- **Adhesive and coating durability.** The fingerboard glue lines and the finish must survive the same load and humidity cycling; lap shear tests on glued joints and finish adhesion checks after cycling would close this, extending the point noted in Section 6.2.4.

Completed, this programme would move viability from a reasoned expectation to a measured result. It is the single largest body of work still standing between this pilot and a qualified neck material, and the stability advantage argued above is the reason it is worth undertaking.

7.3 Statistical replication

Underlying all of the above is the single specimen limitation – one blank per material, a limit set by facility access, processing time, and material supply rather than by design, stated in Chapter 4. Every characterisation result rests on one blank per material, so the numbers describe particular specimens, not the material in general. Before the conclusions here are treated as established, the hardness, stiffness, and acoustic tests should be repeated on several independently processed blanks per condition, so that variation between blanks can be separated from measurement scatter.

7.4 Closing remark

Taken together, the work delivers a faster and more accessible route to a densified wood that satisfies the mechanical demands of a guitar neck, fabricates like conventional timber, and plausibly resists humidity better than natural wood. It contributes a transferable, physically grounded account of what makes a material sound the way it does. And it defines, in the optimal densification hypothesis and the durability programme above, a clear path for the work that should follow.

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Appendix A. Detailed Experimental Record: Experiments 1 to 5

This appendix contains the full method and results of each development experiment summarised in Chapter 3.

A.1 Phase 1

These experiments constitute the first practical trial in the development of a workshop-scale superwood production process for lutherie applications. The broader project aims to densify an abundantly cultivated species to match the mechanical and acoustic properties of maple (*Acer saccharum*), the conventional tonewood used in electric guitar neck construction.

A.2 Aim and Scope

The primary aim of this experiment was to establish the feasibility of the two-step alkaline delignification and hot-pressing process at workshop scale, using accessible laboratory equipment and commercially available reagents. No scientific material characterisation testing was performed at this stage. The experiment was exploratory, intended to observe the qualitative outcomes of the process and identify parameters requiring refinement in subsequent iterations.

Secondary aims included ironing out finer details in the process and tweaking it for this use case, establishing a working baseline for solution concentration, boiling duration, and press parameters, and identifying failure modes or process risks not anticipated in the literature.

A.3 Sample Preparation

Norway spruce (Fig.A.1) (*Picea abies*) was selected as the substrate for this initial trials. Spruce is a fast-growing, abundantly cultivated European softwood with a baseline density of approximately 0.45 g/cm^3 , significantly lower than the target maple density of $0.60\text{--}0.75 \text{ g/cm}^3$.^[14] It is therefore an appropriate candidate for densification. The species is also noteworthy in the context of lutherie, as it is the tonewood of choice for acoustic guitar and violin top plates,^[43] providing relevant acoustic context for the research. The samples for all the experiments in this phase were kept identical, and are shown untreated in Figure A.1.



Figure A.1 Untreated Spruce Samples

The orientation for all the samples in the experiments is standardised as shown (Fig A.2), with the longest face of the sample treated as the Length (L), adjacent to the Width (W) and Height (H), which

is also the pressing direction. All pressing is done tangential to the rings. The parameters are shown in Table A.1.

Parameter	Value
Species	Norway Spruce (Picea abies)
Length (L)	100 mm
Width (W)	50 mm
Height (H)	46 mm
Mass	100-103 g
Volume	277.15 cm ³
Density	0.44-0.45 g/cm ³
Grain orientation	Tangential
Press direction	Normal to grain

Table A.1 Untreated Sample Parameters

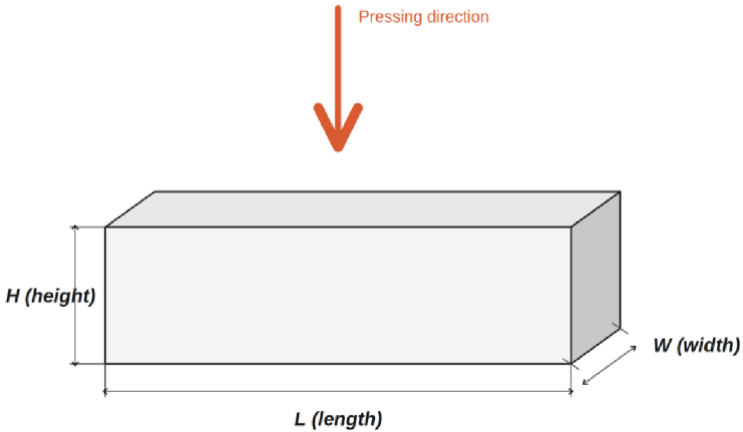


Figure A.2 Press Direction & Orientation 1

A.4 Experiment 1 - Norway Spruce

For the first trial, sodium hydroxide (NaOH) was the sole reagent used; sodium sulphite (Na₂SO₃) was not included at this stage (see Table A.2 for Composition). This is an acknowledged deviation from the full Song et al. protocol.^[5]

Reagent	Quantity	Notes
Tap water	330-340 mL	Approximate, to submerge sample
Sodium hydroxide (NaOH)	34 g	Added at approx. 50°C, stirred to dissolve
Sodium sulphite (Na ₂ SO ₃)	Not used	Omitted in this trial; to be included in subsequent experiments

Table A.2 Reagent composition, Experiment 1

A.4.1 Boiling (Delignification)

34 g of NaOH was gradually added to 140 mL of water at room temperature while stirring, until fully dissolved. The solution was then heated on the hot plate to about 80-85°C. The wood sample was submerged in the solution and heat was increased. Boiling was commenced at approximately 10:00 hours and maintained for six hours until 16:00 hours, with a target operating temperature of 85-95°C.

Photographic documentation was taken at hourly intervals throughout the boiling phase (see Figure A.3). As boiling progressed, the solution underwent a marked visual transition, becoming progressively darker with each hour: from transparent at the outset, to a golden amber colour, advancing through brown to a near-black coffee tone by the end of the sixhour period.



Figure A.3 Solution Darkening over Time

Following the six-hour boiling period, the sample was left to soak overnight in the beaker, which was removed from the hot plate and allowed to cool to ambient temperature. By the following morning, the wood had darkened considerably further and had absorbed additional solution. Approximately 80 mL of tap water was added during the boiling phase to maintain full submersion of the sample. Coagulated particulate matter was observed in suspension within the solution; this is attributed, at least in part, to precipitated or degraded resin fragments, though this inference was not confirmed analytically, as it is out of scope of this project.

The wood sample had darkened considerably in colour by this time, and was found to be very alkaline (pH 14) as tested with a pH strip (see Figure A.4).



Figure A.4 Spruce Sample after Boiling

A.4.2 Washing

The sample was rinsed by two successive cycles of boiling in plain tap water (see Figure A.5). In both cycles, the water began colourless and progressively turned yellowish-brown, and suspended coagulated matter was again present. Washing cycles were continued until the wash water reached an acceptably low colour intensity. The surface pH of the sample was monitored using indicator paper; pressing was commenced when the outer surface pH had reduced to approximately 9.



Figure A.5 Washing the Sample in Boiling Water

A.4.3 Hot Pressing

The sample was pressed in a heat press with the compression direction normal to the grain and tangential to the growth rings (see Figure A.6). Two steel plates were placed above and below the sample to protect the press platens from the alkaline solution expressed during compression.

The press was preheated to 95°C prior to loading. Compression was initiated at approximately 2 metric tonnes of force. The platens were monitored at hourly intervals and repressurised as pressure losses occurred due to continued moisture release and material relaxation. Force was increased incrementally to 4 metric tonnes over the course of the pressing cycle. The sample was held under heat and pressure for a total of six hours, after which the heat was turned off, but it was allowed to cool down under pressure overnight.



Figure A.6 Sample Pressed in the Heat Press

A.4.4 Results

Qualitative Observations

Upon removal from the press, the sample was noticeably harder and stiffer to the touch than untreated spruce, consistent with densification. The colour of the pressed sample was very dark throughout, a result of the prolonged NaOH treatment. The sample was still strongly alkaline at the surface and required handling with gloves.

Critically, the sample exhibited significant splitting, cracking, and void formation along the grain direction (see Figure A.7). The extent of this structural damage rendered the sample unusable for standard woodworking operations; a clean, defect-free blank could not be machined from the material. This outcome is classified as a process failure with respect to the final application, though the sample remains of value as a reference for the delignification and densification behaviour of the species.

The cracking observed can be attributed to two compounding causes. First, the omission of Na_2SO_3 left the G-type lignin in Norway spruce incompletely softened. Softwood G-lignin has a higher proportion of condensed C-C bonds relative to the more accessible beta-O-4 ether bonds that NaOH alone can cleave at 100°C . Without the Na_2SO_3 acting on the alphacarbon adjacent to these ether bonds, the cell walls retained significant residual stiffness and brittleness, making plastic deformation under compression impossible and fracture the predominant failure mode.

Second, the absence of lateral constraint during pressing allowed differential strain to develop across the cross-section. Unconstrained compression of a partially delignified wood blank concentrates stress at the outer fibres, which experience the highest strain rate. Without a jig to distribute load across all four lateral faces simultaneously, these fibres exceeded their strain limit and cracked.



Figure A.7 First Densified Sample after Pressing

Dimensional Outcomes

The dimensional and mass measurements taken before and after processing are presented below, along with the calculated percentage changes.

Parameter	Before Processing	After Processing	Change
Length (L)	100 mm	100 mm	0%
Width (W)	50 mm	50 mm	0%
Height (H) - press direction	46 mm	32 mm	-30.4%
Mass	100 g	104 g	+4.0%
Volume	230.0 cm ³	160.0 cm ³	-30.4%
Density	0.435 g/cm ³	0.650 g/cm ³	+49.4%

Table A.3 Dimensional outcomes, Experiment 1

The achieved density of 0.650 g/cm³ falls within the target range of 0.60-0.80 g/cm³ established to approximate the density of maple.^[14] The slight increase in height (+2.07%) is attributed to springback along the unconstrained longitudinal axis.

The mass increase of 4.03% is modest and likely reflects residual absorbed solution and retained moisture that was not fully expressed during pressing.

A.4.5 Analysis

The density outcome of 0.650 g/cm³ is a qualified success. Starting from a baseline of 0.447 g/cm³, a densification of approximately 70% was achieved, placing the result within the target range for maple equivalence.^[14] This shows that the alkaline delignification and hot-pressing sequence is fundamentally achievable at workshop-scale without industrial equipment.

However, the structural integrity of the sample is the primary concern. The cracking pattern, concentrated along the grain, indicates that the lignin was insufficiently plasticised prior to pressing, or that the compression rate was too aggressive relative to the moisture state and residual stiffness of the material. In spruce, the tracheid cell walls are relatively thin, and the high proportion of earlywood (low-density, thin-walled cells) makes the structure particularly susceptible to fracture when compressed without adequate cell wall softening.

The omission of sodium sulphite (Na₂SO₃) from the delignification solution is a significant variable. In softwoods, lignin is predominantly of the guaiacyl (G) type, which is less reactive to NaOH alone and requires the sulphonation action of Na₂SO₃ to facilitate adequate removal. The reference protocol^[5] specifies 0.4 M Na₂SO₃ in combination with 2.5 M NaOH for precisely this reason. It is plausible that the single-reagent treatment achieved insufficient lignin removal to allow the required degree of plastic deformation, contributing to brittle fracture under compression.

The overnight soaking in cooling solution, while unplanned, may have contributed to uneven moisture distribution through the cross-section, introducing differential stress gradients during pressing. This is a procedural variable to be controlled in future experiments.

A.4.6 Discussion and Proposed Improvements

This experiment, while resulting in a structurally compromised sample, was informative in establishing the practical behaviour of the process and highlighting the variables most in need of refinement. Several specific improvements are proposed for subsequent experiments, informed both by the observations made here and by additional literature.

Introduction of Sodium Sulphite

The most consequential process change for the next experiment is the inclusion of Na₂SO₃ in the delignification solution at the concentration specified by Song et al.,^[5] namely 2.5 M NaOH and 0.4 M Na₂SO₃. Spruce contains predominantly G-type lignin, which requires sulphonation to break down effectively. Alqrinawi et al.,^[25] in a parametric study of the Song et al. protocol, confirmed that targeted lignin removal of approximately 10% achieves optimal modulus of rupture (MOR), and that the combination of both reagents is necessary to achieve this in softwoods reliably. The Na₂SO₃ concentration may be increased to 0.6-0.7 M in recognition of the higher G-lignin content of spruce relative to the hardwoods tested in the original study.

Vacuum-Assisted Solution Impregnation

A sub-experiment was conducted in which a wood sample was submerged in water and placed in a vacuum oven at approximately 950 mbar for 30 minutes at room temperature, to assess the rate of solution uptake under reduced pressure (see Figure A.8). While the trial was inconclusive due to solution spillage, the methodology was found to be promising and is supported by the literature.



Figure A.8 Testing Effects of Vacuum in Absorption in Samples

Based on the vacuum and ultrasound pre-treatment findings for poplar reported in a 2021 Forests study (see Section 2.4.3),^[19] a 30 minute vacuum pre-impregnation step prior to boiling was adopted for Experiments 2 and 3, reducing boiling duration and the associated risk of cellulose degradation from prolonged alkaline exposure.

Boiling Duration and Cellulose Integrity

Alqrinawi et al.^[25] also tested boiling durations of three, five, and seven hours under the standard protocol. Their results indicate that three hours is a valid and shorter treatment time, and importantly, that prolonged boiling degrades the crystalline cellulose regions, reducing the structural quality of the densified product. The six-hour boiling duration used in this experiment may therefore have contributed to weakening of the cellulose scaffold, exacerbating the cracking observed during pressing. Future trials will target three to four hours of boiling, supplemented by vacuum pre-impregnation to ensure adequate solution penetration within this shorter window.

Washing and Residual Alkalinity

The washing protocol in Song et al.^[9] involves multiple boiling water rinse cycles conducted over approximately 15 hours in total. The abbreviated washing performed in this experiment, terminated at a surface pH of approximately 9, is likely to have left a higher residual alkali concentration within the bulk of the sample than the reference protocol specifies. Residual NaOH can continue to degrade cellulose during pressing and may affect the quality of the bond formed between densified cell walls. Future experiments will extend the washing duration and consider the use of a dilute acid neutralisation step. Suitable options include a 5% acetic acid solution (comparable to white vinegar, which is workshop-safe and does not chemically interfere with the wood substrate) or a citric acid solution, which additionally functions as a chelating agent, dissolving mineral ions introduced by tap water during washing.

Pressing Rate and Temperature Profile

The incremental pressurisation from 2 to 4 metric tonnes over six hours, while pragmatic, was not governed by a controlled ramp protocol. Uneven pressure application, combined with the observed moisture loss during pressing, may have introduced differential strain across the sample cross-section. Future experiments will benefit from a more direct pressurisation as opposed to stepped, with a height cap as pressing constraint, and not the pressure reading.

A.4.7 Conclusions

The first experiment demonstrated that alkaline delignification and hot pressing of Norway spruce is achievable at workshop scale, producing a density increase of 69.6% from an initial 0.447 g/cm³ to a final 0.760 g/cm³, placing the result within the maple-equivalent density range.^[14] The process was conducted with accessible equipment and commercially available reagents.

The primary failure was extensive grain-direction cracking, rendering the sample unsuitable for machining. This is attributed principally to the omission of sodium sulphite from the delignification solution, which is expected to have resulted in insufficient lignin removal and inadequate plasticisation of the spruce cell walls prior to compression. Secondary contributing factors include the six-hour boiling duration, potentially degrading crystalline cellulose,^[25] and the abbreviated washing protocol leaving elevated residual alkalinity.^[5]

The experiment produced clear and actionable process improvements, which will be incorporated into subsequent trials. The principal changes are the inclusion of Na₂SO₃ at 0.4-0.6 M, the introduction of vacuum pre-impregnation,^[19] a reduction in boiling duration to three to four hours, and an extended washing protocol. The density target of 0.60-0.80 g/cm³ has been demonstrated as achievable; the focus of future work is structural integrity.

A.5 Experiment 2 - Norway Spruce

A.5.1 Introduction

Experiment 2 was designed to address the principal failure modes identified in Experiment 1, in which the sample was successfully densified but rendered structurally unusable by extensive grain-direction cracking. Three targeted process changes were implemented: the introduction of sodium sulphite (Na₂SO₃) to the delignification solution, the addition of a vacuum pre-impregnation step prior to boiling,^[19] and the use of a fabricated steel constraining jig during pressing. The boiling duration was also reduced from six hours to 3.5 hours.^[25]

A further significant change in this experiment was the use of a cold press rather than a heated press. This was primarily a practical decision given the constraints of the available equipment, and its implications for hydrogen bond reformation and dimensional stability are discussed in the Experiment 3 write up (Section A.6).

A.5.2 Aim and Scope

The primary aim of Experiment 2 was to produce a structurally intact, crack-free densified spruce sample by correcting the delignification chemistry and introducing lateral constraint during pressing. Secondary aims were to evaluate the effect of vacuum pre-impregnation on solution uptake and to observe the dimensional behaviour of the sample under cold pressing with a defined height constraint. As with Experiment 1, no mechanical characterisation testing was performed at this stage.

A.5.3 Solution - Mixing Ratios and Molarity

The delignification solution was prepared with both NaOH and Na₂SO₃, following the full two-reagent protocol established by Song et al.^[5] The concentration of Na₂SO₃ was increased slightly above the Song et al. specification of 0.4 M to 0.6 M, in recognition of the higher proportion of guaiacyl (G) lignin in spruce relative to the hardwood species used in the original study (see Table A.4 for Composition).

Reagent	Quantity	Target Concentration	Notes
Deionised / tap water	750 mL	-	Increased volume relative to Experiment 1
Sodium hydroxide (NaOH)	75 g	2.5M	Added at approx. 80-85°C, stirred to dissolve
Sodium sulphite (Na ₂ SO ₃)	56 g	0.6M	Included for the first time; elevated above 0.4M for G-lignin reactivity

Table A.4 Reagent composition, Experiment 2

A.5.4 Method

Solution Preparation and Vacuum Pre-impregnation

The NaOH and Na₂SO₃ solution was prepared in a beaker with 750 mL of water and brought up to approximately 80-85°C. The wood sample was submerged in the solution, and the beaker was transferred to a vacuum oven (see Figure A.9). A vacuum of approximately 950 mbar was applied for 30 minutes at ambient temperature. This step was intended to evacuate air from the cell lumens of the wood, creating a pressure differential upon vacuum release that drives the alkaline solution into the cellular structure, improving the depth and uniformity of reagent penetration prior to boiling.



Figure A.9 Solution and Sample Placed in Vacuum Chamber

Delignification by Boiling

Following the vacuum impregnation step, the beaker was transferred to a hot plate without changing the solution or removing the sample. Boiling was conducted for 3.5 hours. The solution colour progression was used as a qualitative indicator of lignin extraction:^[5] the target endpoint was a dark golden colour, deliberately stopping short of the nearblack colour reached in Experiment 1. This was intended to limit the degree of delignification and preserve a greater proportion of the lignin scaffold, reducing the risk of over-weakening the cell wall structure prior to pressing.

Washing

The sample was washed immediately after boiling in three successive cycles of boiling tap water, while the sample was still hot and moist. In each cycle, the wash water initially ran colourless and progressed to a yellowish tone with some foam, indicating continued extraction of soluble degradation products and residual reagents. Washing was continued until the surface pH, measured with indicator paper, had reduced to approximately 8-9.

Cold Pressing with Constraining Jig

A simple steel jig was fabricated for this experiment, designed to constrain the sample laterally during pressing and to cap the compression at a defined height (see Figure A.10). The jig was loosely fastened around the sample to prevent uncontrolled lateral expansion, directing the compression along a single axis only. The target compressed height was set to 30 mm.

The sample was cold pressed (without applied heat) immediately after washing, while still warm and moist from the boiling and washing stages. It was left overnight under load in the jig. Upon removal the following morning, springback was eventually observed: the sample had recovered from the compressed height of 30 mm to approximately 38 mm, a springback of approximately 26.7%.



Figure A.10 Steel Jig to Constrain the Sample During Pressing

A.5.5 Results

Dimensional Outcomes

The dimensional and mass measurements before and after processing are presented below (Table A.5). All post-processing values are recorded after springback, as the sample was measured in its stable released state.

Parameter	Before Processing	After Processing	Change
Length (L)	100 mm	100 mm	0%
Width (W)	50 mm	52 mm	+4.0%
Height (H) - press direction	46 mm	37 mm	-19.6%
Mass	102 g	121 g	+18.6%
Volume	230.0 cm ³	192.4 cm ³	-16.4%
Density	0.443 g/cm ³	0.630 g/cm ³	+42.2%

Table A.5 Dimensional outcomes, Experiment 2. Post-processing values recorded after springback.

The achieved post-springback density of 0.630 g/cm^3 falls within the lower end of the target range for maple equivalence (approximately $0.60\text{--}0.75 \text{ g/cm}^3$).^[14] The compression achieved in the width direction was 19.6%, substantially less than the 54% width reduction observed in Experiment 1, which is consistent with the effect of lateral constraint and the absence of heat during pressing. Springback was observed to stabilise at approximately 38 mm from the compressed 30 mm, while dimensional change was absorbed as a width reduction.

The mass increase of 18.6% is notably higher than the 4.03% recorded in Experiment 1, suggesting that the increased solution volume, the vacuum pre-impregnation, and the more thorough two-reagent chemistry resulted in greater absorption and retention of solution within the cellular structure of the wood.

Qualitative Observations

The most significant qualitative outcome of Experiment 2 was the visual and structural quality of the pressed sample (see Figure A.11). Unlike Experiment 1, the sample exhibited no visible cracking, splitting, or void formation. The surface appearance was described as homogeneous, and the sample felt dimensionally stable. This improvement is attributed to the combined effect of the constrained jig geometry, which limited differential lateral strain, and the corrected delignification chemistry, which provided more uniform cell wall softening.

The sample was noticeably less alkaline than that produced in Experiment 1, indicating that the three-cycle wash protocol brought residual NaOH levels closer to neutral, though the surface pH of 8-9 on removal indicates that some residual alkalinity remained within the bulk of the material.

Springback of approximately 26.7% from the target compressed height was observed upon release from the jig. This is a significant finding: in the absence of heat during pressing, the lignin within the cell walls does not undergo the thermal softening and subsequent glass transition that is understood to be the primary mechanism for locking the compressed cellular geometry in place. Cold pressing therefore produces a metastable compressed state that partially recovers upon load removal.



Figure A.11 Sample 2 After Cold Pressing, Showing Springback Upon Release from Jig

A.5.6 Analysis

The structural success of this sample, relative to Experiment 1, indicates that the inclusion of Na_2SO_3 and the introduction of lateral constraint during pressing were the critical variables for preventing cracking. The G-type lignin in spruce requires the sulphonation action of Na_2SO_3 to be broken down

effectively by an alkaline solution;^[5] without it, delignification is incomplete and the cell walls retain sufficient stiffness to fracture rather than plastically deform under compression.

The density achieved, 0.630 g/cm³, is encouraging but represents only partial densification relative to what was observed in Experiment 1 (0.760 g/cm³). The combination of lateral constraint, which necessarily limits the compression ratio in any given direction, and the springback associated with cold pressing, accounts for the lower final density. This trade-off between structural integrity and density magnitude will need to be resolved in subsequent experiments through the introduction of heat during pressing.

The springback mechanism is well understood in the context of densified wood. Above the glass transition temperature of lignin (approximately 65-85°C in moist wood), lignin softens and flows, allowing the cell walls to deform plastically. Upon cooling under load, the lignin re-solidifies in the compressed configuration, locking the geometry. Cold pressing, by definition, does not trigger this transition, and the elastic energy stored in the deformed cell walls is released upon unloading, producing the observed springback. Heating the press to 100-120°C is expected to substantially reduce or eliminate this behaviour.

The increased mass uptake (+18.6%) relative to Experiment 1 (+4.03%) is consistent with improved solution penetration through the vacuum pre-impregnation step^[19] and the larger solution volume used. While a higher mass uptake does not directly translate to a higher degree of delignification, it suggests that the reagents were more uniformly distributed throughout the cross-section of the sample, which is expected to produce more consistent cell wall softening and more homogeneous mechanical properties in the pressed product.

A.5.7 Discussion and Proposed Improvements

Re-introduction of Heat in Pressing

The most important single change for Experiment 3 is the introduction of heat during pressing. The lignin glass transition is the mechanism by which compressed geometry is locked in place, and cold pressing circumvents this entirely. The target press temperature for subsequent experiments is 120-130°C, consistent with the parameters reported by Song et al.^[5] and the broader densified wood literature. At this temperature, moist lignin softens sufficiently to flow and accommodate the compressed geometry, and upon cooling under load, it resolidifies in the deformed configuration, dramatically reducing springback.

Jig Design and Constraint Tightening

The steel jig used in this experiment was described as loosely fastened, which may have allowed some uncontrolled lateral movement during pressing. A tighter constraint, with defined internal dimensions for all axes, would provide more precise control over the final geometry and reduce variability between samples. For the intended guitar neck application, dimensional consistency is critical, as the final blank must meet defined tolerances before machining.

Residual Alkalinity and Extended Washing

A surface pH of 8-9 upon completion of washing indicates that residual alkali remains within the bulk of the sample. Whilst this is an improvement on Experiment 1, further washing cycles or a dilute acid neutralisation step remain advisable. A 5% acetic acid wash, or a citric acid solution, would neutralise residual NaOH without introducing harmful ionic species and would bring the bulk pH closer to neutral before pressing. This is particularly important if the final product is to be used in a stringed

instrument, where metal hardware components are in direct contact with the wood and could be affected by prolonged alkali exposure.

Solution Colour as a Process Indicator

The decision in this experiment to stop boiling at the dark golden stage, rather than continuing to the near-black endpoint observed in Experiment 1, was a qualitative judgement based on the assumption that lighter colour indicates less lignin removal. This is a plausible heuristic but is not a reliable quantitative measure of delignification. Future experiments should consider gravimetric lignin quantification, or at minimum a comparative acid-insoluble lignin test (Klason lignin method), to establish a relationship between solution colour and actual lignin removal percentage. This would allow the boiling endpoint to be defined by a target lignin removal range (approximately 20-45% as per Song et al.^[5]) rather than visual observation alone.

A.5.8 Conclusions

Experiment 2 produced a structurally intact, visually homogeneous densified spruce sample, representing a significant qualitative improvement over Experiment 1. The elimination of cracking is attributed to the introduction of Na_2SO_3 into the delignification solution and the use of a lateral constraining jig during pressing. A density of 0.630 g/cm^3 was achieved after springback, placing the result within the lower bound of the target maple-equivalent density range.

The primary limitation of this experiment was the use of cold pressing, which resulted in approximately 26.7% springback upon release from the jig. This is mechanistically consistent with the absence of lignin glass transition during pressing, and indicates that heated pressing is a necessary condition for achieving stable geometric densification. The introduction of heat during pressing is identified as the most critical process change for Experiment 3.

Secondary improvements to carry forward include tighter jig constraint geometry, extended washing or acid neutralisation to reduce bulk residual alkalinity, and the development of a more quantitative endpoint criterion for the delignification boiling phase.

A.6 Experiment 3 - Norway Spruce

A.6.1 Introduction

Experiment 3 represents the most complete implementation of the target process to date. The two preceding experiments established the necessity of sodium sulphite in the delignification chemistry, demonstrated the value of lateral constraint during pressing, and confirmed that cold pressing alone is insufficient to lock the compressed cellular geometry in place due to the absence of lignin glass transition. Experiment 3 addresses this directly through the introduction of a heated press, operated at 130°C , alongside two additional refinements: the use of an acid wash step during cleaning to reduce residual alkalinity, and an increase in the boiling temperature to $100\text{-}110^\circ\text{C}$.

The sample used was a Norway spruce (*Picea abies*) blank of the same nominal dimensions as Experiment 2, but a distinct piece of material with a recorded starting mass of 103.7 g.

A.6.2 Aim and Scope

The primary aim of Experiment 3 was to eliminate the springback issue as observed with Experiment 2, by applying heat during pressing and maintaining load through the cooling phase. Secondary aims were to evaluate the effect of elevated boiling temperature on delignification efficiency and sample

quality, and to assess whether the introduction of cooking vinegar during washing produced a measurable improvement in residual alkalinity. No mechanical characterisation testing was performed at this stage.

A.6.3 Solution Preparation and Molarity

The delignification solution was prepared with NaOH and Na₂SO₃ at the same concentrations used in Experiment 2.^[5] The solution volume was reduced from 750 mL to 450 mL, as the larger volume used previously was found to be in excess of what was required to fully submerge the sample. Reagent quantities were scaled proportionally. A 0.6 M concentration of Na₂SO₃ was used in contrast to 0.4 M as specified in the original protocol, as it is suitable to react with the G-lignin present in spruce (See Table 3 for Composition).

Reagent	Quantity	Target Concentration	Notes
Tap water	450 mL	-	Reduced from 750 mL; sufficient to submerge sample
Sodium hydroxide (NaOH)	40 g	2.5M	Added gradually, kept at 80-85°C to avoid boiling during vacuum step
Sodium sulphite (Na ₂ SO ₃)	30 g	0.6M	First compound to be added

Table A.6 Reagent composition, Experiment 3

A.6.4 Method

Solution Preparation and Vacuum Pre-impregnation

As in Experiment 2, the vacuum pre-impregnation process was kept exactly the same,^[19] with the sample submerged in the solution, heated to about 80-85°C and placed in a vacuum chamber at 950 mbar for 30 minutes.

Delignification by Boiling

Following vacuum impregnation, the beaker was transferred to a hot plate and the sample boiled for 3.5 hours.^[25] In this experiment the boiling temperature was maintained at a higher level than in Experiment 2, within the range of 100-110°C, achieved by covering the beaker partially to reduce evaporative cooling. As in Experiment 2, the endpoint was judged by solution colour,^[5] with boiling terminated when the solution had reached a dark golden colour, stopping well short of the near-black endpoint observed in Experiment 1. Total boiling time was the same as Experiment 2: about 3.5 hours.

Washing and Acid Neutralisation

Immediately following boiling, the sample was washed in three successive cycles of boiling tap water, while still hot and moist. Foam was observed in the wash water, consistent with continued extraction of saponified extractives and residual reagents. During the washing phase, an unquantified addition of cooking vinegar (dilute acetic acid, approximately 5% concentration) was introduced to the wash water to assist in neutralising residual NaOH within the sample. The surface pH was reduced to approximately 9 (tested using pH strips) upon completion of washing, an improvement on the pH of

8-9 recorded at the end of Experiment 2, and consistent with the partial neutralisation effect of the acid addition.

Heated Pressing

The heat press, steel plates and steel constraining jig were preheated to 130°C before loading. Preheating the jig and plates, rather than loading a cold jig into a hot press, was identified as an important procedural improvement: it ensures that the full volume of the sample reaches the target temperature uniformly from the moment of contact, rather than undergoing a temperature gradient during ramp-up.

The sample was loaded into the preheated jig and pressed at 130°C for approximately two hours, consistent with the Song et al. approach of pressing under heat.^[5] After this period the heat was turned off, but the sample was kept under full load and allowed to cool to room temperature in the press. It was left under load for two days total before removal.

This protocol, of maintaining load throughout the cooling phase, is identified as a critical process insight: the compressed geometry must be held fixed while the lignin cools below its glass transition temperature and resolidifies in the deformed configuration.

A.6.5 Results

Dimensional Outcomes

Dimensional and mass measurements before and after processing are presented below. Post-processing values, given in Table A.7, reflect the stable final state of the sample after removal from the press.

Parameter	Before Processing	After Processing	Change
Length (L)	100 mm	100 mm	0%
Width (W)	50 mm	47 mm	-6.0%
Height (H) - press direction	46 mm	30 mm	-34.8%
Mass	103.7 g	97.4 g	-6.1%
Volume	230.0 cm ³	141.0 cm ³	-38.7%
Density	0.44 g/cm ³	0.690 g/cm ³	+53.0%

Table A.7 Dimensional outcomes, Experiment 3

The achieved density of 0.690 g/cm³ represents a 53% increase over the starting value and falls comfortably within the target maple-equivalent range of 0.60-0.75 g/cm³.^[14] Critically, no springback was observed upon removal from the press, confirming that the heated pressing protocol successfully locked the compressed geometry through lignin glass transition and resolidification.

The mass decreased by 6.1% relative to the starting value, in contrast to the mass increases observed in Experiments 1 and 2. This reduction is attributed to the expression of absorbed solution and bound moisture under heat and pressure, combined with the more complete neutralisation and washing of residual reagents prior to pressing. The net loss of mass indicates that the combined effect of liquid expression during hot pressing exceeded the residual absorbed solution retained within the sample, consistent with the behaviour described in Song et al.^[5]

Qualitative Observations

The pressed sample was described as clean and tight, with good surface condition and regular geometry, consistent with the constrained jig producing well-defined faces (see Figure A.12). No cracking, splitting, or void formation was observed, continuing the improvement established in Experiment 2. The sample was straightforward to handle without gloves, with a surface pH between 7 and 8, indicating that the combination of three hot water washes and the vinegar addition had brought the bulk chemistry close to neutral.

The absence of springback is the most significant qualitative result of this experiment. It shows that the heated press operating at 130°C, combined with load maintained through the full cooling phase, is sufficient to trigger the lignin glass transition and achieve stable geometric locking of the compressed cell wall structure.



Figure A.12 Sample 3 After Pressing - Clean Surface, No Cracking, No Springback

A.6.6 Analysis

Elimination of Springback

The results of Experiment 3 represent the clearest process success in the series to date. A density of 0.690 g/cm³ was achieved with no springback, no structural damage, and a nearneutral surface pH. The progression across the three experiments shows that each of the key process variables has been correctly identified and addressed.

Density and Compression

The compression ratio of 34.8% in the press direction is substantially greater than the 19.6% achieved in Experiment 2 under cold pressing, and is more consistent with the behaviour expected from a well-plasticised wood structure undergoing hot pressing.^[5] The elevated boiling temperature of 100-110°C, compared with the lower temperatures used in Experiment 2, is likely to have contributed to more thorough delignification within the same 3.5-hour boiling window, producing a more fully plasticised cell wall prior to compression.

Mass Loss

The mass loss of 6.1% warrants consideration. In Experiments 1 and 2, mass increased due to retained absorbed solution. In Experiment 3, the combination of hot pressing at 130°C, which expresses liquid from the cellular structure under pressure, and more complete prepress washing, resulted in a net mass reduction. This is consistent with the behaviour described in Song et al.^[5] for

the standard protocol. The lower final mass relative to the green starting mass reflects a drier, more consolidated sample, which is the desired condition for subsequent dimensional stability.

Pre-heating Jig

The preheating of both the jig and the steel plates is identified as a meaningful procedural improvement. Cold tooling in contact with a hot sample creates a steep thermal gradient at the surfaces, potentially causing the outer cell layers to cool and resolidify before full compression is achieved, and introducing differential strain between the surface and the interior. Preheating the tooling ensures a uniform temperature profile throughout the crosssection from the moment compression begins.

A.6.7 Discussion and Proposed Improvements

Progression Across the Experiment Series

Taken together, the three experiments form a coherent developmental sequence. Experiment 1 established feasibility but produced structural failure due to incomplete delignification chemistry. Experiment 2 corrected the chemistry and introduced lateral constraint, producing a structurally sound sample but with significant springback due to cold pressing. Experiment 3 introduced heat during pressing and maintained load through cooling, eliminating springback and achieving the target density range with good surface quality (see Table A.8 for Comparative Summary).

Parameter	Experiment 1	Experiment 2	Experiment 3
Species	Spruce	Spruce	Spruce
Na ₂ SO ₃ included	No	Yes	Yes
Vacuum preimpregnation	No	Yes	Yes
Boiling duration	6 hrs	3.5 hrs	3.5 hrs
Boiling temperature	85-95°C	85-95°C	100-110°C
Press type	Heated (95°C)	Cold	Heated (130°C)
Constraining jig	No	Yes	Yes (preheated)
Acid wash	No	No	Yes (vinegar)
Final density	0.760 g/cm ³	0.630 g/cm ³	0.690 g/cm ³
Springback	N/A	Yes (~27%)	None
Structural integrity	Fail (cracking)	Pass	Pass
Surface pH	Strongly alkaline	8-9	7-8

Table A.8 Comparative summary of process parameters and outcomes across Experiments 1-3

Vinegar Dosage and Washing Protocol

The cooking vinegar added during washing in this experiment was unquantified. The improvement in surface pH from 8-9 to 7-8 suggests a meaningful effect, but without a defined dosage it is not possible to reproduce this outcome reliably. Future experiments should standardise the acid wash step, using either a measured concentration of acetic acid or citric acid solution, with the volume and contact time recorded. A target post-wash bulk pH of 6.5-7.5 is proposed as the criterion for proceeding to pressing.

A.6.8 Conclusions

Experiment 3 produced the most successful outcome in the experiment series to date. A density of 0.690 g/cm^3 was achieved, representing a 53% increase from the starting value of 0.451 g/cm^3 and placing the result within the target maple-equivalent range.^[14] No springback, cracking, or surface damage was observed, and the sample surface pH of 7-8 indicates near-neutral residual chemistry.

The key advances over Experiment 2 were the introduction of a heated press at 130°C with load maintained through the full cooling phase, the elevation of boiling temperature to $100\text{--}110^\circ\text{C}$, and the preheating of the constraining jig and steel plates. The heated press is confirmed as the critical variable for eliminating springback, operating through the lignin glass transition mechanism to lock the compressed cellular geometry upon cooling.

Three process principles are established from the experiment series as a whole and should be treated as fixed constraints for all subsequent trials: the delignification solution must include Na_2SO_3 for softwood substrates;^[5] lateral constraint during pressing is necessary to prevent cracking and control geometry; and pressing must be conducted under heat with load maintained throughout the cooling phase.^[5]

The process is now sufficiently stable to support two parallel work streams: the introduction of alternative wood species, and the initiation of mechanical characterisation testing on the spruce samples produced to date.

A.7 Experiment 4 - Yellow Poplar Baseline Study

A.7.1 Introduction

With the core superwood process established for Norway spruce across Experiments 1 to 3, Experiment 4 was conducted as a baseline exploration to determine whether the same process would work on a second, commercially relevant species. Yellow poplar (*Liriodendron tulipifera*) was selected as the candidate. It is a fast-growing, abundantly cultivated North American hardwood with no current CITES restrictions, an initial density of 0.40 to 0.45 g/cm^3 ^[14] that offers substantial headroom for densification, and a GS-type lignin structure that is inherently more reactive to alkaline hydrolysis than the G-type lignin of spruce.^[14]

The question being asked in this experiment was simple: does the process work on poplar? No characterisation was attempted. Pre-press mass was not recorded and no mechanical testing was performed. The outcome criteria were structural integrity, absence of springback, and visible cross-sectional quality. Everything else is deferred to Phase 2. A batch of six samples was processed together to give a first indication of process consistency across multiple blanks.

A.7.2 Aim and Scope

The sole aim of this experiment was to establish whether the $\text{NaOH}/\text{Na}_2\text{SO}_3$ delignification and hot-pressing process developed for spruce is transferable to yellow poplar without structural failure. No density calculation, mechanical characterisation, or acoustic measurement was performed. These are reserved for the formal characterisation phase once process transferability is confirmed.

A.7.3 Solution Preparation and Molarity

The same two-reagent protocol used in Experiments 2 and 3 was applied,^[5] with Na_2SO_3 concentration slightly increased to 0.7 M . The increase accounts for the larger blank cross-section

relative to the spruce coupons, which extends the diffusion path and increases reagent demand for uniform penetration throughout the blank. The reagent composition is given in Table A.9.

Reagent	Quantity	Target Concentration	Notes
Tap water	Sufficient to submerge batch	-	Six samples boiled together
Sodium hydroxide (NaOH)	Scaled to batch volume	2.5 M	Added at approx. 80 to 85°C, stirred to dissolve
Sodium sulphite (Na2SO3)	Scaled to batch volume	0.7 M	Elevated above 0.6 M to account for larger blank cross-section

Table A.9 Reagent composition, Experiment 4

A.7.4 Method

Sample Preparation

Three yellow poplar (*Liriodendron tulipifera*) blanks were prepared for this experiment. The sample dimensions are given in Table A.10. The orientation convention is the same as for the spruce experiments: Length (L) along the longest axis, Width (W) across the face, and Height (H) in the pressing direction, normal to grain and tangential to the growth rings.

Parameter	Value
Species	Yellow Poplar (<i>Liriodendron tulipifera</i>)
Number of samples	3 (6 boiled together)
Length (L)	150 mm
Width (W)	26 mm
Height (H), press direction	40 mm
Initial density	Not recorded; expected 0.40 to 0.45 g/cm ³ ^[14]
Grain orientation	Tangential
Press direction	Normal to grain

Table A.10 Initial sample specification, Experiment 4

Vacuum Pre-impregnation and Boiling

The solution was prepared and heated to approximately 80 to 85°C before the samples were submerged. The beaker was placed in the vacuum oven and a vacuum of approximately 950 mbar was applied for 30 minutes, following the pre-impregnation protocol from Experiments 2 and 3.^[19]

Following pre-impregnation, the beaker was transferred to a hot plate and the samples were boiled for approximately 3.5 hours at 100 to 110°C.^[25] The higher boiling temperature was maintained by partially covering the beaker to reduce evaporative cooling. The endpoint was judged by solution colour,^[5] with boiling terminated at a dark golden, amber tone, consistent with the endpoint used in Experiments 2 and 3 (see Figure A.13).



Figure A.13 Yellow poplar blanks after boiling, showing the characteristic dark amber colouration of the solution and the darkened sample surfaces.

Washing and Acid Neutralisation

Samples were washed 3 to 4 times in boiling water immediately after boiling, while still hot and moist, continuing until the wash water turned yellow. Cooking vinegar (dilute acetic acid, approximately 5% concentration) was added during washing to neutralise residual surface alkalinity. This produced noticeably better results than the washing used in Experiment 2.

Heated Pressing

The heat press, steel plates, and constraining jig were preheated to 130°C before loading, consistent with Experiment 3. All six samples were pressed together for approximately 2 hours at 130°C. The heat was then turned off and the samples were left under full load overnight until room temperature was reached. This cooling under load protocol is maintained as a fixed process constraint following the findings of Experiment 3.^[5]

A.7.5 Results

Dimensional Outcomes

Dimensional measurements before and after processing are presented in Table A.11. Mass was not recorded in this exploratory trial.

Parameter	Before Processing	After Processing	Change
Length (L)	150 mm	150 mm	0%
Width (W)	26 mm	26 mm	0%
Height (H), press direction	40 mm	30 mm	-25.0%
Mass	Not recorded	Not recorded	-
Density	Not recorded	Not recorded	-

Table A.11 Dimensional outcomes, Experiment 4. Mass and density were not recorded in this feasibility trial.

A compression ratio of 25.0% was achieved in the pressing direction with no springback observed upon removal from the press, confirming that the heated pressing protocol successfully locked the compressed geometry through lignin glass transition and resolidification, consistent with the behaviour established in Experiment 3.

Structural Integrity

All three blanks came out structurally intact. No cracking, splitting, or void formation was observed. No axial expansion occurred. The surfaces were very slightly warped but cleanable by surface planing. For a first run on a new species at a larger blank size than the spruce coupons, this is a clear positive result.

Cross-Sectional Appearance

The blanks were cut open into thinner strips (see Figure A.14), revealing a dark border on the outer surfaces surrounding a lighter coloured core. The initial interpretation was that densification was non-uniform, with the outer region more extensively processed than the interior. After a closer examination of grain direction and structural continuity across the cross-section, this was ruled out. The densification was found to be uniform and the colouration is attributed to surface effects. Two explanations are proposed:

- Residual solution: treatment chemicals not fully rinsed from the outer surfaces, darkening under press heat.
- Surface oxidation or scorch: direct contact with the steel press plates preheated to 130°C causing localised darkening through thermal oxidation of surface compounds.

Both were confirmed as surface phenomena by a brief physical test. The material beneath the coloured layer was consistent with the lighter interior.



Figure A.14 Cross-sections of the three yellow poplar blanks after processing. The dark peripheral border surrounding the lighter core was confirmed to be a surface colouration effect rather than a density gradient. Densification is uniform.

A.7.6 Analysis

The experiment answered the question it was designed to answer: the process works on yellow poplar. Three structurally intact blanks with 25% compression and no springback on a first attempt on a new species is a strong baseline result.

The GS-type lignin in poplar responded well to the NaOH/Na₂SO₃ chemistry, as expected given its higher reactivity relative to spruce G-type lignin.^[14] The successful lateral constraint prevented cracking despite the larger blank dimensions, confirming that the jig design is not species-specific. The absence of springback justifies the lignin glass transition mechanism operates in poplar at 130°C, consistent with the general applicability of the process demonstrated by Song et al.^[5]

The surface colouration is noted but does not represent a structural concern. It is a surface phenomenon that is removable by machining and does not affect the usable material beneath.

What this experiment does not tell us is equally important to state clearly: density, hardness, stiffness, and acoustic properties of the processed poplar are all unknown. The compression ratio of 25% gives a directional indication of densification, but without pre and post mass measurements no density figure can be derived. These measurements are the first priority in the next processing run.

A.7.7 Next Steps

This feasibility result justifies moving forward with yellow poplar as the primary candidate for neck-blank scale processing. The following are identified as immediate priorities before formal characterisation:

- Record mass before and after each processing stage in all subsequent runs to enable density calculation and comparison against the maple target range of 0.60 to 0.75 g/cm³.^[14]
- Introduce a release sheet between sample faces and steel press plates to limit surface scorch without affecting heat transfer.
- Increase blank dimensions toward full neck-blank scale and assess whether 25% compression is maintained or whether the larger geometry requires adjustment to boiling duration or press parameters.
- Apply Klason lignin analysis to a subset of blanks to quantify actual lignin removal and confirm it falls within the 20 to 45% optimal range.^[5]

A.7.8 Conclusions

Experiment 4 confirmed that the superwood process is transferable to yellow poplar (*Liriodendron tulipifera*). Three blanks processed in a first exploratory run produced structurally intact, crack-free specimens with 25% compression and no springback. The process parameters, 2.5 M NaOH / 0.7 M Na₂SO₃, vacuum pre-impregnation, 3.5 hours boiling at 100 to 110°C, acid wash, and heated pressing at 130°C under load through cooling, transferred directly to the new species without modification.

Surface colouration on the outer faces was initially interpreted as non-uniform densification but was confirmed to be a surface phenomenon attributable to residual solution darkening or thermal scorch from the press plates. Densification across the cross-section was found to be uniform.

On this blank, the process works. Characterisation of what it produces is the next step.

A.8 Experiment 5 - Process Refinement: The Final Protocol

A.8.1 Introduction and Rationale

Experiments 1 to 4 established that the NaOH/Na₂SO₃ process could densify both Norway spruce and yellow poplar, but the protocol as run to this point depended on laboratory infrastructure, specifically a fume hood for the alkaline boiling step, that would not be available in a genuine workshop setting. Experiment 5 refines the process to remove this dependency while producing the specimens used in the final mechanical and acoustic characterisation reported in this chapter and in the accompanying Janka, MOE, and Acoustic Tap Tone reports.

A.8.2 Solution Screening Sub-experiment

Before refining the boiling method itself, a small scale sub-experiment was run to check whether the alkaline solution could be simplified without compromising delignification, to ease the handling and cleaning burden in the workshop. Small samples of spruce and poplar were submerged overnight, unheated, in three candidate solutions (see Figure A.15), the findings are summarised in Table A.12.

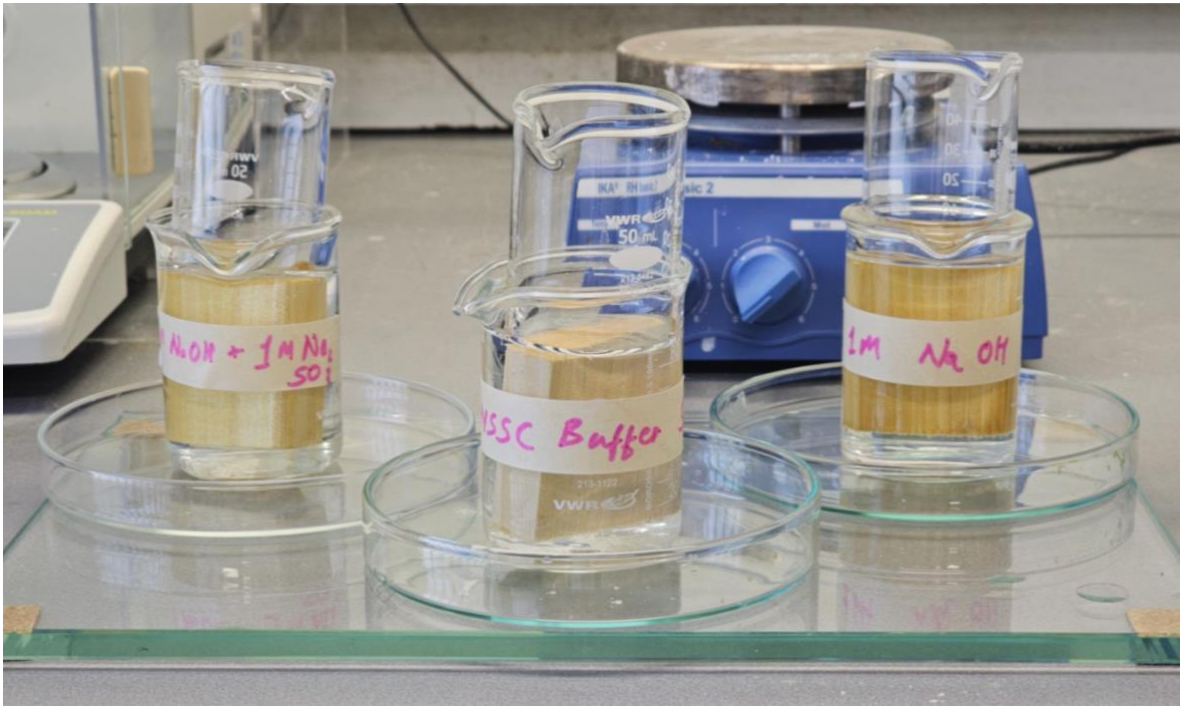


Figure A.15 The three candidate solutions of the screening sub-experiment, with spruce and poplar samples immersed overnight without heat: 1M NaOH + 1M Na₂SO₃ (left), NSSC buffer (centre), and 1M NaOH (right).

Solution	Composition	Observed Result	Interpretation
NSSC	Neutral sulphite (Na ₂ SO ₃ -based)	Most rigid of the three samples	Little to no delignification
NaOH	Sodium hydroxide alone	Intermediate rigidity	Partial delignification
1M NaOH + 1M Na ₂ SO ₃	Combined alkaline sulphite	Yellowish colour; slightly squishy yet hard, plastic-like texture	Highest degree of delignification

Table A.12 Overnight solution screening sub-experiment, spruce and poplar, unheated immersion

The combined 1M NaOH + 1M Na₂SO₃ solution produced the most extensively delignified sample even without heating, and was adopted for all subsequent processing in this experiment, replacing the 2.5M NaOH / 0.7M Na₂SO₃ solution used in Experiments 1 to 4.

A.8.3 Process Chemistry Rationale

NaOH and Na₂SO₃ play distinct roles in the delignification solution. NaOH begins breaking down the cell wall structure, without fully dissolving it, producing a more porous cellular structure and assisting the movement of fluid through the wood by capillary action. Na₂SO₃ acts through sulphonation, bonding to lignin and blocking its recondensation, which keeps the lignin in a soluble state once it has been mobilised. This mobilisation still requires heat: the lignin must reach its glass transition temperature, 65 to 85°C (see Section 2.5.2), before it plasticises and begins to dissolve into solution.

In the process used for Experiments 1 to 4, the wood was boiled directly in the alkaline solution to bring the lignin to this state after an initial vacuum step. For Experiment 5, this was reconsidered by analogy with defrosting and sous vide cooking, where food is heated inside a sealed bag immersed in water rather than in direct contact with the cooking liquid. If the alkaline solution is drawn into the wood by vacuum beforehand, boiling the sample in plain water should still heat the internalised solution enough to reach the lignin glass transition, while the surrounding water simultaneously begins washing the sample as the internalised solution diffuses back out. Vacuum impregnation time was increased slightly, to approximately 45 minutes to an hour, to ensure sufficient solution uptake before this boil in water step replaced boiling directly in solution.

Boiling in plain water rather than in the alkaline solution also removes the need for a fume hood: delignification and washing both proceed largely in water, so the process can run on a standard stove and saucepan instead of a laboratory hot plate. This also allows a harder, more sustained boil with more vigorous water movement than the lab hot plate could sustain, which was found to assist both delignification and washing.

A.8.4 Method

Vacuum Pre-impregnation

The prepared wood samples were vacuum impregnated in the 1M NaOH + 1M Na₂SO₃ solution for approximately 45 minutes to an hour, longer than the 30 minute impregnation step used in Experiments 2 to 4, to ensure the solution fully penetrated the sample before the boil in water step. Figure A.16 shows a raw untreated poplar blank against a soaked blank, which has a darker amber colour.

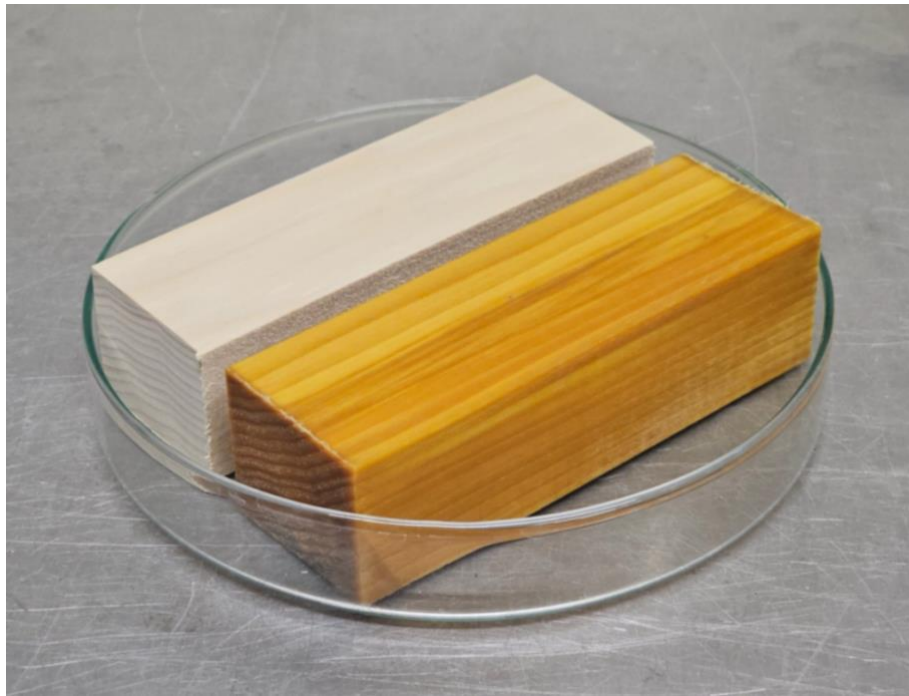


Figure A.16 A raw untreated yellow poplar blank (left) beside a blank after 45 to 60 minutes of vacuum impregnation in the 1M NaOH + 1M Na₂SO₃ solution (right), showing the darker amber colouration.

Cyclic Boiling and Vacuum Extraction

Following impregnation, the sample was boiled directly in tap water, in cycles of approximately one hour each (see Figure A.17). After each boiling cycle, the sample was removed and returned to the vacuum chamber without any solution present, drawing residual alkaline solution and dissolved lignin further out of the wood. The sample was then returned to a fresh change of boiling water for the next cycle. This alternation of boiling and solution free vacuum extraction combined the delignification and washing steps into a single repeating cycle, rather than treating them as separate stages.



Figure A.17 The cyclic boiling step running in plain tap water on a domestic hot plate under extraction (left), and a poplar blank in the boiling water between cycles, with dissolved lignin colouring the water (right).

Washing Endpoint and pH Monitoring

The pH of the boiling water was recorded after each cycle, and boiling cycles were repeated until the water reached a neutral pH of approximately 7, replacing the fixed rinse count or colour based endpoints used in earlier experiments with a measurable, repeatable stopping criterion (see Figure A.18).

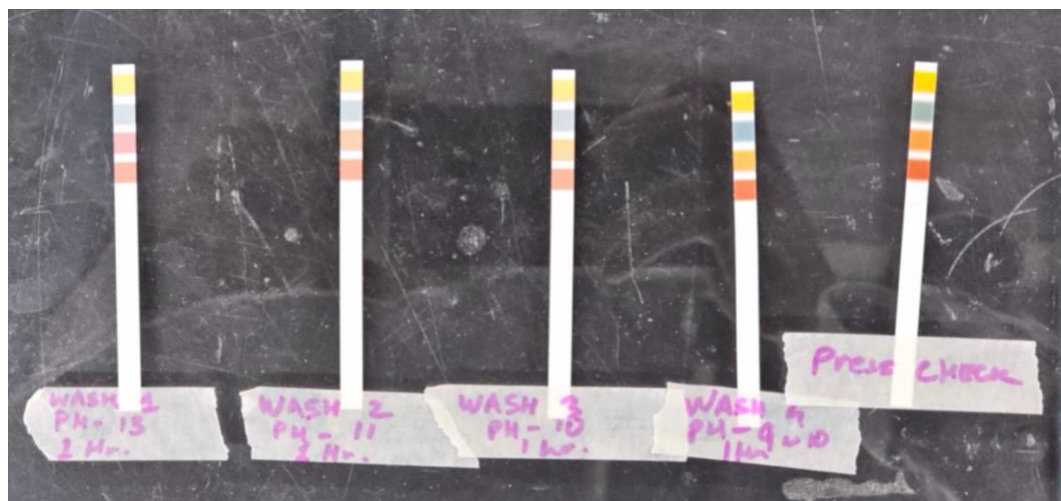


Figure A.18 pH strips recorded after successive washing cycles, from pH 13 after the first two hour boil down to pH 9 to 10 after the fourth cycle, alongside the strip taken as a press check.

Heated Pressing

Once the neutral pH endpoint was reached, the sample was pressed in the same constraining jig used in Experiments 3 and 4, in the heat press at 140°C, held under heat for approximately 1.5 to 2 hours. The heat was then switched off while pressure was maintained, and the sample was allowed to cool naturally under full load until the lignin resolidified in its compressed geometry, consistent with the cooling under load protocol established in Experiment 3.^[5]

Results

This process yielded uniformly treated blanks. A cross section cut was done to confirm the uniform washing (solution removal), which showed uniform surfaces across axial and normal planes (see Figure A.19). These blanks were machined to the testing dimensions.

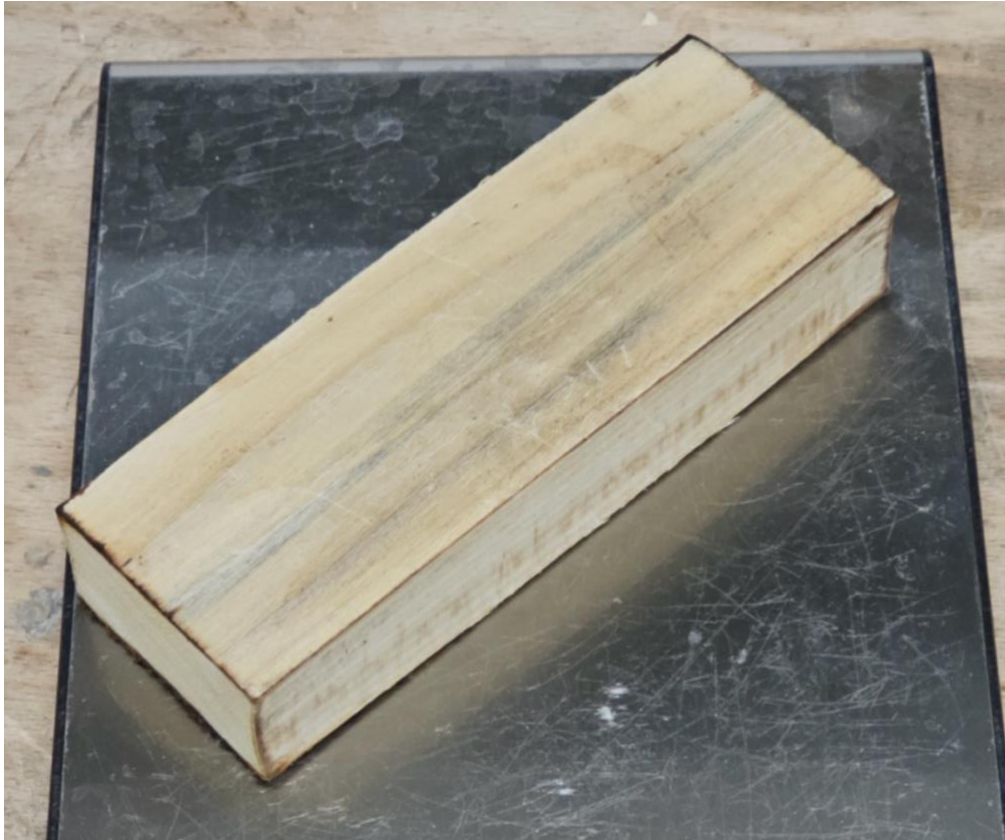


Figure A.19 A washed and cross sectioned yellow poplar blank on the balance before machining to test dimensions, showing uniform colour across the cut face.

A.8.5 Discussion

The refined process changes two things relative to Experiments 1 to 4: the solution is simplified to a single 1M NaOH + 1M Na₂SO₃ mixture selected by direct comparison rather than carried over from Song et al.'s original formulation, and the alkaline boiling step is replaced by a vacuum impregnation followed by boiling in plain water, with the pH linked washing folded into the same cyclic step. Both changes were motivated by workshop practicality rather than by a change in the underlying mechanism: the lignin glass transition and sulphonation chemistry established in Sections 2.4 and 2.4 still govern the process, only the means of delivering heat and removing dissolved lignin have changed.

Removing the requirement to boil directly in an alkaline solution removes the requirement for a fume hood, which is the single largest barrier to running this process outside a chemistry laboratory. Combined with the increased boiling temperature achievable on a domestic stove compared with a laboratory hot plate, this makes the process meaningfully closer to a genuine workshop-scale pipeline than the protocol used in Experiments 1 to 4.

A.8.6 Conclusions

Experiment 5 established the final process used to produce the characterisation specimens reported in this chapter and in the accompanying Janka, MOE, and Acoustic Tap Tone reports: vacuum impregnation in a 1M NaOH + 1M Na₂SO₃ solution, cyclic boiling in plain water with solution free vacuum extraction between cycles, washing to a neutral pH endpoint, and heated pressing at 140°C under load through cooling. This protocol removes the fume hood dependency of the earlier alkaline

boiling method while remaining grounded in the same delignification and glass transition chemistry, and represents the process this project puts forward as workshop feasible.

Appendix B. Test Standards and Specifications

This appendix consolidates the standards that inform the testing chapter into a single reference table. Each test is listed with its governing standard, whether it damages the specimen, the specimen aspect ratio the standard specifies, and the quantity it yields.

Standard (full name)	Test type	Standard specimen ratio	Output
ASTM D4933-16, Moisture Conditioning of Wood and Wood-Based Materials	Non-destructive	Not defined by ratio (all specimens)	Equilibrium moisture content (%)
ASTM D2395-17, Density and Specific Gravity of Wood and Wood-Based Materials	Non-destructive	Not defined by ratio	Density (kg/m ³), specific gravity
ASTM D143-22, Small Clear Specimens of Timber - three point bending	Destructive (specimens splintered)	Span / depth ≥ 14	Modulus of elasticity (GPa)
ASTM D143-22, Small Clear Specimens of Timber - Janka hardness	Destructive (localised)	11.28 mm ball to half diameter (5.5 mm)	Hardness (N)
ASTM D6874-22 / ASTM E1876-21, dynamic modulus, free-free beam	Non-destructive	Slender bar, length $\gg$ thickness	Sound velocity (m/s), dynamic MOE (GPa), f_1
ASTM E756-05 / ISO 6721-3, damping loss factor	Non-destructive	Same beam as above	Loss factor η , quality factor Q

Compression (ASTM D143-22 Section10) and tension (ASTM D143-22 Section14), both fully destructive, appeared in the original test plan but were excluded from the final suite. The truss rod carries the sustained string tension, and the bending test already captures the flexural failure, so parallel to grain compression and tension testing were not required.

Appendix C. Janka Hardness, Full Report

C.1 Context and Test Rationale

C.1.1 Project context and motivation for hardness testing

This report documents Janka hardness testing carried out as part of a workshop-scale superwood development study for electric guitar lutherie. The broader project investigates whether abundantly cultivated species, specifically the softwood Norway spruce (*Picea abies*) and the hardwood yellow poplar (*Liriodendron tulipifera*), can be chemically delignified and thermally densified to match or exceed the mechanical and acoustic properties of North American hard maple (*Acer saccharum*), the reference tonewood adopted for this study and the species used for electric guitar necks.

Hardness matters at this stage because it relates directly to the main ways a guitar neck wears in service: resistance to fret slot wear, denting from strings and hardware, and surface durability under repeated playing.

The rationale for hardness testing, what the Janka index measures, the distinction between the normal (face) and parallel (edge) directions, and the conventions for reporting each condition as a percentage of the maple benchmark and for flagging caveated values, are set out in Section 4.2.1 and are not repeated here. This appendix gives the full method, the complete indentation data, and the analysis.

C.2 Method

C.2.1 Applicable standard and directional averaging

Testing followed ASTM D143-22, Standard Test Methods for Small Clear Specimens of Timber.^[27] For side hardness, ASTM D143 places indentations on the radial and tangential faces, which are the two long faces of the blank introduced in Section A.1.2, the flat and edge faces named here by how they meet the growth rings. The reported Janka value is the average of these side measurements. Hardness measured on the end grain, the face where the fibres are cut across, like the cut end of a bundle of straws, is a separate ASTM measurement. It is not part of the side hardness value and was not tested here, because a neck wears on its long faces rather than its ends.

Wood hardness is anisotropic: resistance on a face normal to the growth rings can differ from resistance on a face parallel to them. Green and Begel (USDA FPL-RN-303) found no statistically significant difference between radial and tangential side hardness across most species, which is why ASTM D143 averages the two side orientations.^[28] Both faces tested here are side faces, with the load applied perpendicular to the grain. No end grain hardness was measured.

Indentations were taken on both flat faces and both edge faces, up to 14 indentations per specimen; the full scheme is given in Section A.2.3 (Table C.2). Results are reported by direction and as a combined weighted mean. The combined mean is the primary comparative figure and corresponds to the value ASTM D143 would report. Where a directional difference appears between the two side orientations, it is treated as a specimen level observation in Section A.5.2, since the averaging above concerns population level results rather than individual specimen sets.

C.2.2 Apparatus, ball geometry, and specimen conditioning

All testing used a single universal testing machine (UTM) fitted with an 11.3 mm hardened steel ball. Load and displacement were recorded continuously throughout each indentation. Every specimen, including the maple reference, was tested on this rig with the same ball under the same calibration state. Because the maple reference shares these conditions with all other specimens, any systematic rig effect is common to every condition and does not affect the relative comparisons that follow.

ASTM D143-22 specifies an 11.28 mm ball and a 5.64 mm target depth.^[27] The 11.3 mm ball corresponds to a 5.65 mm target, a deviation of 0.02 mm (0.18%). Because the same ball was used for every specimen, this deviation does not affect the percentage of maple comparisons. Green and Begel report that ball geometry deviations of this magnitude do not produce statistically meaningful differences in hardness when testing is consistent.^[28]

The test prerequisites are summarised in Table C.1.

Rig	Universal testing machine (UTM), single rig used throughout
Indenter	11.3 mm hardened steel ball, same ball used for all conditions
Load application	2 mm/min constant displacement rate for each indentation
Data recording	Continuous load and displacement acquisition throughout each indentation
Specimen conditioning	All specimens conditioned to equilibrium moisture content in a controlled environment before testing
Indentation spacing	Sufficient spacing between adjacent indentations to avoid plastic zone interaction
Rig calibration	Load cell calibration verified before the test campaign and held constant across all conditions
Reference benchmark	Maple tested in the same session on the same rig as all other conditions

Table C.1. Test prerequisites and rig configuration.

C.2.3 Indentation scheme and target penetration depth

Each specimen was indented following the scheme in Table C.2, based on ASTM D143-22 with an adapted count per face to improve statistical coverage. Four indentations were placed on each of the two flat faces (normal to rings, 8 in total) and three on each of the two edge faces (parallel to rings, 6 in total), giving up to 14 indentations per specimen. Indentations were spaced to avoid interaction between adjacent plastic zones, and all specimens were conditioned to equilibrium moisture content in a controlled environment before testing.

Face	Orientation	Indentations per specimen
Two flat faces (top and bottom)	Normal to growth rings	4 per face (8 in total)
Two edge faces (left and right)	Parallel to growth rings	3 per face (6 in total)
Total per specimen		Up to 14 indentations

Table C.2. Indentation scheme per specimen.

The target penetration depth is 5.65 mm, half the 11.3 mm ball diameter. The peak force at this depth is the Janka hardness for that indentation. For Poplar 50% specimens that reached the machine load limit before this depth, a conservative treatment was applied, described in Section A.4.2.

C.3 Specimen Conditions Tested

The following conditions were included in the test campaign:

- **Maple raw:** North American hard maple, uncompressed. Primary mechanical reference benchmark.
- **Poplar raw:** yellow poplar, uncompressed. Baseline for the densification gain calculation.
- **Poplar 25%:** yellow poplar compressed by 25% in thickness through delignification and hot pressing.
- **Poplar 50%:** yellow poplar compressed by 50% in thickness through delignification and hot pressing. The machine load limit was reached before target depth on most indentations (see Section A.4.2).
- **Spruce raw:** Norway spruce, uncompressed. Baseline for spruce assessment.
- **Spruce 25%:** Norway spruce compressed by 25% in thickness through delignification and hot pressing. Specimens fractured during indentation, so the values represent fracture load, not Janka hardness (see Section A.4.3).
- **Spruce 50%:** Norway spruce compressed by 50% in thickness through delignification and hot pressing. Specimens failed catastrophically and the UTM captured no valid load record. No data available (see Section A.4.3).

C.4 Results

C.4.1 Primary results

Table C.3 gives the mean hardness, standard deviation, and percentage of the maple benchmark for each condition and direction. Combined values are ordinary averages across all indentations per condition, weighted so that a direction with more indentations counts proportionally more. Averaged hardness across all conditions is compared in Figure C.1.

Condition	Direction	n	Mean (N)	SD (N)	% of maple	Notes
Maple raw	Normal	8	7,610	186	n/a	Reference benchmark
Maple raw	Parallel	6	6,433	133	n/a	
Maple raw	Combined	14	7,106	625	100%	
Poplar raw	Normal	8	4,229	208	59.5%	
Poplar raw	Parallel	6	3,753	256	52.8%	
Poplar raw	Combined	14	4,025	329	56.6%	
Poplar 25%	Normal	6	4,165	226	58.6%	

Poplar 25%	Parallel	6	4,265	269	60.0%	
Poplar 25%	Combined	12	4,215	243	59.3%	+4.7% over raw
Poplar 50%	Normal (Version A)	8	8,686	431	114.1%	Lower bound, machine limit
Poplar 50%	Parallel	6	6,572	76	102.2%	
Poplar 50%	Combined	14	7,780	n/a	109.5%	Version A normal and parallel
Spruce raw	Normal	8	1,908	88	26.8%	
Spruce raw	Parallel	6	1,976	245	27.8%	
Spruce raw	Combined	14	1,937	169	27.3%	
Spruce 25%	Normal	5	3,160	183	44.5%	Fracture, not hardness
Spruce 50%	Normal	n/a	n/a	n/a	n/a	Failed, no data recorded

Table C.3. Janka hardness results by condition and direction. Blue shading marks the maple reference benchmark, grey marks the combined mean rows, and orange marks results requiring caveat interpretation (see Sections A.4.2 and 4.3). A single standard deviation is not reported for the Poplar 50% combined row, because it pools the normal and parallel groups, whose means differ substantially; the directional values are given in their own rows. Spruce 50% has no recorded values, owing to catastrophic specimen failure before data acquisition.

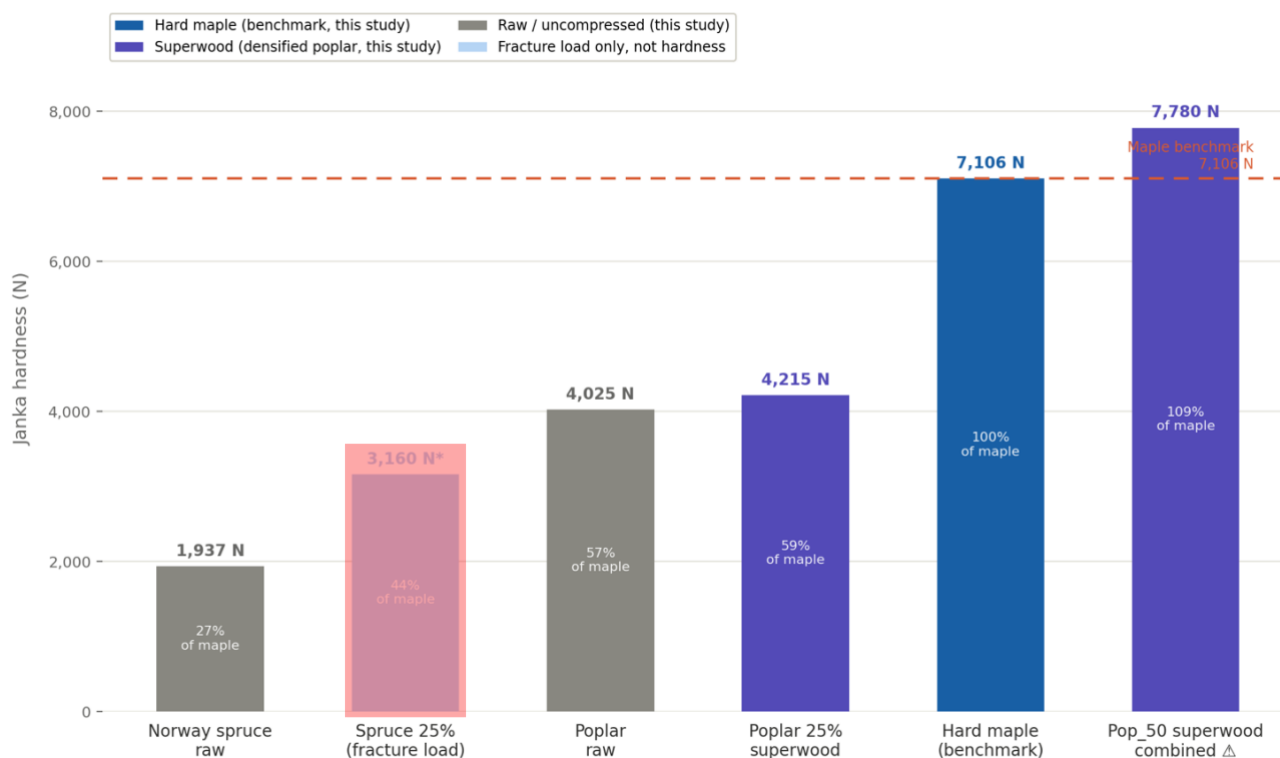


Figure C.1. Janka hardness of each condition as a percentage of the maple combined benchmark (7,106 N). The dashed line marks the maple reference at 100%. Bars carrying caveats are shaded accordingly: Poplar 50% is a conservative lower bound limited by the machine load ceiling (Section A.4.2), and Spruce 25% (highlighted red) is a fracture load rather than a true Janka hardness value (Section A.4.3). Spruce 50% produced no recordable data.

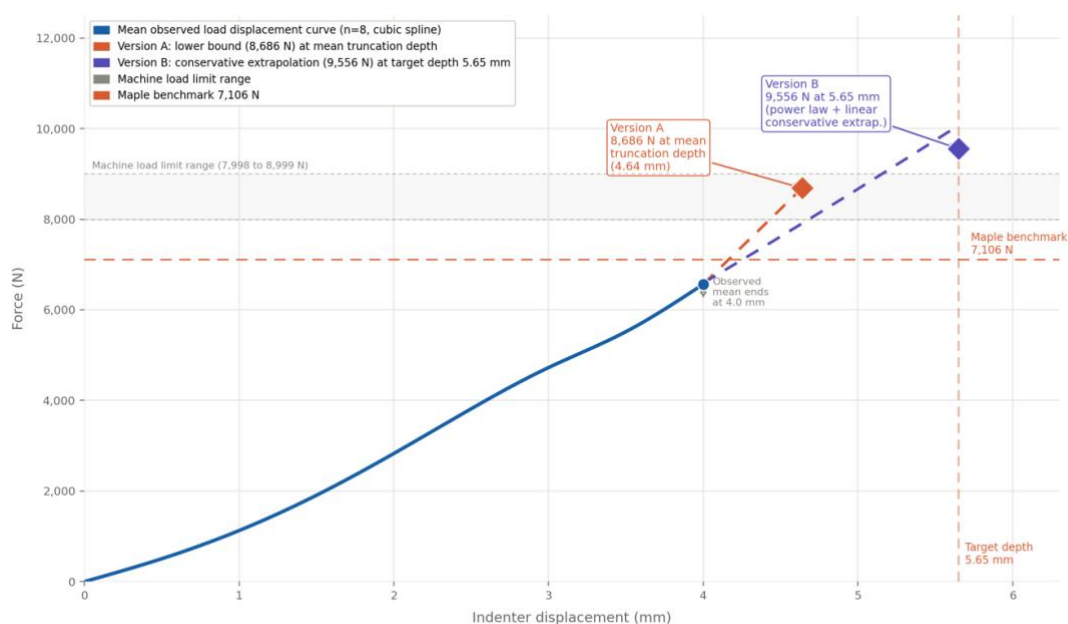
C.4.2 Poplar 50%: machine load limit and conservative extrapolation

For Poplar 50%, the material was hard enough that the UTM reached its maximum force before the 5.65 mm target depth in seven of the eight normal face indentations. Only one indentation (Poplar 50%, specimen 4) reached full depth, recording 8,363 N. Because this indentation ran to completion, its force curve serves as the reference for estimating the seven that stopped short.

Because most indentations stopped short of full depth, the hardness at full depth cannot be read off directly, so two treatments were produced to bracket it. Version A is a conservative floor: it uses only the force actually measured, with no estimation, so it cannot overstate the hardness. Version B is an estimate of the true value at full depth, obtained by extending each curve. Version A is the value used throughout the report, and Version B is supplementary, showing how much higher the real figure is likely to be. Both are defined in detail below.

Version A, lower bound. Version A takes the force reached at the moment the machine stopped and reports it directly, with no estimation. These truncation forces range from 7,998 N to 8,999 N, with a mean of 8,686 N (SD 431 N, CV 5.0%). Because the test halted early, these figures understate the true hardness at full depth. Even so, the lowest normal face truncation force, 7,998 N, already exceeds the maple normal face mean of 7,610 N, and the combined Version A value of 7,780 N exceeds the maple combined benchmark of 7,106 N. The conclusion that Poplar 50% is harder than maple therefore holds on the raw measurements alone, without any curve fitting. Figure C.2 shows the mean observed curve together with the Version A lower bound.

Version B, curve fit extrapolation. To estimate how much higher the force would have risen had the machine continued, each force and displacement curve was extended mathematically. A power law of the form $F = a \cdot x^b$ captures the rising shape, with the exponent b fixed at 1.185, the value measured from specimen 4, the only specimen that reached full depth. A simpler straight line extension of each curve tail was also computed as an independent check, and for every indentation the lower of the two estimates was kept. A conservative extrapolation from the pooled mean curve gives about 9,556 N (134.5% of maple), shown in Figure C.2, while averaging the individual specimen extrapolations gives 10,546 N (CV 14.3%, 148% of maple), shown in Figure C.3.



Observed portion: cubic spline through the mean of 8 Pop_50 normal face indentations at common displacement checkpoints (0 to 4.0 mm).
Version A: linear interpolation from observed mean to mean truncation depth; value is mean of raw machine limit forces. Version B: power law ($F = a \cdot x^b$) fit to mean curve, conservative lower value of power law and linear tail taken.

Figure C.2. Mean observed force and displacement curve for the eight Poplar 50% normal face indentations, taken as a cubic spline through the pooled mean. Version A is the lower bound at the mean truncation depth (8,686 N). Version B is a conservative extrapolation to the 5.65 mm target depth (9,556 N), combining a power law fit and a linear tail. The maple benchmark (7,106 N) and the machine load limit range are marked for reference.

The Poplar 50% flat face results fall into two groups rather than scattering around a single value, that is, a bimodal distribution. Cluster A (5 indentations, mean 9,539 N, CV 7.1%) and a harder Cluster B (3 indentations, mean 12,225 N, CV 3.9%) are shown in Figure C.3. The most plausible explanation is uneven density across the blank, likely from variation in pressure or moisture content during pressing, which would leave some regions denser and harder than others.

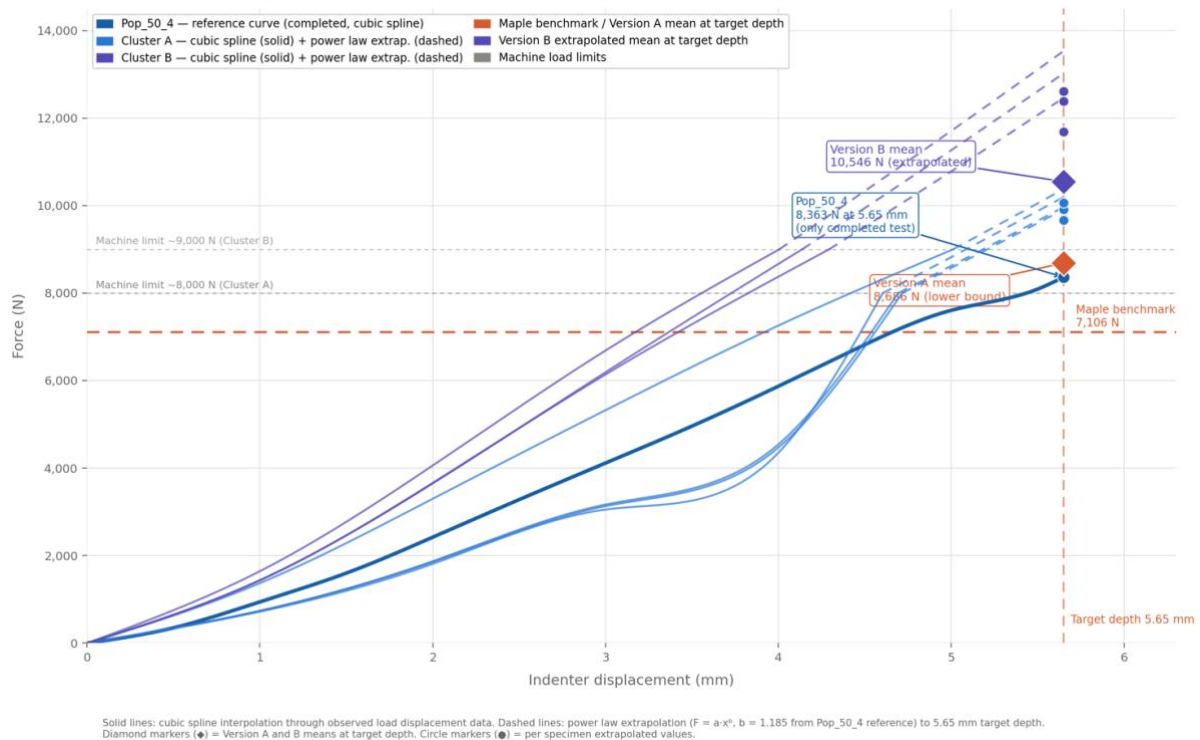


Figure C.3. Per specimen force and displacement curves for Poplar 50%, showing the bimodal split into Cluster A and Cluster B. Solid lines are cubic spline interpolations through the measured data, and dashed lines are power law extrapolations ($b = 1.185$ from specimen 4) to the target depth. Diamond markers give the Version A and Version B means; the per specimen Version B average is 10,546 N.

Note. Version A, the measured and understated value, is the figure used throughout this report. Version B is offered only as a supporting indication and should not be treated as a design specification until it is confirmed by testing on a machine with a higher force capacity.

C.4.3 Norway spruce: specimen fracture and test failure

All Norway spruce specimens at 25% compression fractured during indentation rather than deforming plastically. The forces recorded at fracture (mean 3,160 N, CV 5.8%) represent failure load, not Janka hardness, and cannot be compared directly with the ductile indentation response of maple or poplar. The pattern is consistent with residual brittleness in the densified cell wall: at 25% compression the lumen space is only partly closed, but the walls have not consolidated enough to resist the lateral tensile stresses beneath the advancing ball, which most plausibly leads to splitting along the grain, as seen in Figure C.4.



Figure C.4. A Norway spruce specimen at 25% compression after indentation, showing a longitudinal split propagating from the indented surface along the grain instead of a plastic indentation.

The Norway spruce specimens at 50% compression failed catastrophically. The failure mode was instantaneous brittle fracture, and it occurred before the UTM could capture a valid load record, so no force or displacement data were recorded. This is more severe than the 25% case: the higher compression ratio produces a denser, more brittle structure with even less capacity to accommodate the lateral stress field, and the failure was too sudden to be captured, occurring faster than the data recorder could sample. Figure C.5 shows the resulting fracture.



Figure C.5. A Norway spruce specimen at 50% compression after indentation, showing catastrophic brittle fracture in which the coupon split along its full length into separate halves.

Both spruce conditions therefore produced specimens that are incompatible with Janka hardness testing under the current geometry and machine configuration, and neither can contribute to the

benchmarking dataset. At the compression ratios tested, densified Norway spruce does not show the ductile indentation behaviour the Janka test assumes; it fractures before the ball reaches target depth.

Note. Spruce 25% values (3,160 N mean) are retained in Table C.3 as labelled fracture load data for completeness only, and are excluded from all hardness comparisons. Spruce 50% has no recorded values. Neither condition is carried forward as a hardness result. The implications for species selection are discussed in Section A.5.4.

C.5 Discussion

C.5.1 Compression ratio as the dominant processing variable

The results indicate a strongly nonlinear relationship between compression ratio and Janka hardness in yellow poplar. The gain from raw to 25% compression is only about 4.7%, which sits within measurement scatter, so 25% compression leaves the hardness very close to raw poplar and produces no meaningful densification. The step to 50% is different in kind. On a combined basis the hardness rises from 4,025 N (raw) to 7,780 N, a gain of about 93% even on the conservative Version A lower bound, which places the material above the maple benchmark. This relationship is shown in Figure C.6.

This nonlinearity is consistent with the densification model proposed by Song et al.^[5] At moderate compression the cell lumina collapse but the walls remain separated, so the indenter still interfaces with a material governed by cellular structure. Beyond a critical ratio, the collapsed walls begin to form a mass that is almost solid, whose hardness approaches that of the cell wall material itself. The 50% data point appears to sit just past this threshold. The hardness jump itself is estimated to fall somewhere in the 40% to 50% range for diffuse porous hardwoods, though the present data cannot locate it precisely, so this should be read as an interpretation rather than an established value.

A further test specimen at 35% or 40% compression, between the levels already tested, would help locate this jump and show whether the gain is concentrated at a specific ratio or spread across a range.

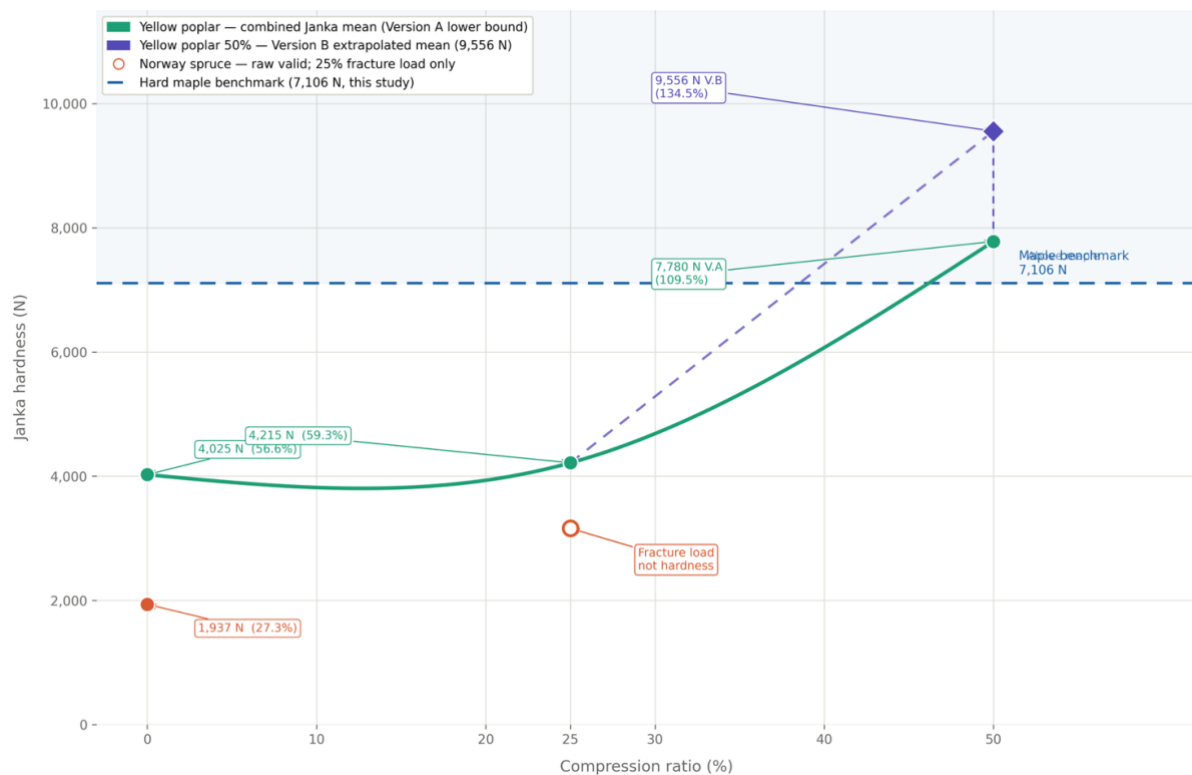


Figure C.6. Janka hardness against compression ratio for yellow poplar, with Norway spruce and the maple benchmark shown for reference. The combined Version A lower bound reaches 7,780 N (109.5% of maple) at 50% compression. The Version B extrapolated mean is shown for comparison. The Spruce 25% point is a fracture load, not a hardness value.

C.5.2 Directional response in compressed poplar

Raw maple shows an 18% difference between normal face and parallel face hardness (7,610 N against 6,433 N). This is best read as a specimen level observation rather than a species characteristic, and its size is larger than is typical for a diffuse porous hardwood, so specimen orientation or sampling may contribute. Green and Begel's finding of no significant radial to tangential difference concerns population averages^{29]}, so it does not rule out a difference of this size in a particular specimen set.

The two poplar conditions behave very differently by direction, and only Poplar 50% is a candidate. Poplar 50% is strongly anisotropic in hardness: at least 8,686 N on the normal face against 6,572 N on the edge, a difference of more than 2,000 N, and larger still because the normal face value is a machine limited lower bound. The densification consolidates the face far more than the edge, which is expected for a material pressed through its thickness. Two consequences follow for how the result is used. The edge readings were taken on the 20 mm dimension, the thinnest dimension of the blank, where the indentation sits close to the opposite surface, so those edge values are less reliable than the face values. And because the bending test also loads the material through the face, the normal face is the direction that matches the stiffness measurement. For both reasons the maple comparison in this report uses the normal face, while all readings in both directions are reported in Table C.3.

C.5.3 Benchmarking against maple

The maple combined benchmark of 7,106 N comes from 14 indentations on hard maple tested on the same rig under the same conditions, so it is directly comparable with the other results here. The

published Janka side hardness of hard maple is about 6,450 N (1,450 lbf) in the USDA Wood Handbook.^[14] The parallel face mean measured here, 6,433 N, agrees closely with that published value, which is consistent with the rig producing valid absolute values and not only valid relative comparisons.

The combined benchmark (7,106 N) and the normal face mean (7,610 N) sit above the published figure by roughly 10% and 18%. This is most likely due to the particular maple stock used and its moisture state. It does not affect the internal comparisons, since every condition is measured against this same in study benchmark, but it does mean the benchmark should be read as specific to this material rather than as a general value for the species.

The comparison against maple uses the normal face, for two reasons: it is the surface into which frets are seated and which takes the most wear, and it is the direction in which the bending test loads the material, so it is the like for like partner to the stiffness result. On that basis, Poplar 50% (Version A lower bound) at 8,686 N is 114.1% of the maple normal face mean of 7,610 N, so at least about 14.1% harder. The edge readings, taken on the thin 20 mm dimension, are less reliable and are not used for the comparison, though all readings were taken and appear in full in Table C.3; note the large directional delta in Poplar 50%, 8,686 N on the face against 6,572 N on the edge. Raw poplar, at 4,025 N combined, is far below maple, and Poplar 25% at 4,215 N is very close to raw poplar, confirming that the hardness is created by the densification at 50% and not by moderate compression. Poplar 25% is therefore not carried forward, and neither is spruce, which fractured and cracked under indentation.

C.5.4 Norway spruce: decision gate

Norway spruce (*Picea abies*) is not carried forward as a candidate species for superwood neck manufacture. This decision rests on the following.

Structural failure under Janka loading. At both 25% and 50% compression, densified spruce failed by brittle fracture rather than plastic indentation. At 25% the fracture loads averaged 3,160 N, well below the maple benchmark and produced by a mode that is qualitatively different from ductile indentation. At 50% the specimen split before any load could be recorded. This progression, from brittle fracture at moderate compression to instantaneous failure at high compression, indicates that densification makes spruce more brittle rather than converting it to a tough, indentation resistant material.

Structural basis for the brittleness. Norway spruce is a softwood whose cell wall is dominated by guaiacyl (G) type lignin. This lignin has a higher proportion of condensed carbon to carbon bonds relative to the beta-O-4 ether linkages that the NaOH and Na₂SO₃ chemistry cleaves more readily.^[5] Even with elevated Na₂SO₃ (0.6 M, the concentration used in the later experiments of this project), complete softening of the G lignin is not guaranteed. As the lumen collapses, residual lignin in the walls can shift from ductile to brittle behaviour, because the constraint from neighbouring walls removes the energy absorption path that open lumen wood relies on. The result is a material that is dense but brittle, which is unsuitable where concentrated contact loading dominates.

Practical implications. Continuing with spruce would mean resolving this brittleness, most likely through changes to the delignification chemistry, the compression rate, or the specimen geometry, before Janka testing could even be repeated. Since Poplar 50% already exceeds the maple benchmark on a conservative lower bound, the main objective, a maple substitute that meets the mechanical bar for hardness, is reachable through Poplar, without further Spruce development.

Norway spruce remains useful as a tonewood for acoustic guitar tops and violin plates, where its low density and high specific stiffness are assets. For electric guitar necks, its brittle fracture under indentation makes densified spruce unsuitable at the ratios and parameters explored here. Its acoustic behaviour is assessed separately in the acoustic tap tone report, and the two lines of evidence together support setting spruce aside. Further spruce development is therefore deprioritised, with no further hardness or acoustic testing planned at this stage.

C.6 Conclusions

The following conclusions are drawn from the current dataset:

- **Poplar 50% exceeds maple.** On a like for like basis, and on the neck relevant normal face, yellow poplar at 50% compression is at least about 14.1% harder than maple (8,686 N against 7,610 N), even on the conservative Version A lower bound. The result is robust: the combined Version A value of 7,780 N also exceeds the maple combined mean of 7,106 N, and every single normal face indentation exceeded the maple normal face mean of 7,610 N.
- **Nonlinear compression response.** The hardness gain is strongly nonlinear. A 25% ratio gives only about 4.7% over raw poplar, within measurement scatter, so 25% compression produces no meaningful densification and Poplar 25% is not carried forward as a candidate, while 50% gives at least a 93% gain on a combined basis. A further test point near 35% to 40%, to locate where the jump begins, is recommended.
- **Directional response.** Poplar 50% is strongly anisotropic in hardness, at least 8,686 N on the normal face against 6,572 N on the edge, a difference of more than 2,000 N and larger still once the machine limited face value is accounted for. The face is much harder than the edge, as expected for a material densified through its thickness. Because the edge readings sit on the thin 20 mm dimension and are less reliable, and because the neck and the bending test both load the face, the comparison against maple uses the normal face.
- **Spruce excluded as a candidate.** Norway spruce failed by brittle fracture at both 25% and 50% compression, and Spruce 50% produced no recordable data. With the acoustic evidence reported separately, spruce is not carried forward, and the poplar pathway is sufficient to meet the objective. Spruce 25% fracture loads (mean 3,160 N) are retained as labelled documentary data only and are excluded from all hardness comparisons.
- **Comparisons internally valid.** Every condition, including the maple reference, was tested on the same rig under the same conditions, so comparisons across conditions are robust to any systematic rig offset.
- **n = 1 limitation.** All hardness values are from a single blank per condition; the multiple indentations are technical repetitions on that one blank, not independent specimens (Section 4.1.2). Replication at $n \geq 5$ is needed to confirm these margins hold across blanks.

Appendix D. Modulus of Elasticity, Full Report

D.1 Context and Test Rationale

The rationale for the bending test, what the three point bending modulus measures, the governing formula, and the two ways the result is reported, against published maple benchmarks and against the two supporting lines from this study, are set out in Section 4.3.1 and are not repeated here. This appendix gives the full method, data, and analysis.

D.1.1 L/t ratio: deviation from standard

ASTM D143-22^[27] specifies a span to depth (L/t) ratio of 14 to 1 for three point bending MOE tests on small clear specimens. The specimens here have a span $L = 125\text{ mm}$ and a thickness $t = 9\text{ mm}$, giving $L/t = 13.9$, a shortfall of 0.7% from the minimum.

Because the maple reference and the Poplar 50% specimen share identical geometry, this contribution is systematic and cancels in the relative comparison, although it means the absolute MOE values are likely underestimates.

D.1.2 Prerequisites and specimen configuration

The test prerequisites and rig configuration are summarised in Table D.1.

Machine	Universal testing machine (UTM), Zwick Z010, single rig used throughout
Load application	1.5 mm/min displacement rate at midspan through a rounded nose roller
Data recording	Continuous load and crosshead displacement acquisition throughout each test
Linear region	0.05 mm to 40% of F_{max} ; least squares linear regression, R^2 greater than 0.999 for both specimens
Reference benchmark	Maple reference specimen tested in the same session on the same rig as Poplar 50%

Table D.1. Test prerequisites and specimen configuration.

Full moisture conditioning to a reference state was not applied at this stage. Since MOE is moisture dependent, and a raw specimen and a chemically processed specimen may equilibrate at different moisture contents, conditioning both to the same state is noted as future work in Section B.6.

D.1.3 Rationale for $n = 1$

Both the maple reference and the Poplar 50% specimen are single specimens ($n = 1$). Workshop-scale superwood production yields small batches. The process produced a single viable Poplar 50% blank of sufficient size for both Janka and MOE testing within the thesis timeline, given the two day minimum processing cycle per batch and the limited availability of press time.

With $n = 1$ there is no within condition variance and no inferential statistics for the MOE comparison, so the result is a pilot characterisation value rather than a population mean. The supporting checks in Section B.5 are broadly consistent with the Poplar 50% MOE but do not independently confirm it. A minimum of $n = 5$ per condition from independently processed blanks is recommended for future work.

D.2 Test Standard

D.2.1 Applicable standard

The test was conducted in accordance with ASTM D143-22, Standard Test Methods for Small Clear Specimens of Timber, Section 8 (Static Bending)^[27]. ASTM D143 specifies testing on small, defect free specimens to characterise the inherent properties of the wood material, independent of structural scale defects. The specified geometry is a three point bending configuration at a span to depth ratio of 14 to 1, from which this study deviates only marginally (Section B.1.4).

D.3 Specimen Description

D.3.1 Species and conditions tested

Two material conditions were tested:

- **Maple reference:** North American hard maple, uncompressed. Primary mechanical reference benchmark.
- **Poplar 50%:** yellow poplar compressed to 50% in thickness through the chemical delignification and hot pressing process. Primary candidate condition.

D.3.2 Specimen geometry

Both specimens share identical dimensions, listed in Table D.2. The loading configuration is shown in Figure D.1.

Parameter	Value	Note
Total length	146 mm	
Test span (L)	125 mm	10.5 mm overhang at each support
Thickness (t)	9 mm	
Width (b)	24 mm	
L/t ratio	13.9	Slight deviation from ASTM D143 minimum = 14
Cross section (b × t)	216 mm ²	

Table D.2. Specimen geometry. The maple reference and Poplar 50% specimens share identical dimensions.

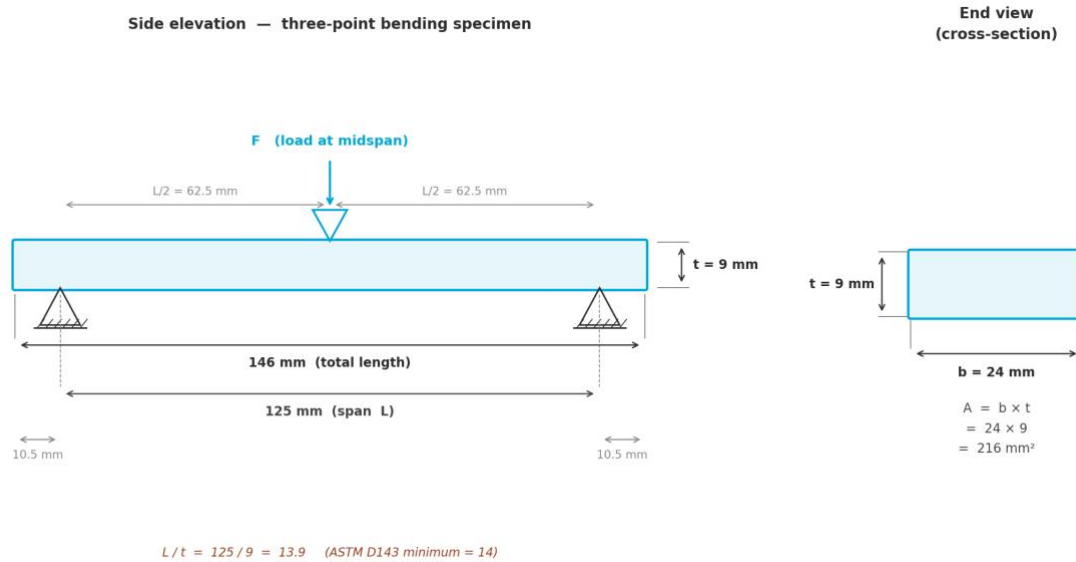


Figure D.1. Specimen geometry and three point bending test configuration, showing the span, cross section, and loading point. ASTM D143-22, Zwick Z1010, load rate 1.5 mm/min.

D.4 Results

D.4.1 Primary results

Table D.3 presents the measured stiffness, calculated MOE, and comparative benchmarks for the two conditions, alongside two certified literature sources for hard maple. The load and deflection curves for both specimens are shown in Figure D.2.

Parameter	Maple (this study)	Poplar 50% (this study)	USDA hard maple (Kretschmann 2010)	FPJ hard maple (Hernandez 2020)
Peak load $F_{\max}$ (N)	1,406.9	1,407.9	n/a	n/a
k (N/mm)	474.0	438.2	n/a	n/a
MOE (GPa)	13.23	12.23	12.62	12.42
% of USDA benchmark (12.62 GPa)	104.8%	96.9%	100%	98.4%
% of FPJ benchmark (12.42 GPa)	106.5%	98.5%	n/a	100%
n (specimens)	1	1	not stated	multiple

Table D.3. MOE results for the maple reference and Poplar 50% alongside two certified hard maple literature benchmarks. The MOE row is highlighted; percentage comparison rows are lightly shaded. Both tested specimens are $n = 1$ (see Section B.1.6).

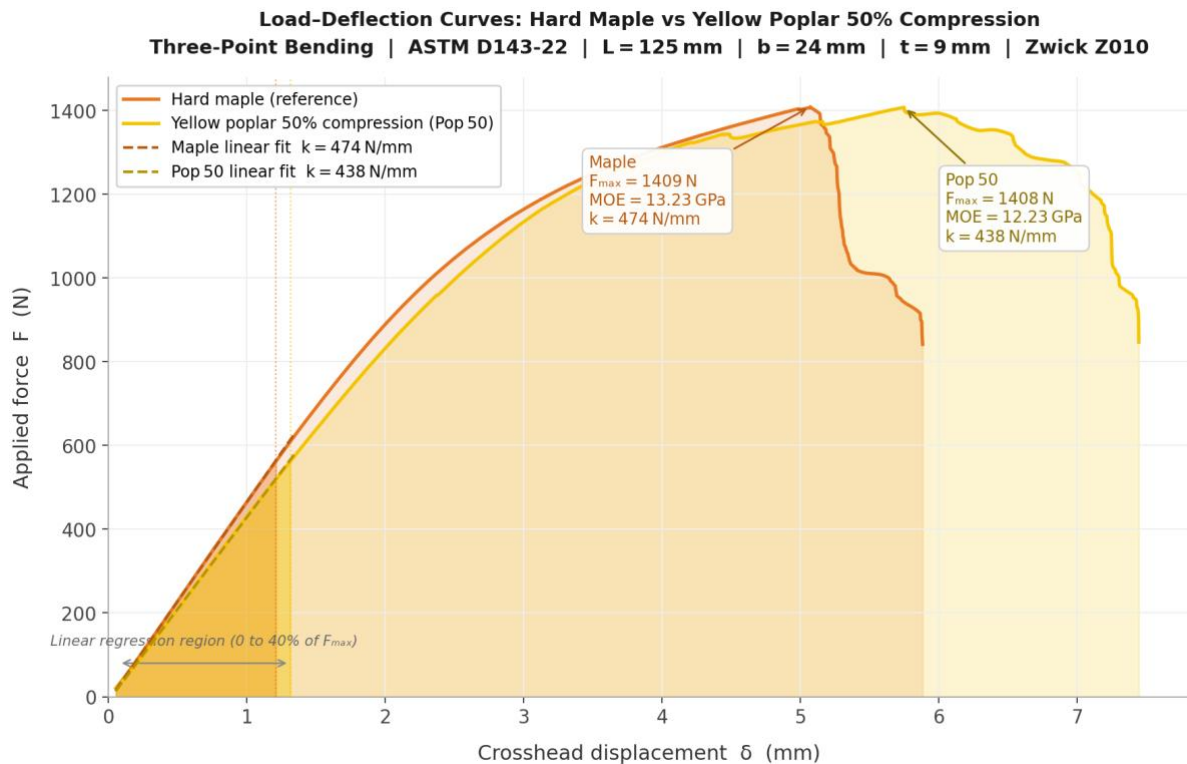


Figure D.2. Load and crosshead displacement curves for the maple reference and Poplar 50% in three point bending, with the fitted stiffness k , calculated MOE, and peak load for each. The linear regression region (0 to 40% of F_{max}) is indicated. Pop 50 in the figure denotes Poplar 50%.

D.4.2 Key findings

Poplar 50% reaches MOE = 12.23 GPa, which is 96.9% of the USDA hard maple benchmark (12.62 GPa) and 98.5% of the peer reviewed Hernandez et al. 2020 hard maple mean (12.42 GPa).^[31] The maple reference specimen reads 13.23 GPa, sitting 4.8% above the USDA benchmark and 6.5% above the Hernandez mean, which places it in the upper part of the published range and is consistent with a correctly performing rig.

Both specimens reached almost identical peak loads ($F_{max} \approx 1,407$ N), indicating comparable peak load capacity under this geometry. The Poplar 50% stiffness k of 438.2 N/mm is 7.6% below the maple reference of 474.0 N/mm. For identical geometry the MOE gap equals the stiffness gap, so the calculated MOE also differs by 7.6% (13.23 against 12.23 GPa). The interpretation of these findings is developed in Section B.6.

D.5 Triangulation of the Poplar 50% MOE

Because the MOE comparison rests on single specimens, this section compares the Poplar 50% result against two further lines from this study, acoustic tap tone resonant frequency and Janka hardness, neither of which needs additional specimens. Both are supporting checks rather than independent confirmations of the MOE value, and one of them reuses the maple bending result as its anchor, as noted below.

D.5.1 Acoustic tap tone resonant frequency

For a beam vibrating in bending with both ends free, the first resonant frequency f_1 scales as:

$$f_1 \propto \sqrt{(E/\rho)}$$

where E is MOE and ρ is density. For the same specimen geometry, the ratio of f_1 between two materials reflects only the ratio of their specific stiffness. The tap tone testing recorded a Poplar 50% first flexural frequency of 3,792 Hz and a maple value of 4,299 Hz.

Taking the measured densities of maple, 710 kg/m³, and Poplar 50%, 942 kg/m³ (raw poplar 594 kg/m³, a factor of 1.59 densification), and anchoring on the directly measured maple MOE of 13.23 GPa, the inferred Poplar 50% MOE is:

$$E_{\text{Poplar 50\%}} = E_{\text{maple}} \times (f_{1,\text{Poplar 50\%}} / f_{1,\text{maple}})^2 \times (\rho_{\text{Poplar 50\%}} / \rho_{\text{maple}})$$

$$= 13.23 \times (3792 / 4299)^2 \times (942 / 710) = 13.66 \text{ GPa}$$

Quantity	Value
MOE measured by three point bending	12.23 GPa
E inferred from acoustic f_1 ratio, measured maple anchor	13.66 GPa
Difference from static MOE	about 12% above
Dynamic maple E from f_1 (reference)	about 15.7 GPa

Table D.4. Acoustic triangulation of the Poplar 50% MOE. Anchored on this study's maple MOE and the measured densities, the acoustic first frequency ratio infers a modulus about 12% above the static bending value, in the expected dynamic above static direction. The absolute dynamic values are indicative, because they are not corrected for shear in a bar this thick relative to its length.

Anchored on the measured maple MOE and the measured densities, the acoustic estimate of 13.66 GPa sits about 12% above the direct bending result of 12.23 GPa. This is the expected direction. A modulus measured dynamically, from a fast vibration, is consistently higher than one measured in a slow static bend, because the static test includes a small amount of time dependent give that the tap does not. The maple shows the same effect: its first frequency implies a dynamic modulus of about 15.7 GPa against a static 13.23 GPa. The check is supporting rather than fully independent, because the anchor uses the maple MOE obtained in the same bending test.

The absolute dynamic values are computed from a simple beam relation that does not correct for shear, which is not negligible for a bar this thick relative to its length, so they are indicative. The frequency ratio cross check itself relies on identical geometry, where that correction largely cancels, so the roughly 12% agreement is more robust than the absolute figures. The inference also assumes a homogeneous beam, whereas the Poplar 50% blank is density graded, so the residual gap is consistent with that gradient and with the single specimen comparison.

D.5.2 Janka hardness decoupling

The Janka hardness test and the MOE bending test measure different things. Janka hardness reflects localised surface contact in a small zone beneath the indenter ball. MOE reflects the average bulk bending stiffness across the whole cross section, including any density gradient through the thickness. In a densified wood where the surface is more fully consolidated than the core, Janka hardness will outpace MOE gain relative to a homogeneous reference. This decoupling is therefore an expected consequence of the compression morphology rather than a contradiction. Table D.5 sets the two measures side by side on a like for like basis.

Property	Maple (this study)	Poplar 50%	Difference
Janka hardness (N), normal face, Version A lower bound	7,610	8,686	at least 14.1% higher
MOE (GPa), three point bending	13.23	12.23	7.6% lower

Table D.5. Janka hardness and MOE for the maple reference and Poplar 50%, on a like for like normal face basis. Janka hardness is the Version A normal face lower bound from the companion Janka report.

On a like for like normal face basis, Poplar 50% is at least about 14.1% harder than maple in Janka hardness while 7.6% lower in MOE. The normal face is the surface into which frets are seated and which takes the most wear, and it is also the direction in which this bending test loads the material, so hardness and stiffness are compared in the same direction. The direction of the effect is the same on either measure: surface hardness rises above maple while bulk stiffness sits slightly below it. This pattern matches the density gradient interpretation developed in Section B.6.2.

D.5.3 Triangulation summary

Line	Method	Poplar 50% value or relation	Role
1	Acoustic tap tone f_t ratio (3792 Hz / 4299 Hz)	13.66 GPa, about 12% above static (dynamic above static)	Supporting estimate; a dynamic modulus, above the static value as expected
2	Janka versus MOE decoupling	Janka higher, MOE slightly lower, as expected	Coherence check on the density gradient; no extra specimen needed
3	Maple reference versus published literature	13.23 GPa against 12.62 and 12.42 GPa	Rig validation; points to no large systematic rig offset

Table D.6. Triangulation summary. One semi independent supporting estimate (line 1) and two coherence checks (lines 2 and 3) are broadly consistent with a Poplar 50% MOE of 12.23 GPa. Only line 1 bears directly on the MOE value, and it is anchored partly on the maple bending result.

D.6 Discussion

D.6.1 MOE as a benchmark for guitar neck equivalence

Poplar 50% compression reaches MOE = 12.23 GPa. The published range for hard maple across the Hernandez et al. 2020 dataset spans 7.27 to 15.80 GPa, more than 8 GPa within a single species.^[31] The roughly 3% shortfall of Poplar 50% from the USDA mean of 12.62 GPa sits comfortably within the material variation that luthiers and manufacturers already accept when buying maple stock. On this pilot specimen, Poplar 50% can therefore be regarded as comparable to hard maple in bending stiffness for the purposes of neck design.

This equivalence should be read with the wide natural spread in mind. Because hard maple MOE varies by more than 8 GPa across the reference dataset, a single specimen constrains the population mean only weakly, so the comparison here is a first indication rather than a settled result. Yellow poplar is a fast-growing, widely cultivated species available at a fraction of the supply cost and scarcity risk of maple. Reaching near parity MOE through a scalable densification route is the central mechanical claim of the superwood approach, and this pilot result provides the first direct bending stiffness evidence for it.

D.6.2 Why Janka exceeds maple while MOE falls slightly short

Poplar 50% is at least about 14.1% harder than maple in Janka hardness (normal face, Version A lower bound) while its MOE sits 7.6% below the maple reference. Far from being contradictory, this pattern is mechanistically expected. Janka hardness is set by the contact zone directly beneath the indenter ball, the most compressed and most consolidated region of the blank. MOE is set by the average stiffness of the whole cross section, which includes any residual lumen space or density gradient left after 50% compression.

Song et al. 2018 proposed that beyond a critical compression ratio, approximately 40 to 50% for diffuse porous hardwoods, the collapsed cell walls begin to form a mass that is almost solid.^[5] The Poplar 50% specimens sit near this threshold. The bimodal Janka distribution reported in the companion Janka report suggests that the blank is not uniformly consolidated through its thickness: dense surface regions dominate the Janka response, while the bulk average that governs MOE also includes lower density interior zones. This gradient is the physical explanation for the observed decoupling between surface hardness and bulk stiffness.

It is worth noting that the blanks were cleaned, sanded, and planed after pressing, so much of the outermost pressed layer was already removed. The Janka indentations therefore sampled a plane just below the surface rather than the as pressed skin, and the reported hardness should be read as characterising that finished sub surface rather than the peak density outer layer.

D.6.3 Limitations and recommended future work

- **n = 1 per condition.** Future testing needs a minimum of $n = 5$ from independently processed blanks to enable statistical comparison. The triangulation in Section B.5 supports but does not replace this.
- **Shear and $L/t = 13.9$.** The shear contribution should be quantified with a measured shear modulus and a Timoshenko correction applied to the absolute MOE values in the final thesis. The relative comparison between maple and Poplar 50% is unaffected.
- **Crosshead based deflection.** Deflection was taken from crosshead travel, which includes machine compliance and local indentation. A direct midspan transducer would refine the absolute MOE. As with shear, this cancels in the maple to poplar comparison.
- **Moisture state.** Neither specimen was conditioned to a common moisture state. Since a raw and a processed specimen may equilibrate at different moisture contents, and MOE is moisture dependent, conditioning both to a reference state (for example ASTM D4933) is recommended so the comparison is not affected by a moisture difference.
- **Density measured geometrically.** Bulk densities were obtained as mass over external volume. For a density graded material this is a crude measure, sensitive to small errors in the finished dimensions, and it does not capture the through thickness gradient that the acoustic inference depends on. An immersion or displacement measurement (for example ASTM D2395), ideally sub sampled through the thickness, is recommended to refine the density values and may account for part of the acoustic discrepancy.

D.7 Conclusions

The following conclusions are drawn from the current dataset:

- **Poplar 50% MOE at 96.9% of the maple benchmark.** Poplar 50% reaches MOE = 12.23 GPa, 96.9% of the USDA hard maple benchmark and 98.5% of the Hernandez et al. 2020 mean. The shortfall is within the natural variability of hard maple and is not functionally significant for guitar neck use, on the basis of this pilot specimen.
- **Maple reference setup validation.** The maple specimen tested on the same rig produced MOE = 13.23 GPa, in the upper part of the published range, which is consistent with a correctly performing rig.
- Acoustic triangulation is broadly supportive. Anchored on the measured maple MOE and measured densities, the acoustic tap tone ratio infers a Poplar 50% MOE of 13.66 GPa, about 12% above the direct 12.23 GPa result, in the expected dynamic above static direction. The check is supporting rather than independent, since it reuses the maple bending result.
- Janka and MOE decoupling is physically coherent. On a like for like normal face basis, Janka hardness is at least about 14.1% higher while MOE is 7.6% lower. This is consistent with surface consolidation outpacing bulk stiffness at 50% compression and is not a contradiction.
- **n = 1 limitation.** All results are pilot characterisation values. Replication at $n \geq 5$ is a priority for the next processing batch.
- **Comparisons internally valid.** Both specimens were tested on the same rig under the same conditions, so the cross condition comparison is robust to any systematic rig offset.

Appendix E. Acoustic Tap Tone, Full Report

E.1 Introduction and Objective

The rationale for the tap tone test, what the first flexural frequency measures, the specific stiffness relation it rests on, and the reading conventions for the three materials, are set out in Section 4.4.1 and are not repeated here. This appendix gives the full setup evolution, signal analysis, results, and the exploratory damping and harmonic analysis. The reasons the damping and harmonic values are treated as preliminary are given in Section E.8.

E.2 Test Standard

E.2.1 Applicable standards and the adapted method

The method was adapted from, and informed by, ASTM E1876-21^[29] and ASTM D6874-22^[30]. Both standards describe a freely suspended beam excited by a single impulse and analysed in the frequency domain, which is the principle used here. The setup was not fully compliant with either standard: the specimen was suspended on elastic bands rather than on the prescribed supports, and it was excited with a soft mallet rather than a calibrated impulse tool. It is therefore treated as an adapted comparative test rather than a standard compliant measurement, which is appropriate given that its role is to compare materials of identical geometry against each other and against the bending result, not to certify absolute values.

E.3 Specimen Description

E.3.1 Materials tested

Three material conditions were tested acoustically:

- **Hard maple, raw:** North American hard maple, uncompressed. The reference tonewood and benchmark.
- **Yellow poplar, raw:** uncompressed yellow poplar. The unprocessed baseline.
- **Poplar 50%:** yellow poplar densified by 50% in thickness through the chemical delignification and hot pressing process. The primary candidate condition.

Norway spruce was excluded from the acoustic dataset. It failed by brittle fracture under Janka indentation and has been set aside as a candidate neck material on mechanical grounds, so it is not carried through the acoustic comparison. This decision is documented in the Janka hardness test chapter.

E.3.2 Geometry and measured density

All blanks were machined to identical dimensions before testing, listed in Table E.1, which is what allows the frequency ratio to be read directly as a stiffness ratio.

Parameter	Value	Note
Length	150 mm	Measured, Identical for all specimens

Width	46 mm	22.4% of length, first flexural nodes
Thickness	20 mm	
Volume	138.0 cm ³	
Nodal support positions	33.6 mm from each end	

Table E.1. Specimen geometry. All blanks were machined to the same dimensions, giving a common volume of 138.0 cm³.

Density was measured directly, by weighing each blank and dividing by the 138.0 cm³ volume. The measured values are given in Table E.2. Because the tests were run in order on the same blank, these densities carry across to the Janka and MOE chapters, where the same three materials are used.

Material	Mass (g)	Density (kg/m ³)	Note
Hard maple, raw	98	710	Benchmark
Yellow poplar, raw	82	594	
Poplar 50%	130	942	1.59 times the raw poplar density

Table E.2. Measured densities, from mass over volume on the full blank. These are the reference densities used across all three test chapters.

E.3.3 Moisture state

The two raw materials, hard maple and yellow poplar, were both at 8% (this is a written specification from the vendor), so the comparison between them is not affected by a moisture difference. The Poplar 50% specimen followed a different path. After boiling and hot pressing at 145 °C, it was vacuum oven dried for 6 hours at 90 °C and 950 mBar, then rested at ambient laboratory conditions for a few days before testing. Its moisture content at test was not measured and is likely to be higher than the 8% of the raw blanks.

E.4 Setup Evolution and Rationale for Change

E.4.1 Initial setup

The initial apparatus comprised a wooden baseboard, a spring loaded pendulum striker arm with a controlled pulling distance and two open cell polyurethane foam blocks as specimen supports at the ends (Figure E.1).

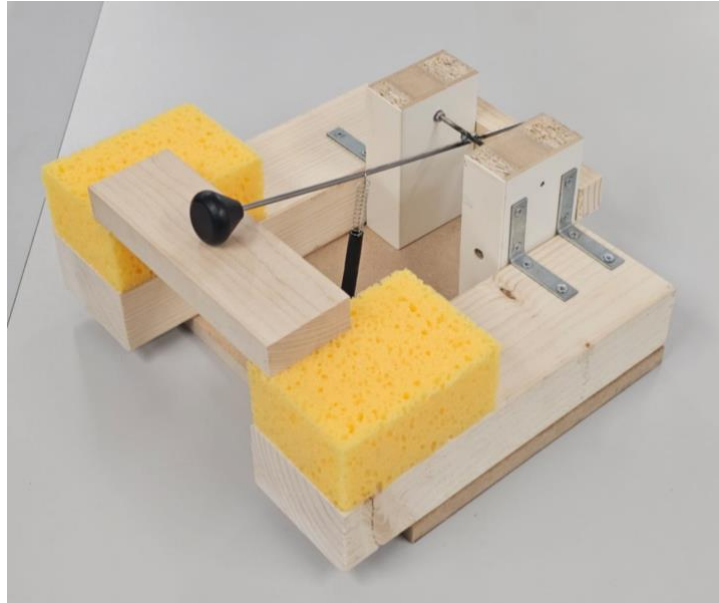


Figure E.1. Initial test setup apparatus.

The initial setup had three deviations from the ASTM E1876 free protocol:

- Foam blocks placed at the specimen ends rather than at the nodal points (22.4% from each end). The ends are points of maximum displacement in the first flexural mode, so supporting there constrains the vibration and raises the apparent damping.
- The striker contacting the top face at mid span rather than the end face. Centre tapping gives weaker and spectrally less pure excitation of the first flexural mode.
- Open cell polyurethane foam of high stiffness and large contact area, adding damping common to all specimens.

The intended free configuration is shown in Figure E.2.

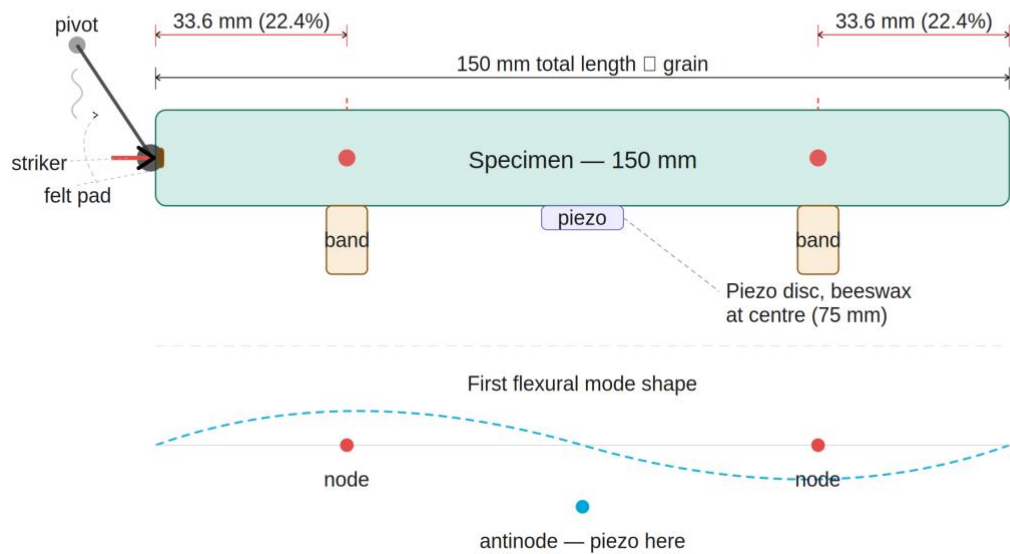


Figure E.2. Ideal test setup concept.

E.4.2 Elastic band suspension at nodal points

Figure E.3 shows the intermediate setup, made to roughly test the effect of elastic band suspension against foam blocks by ear.

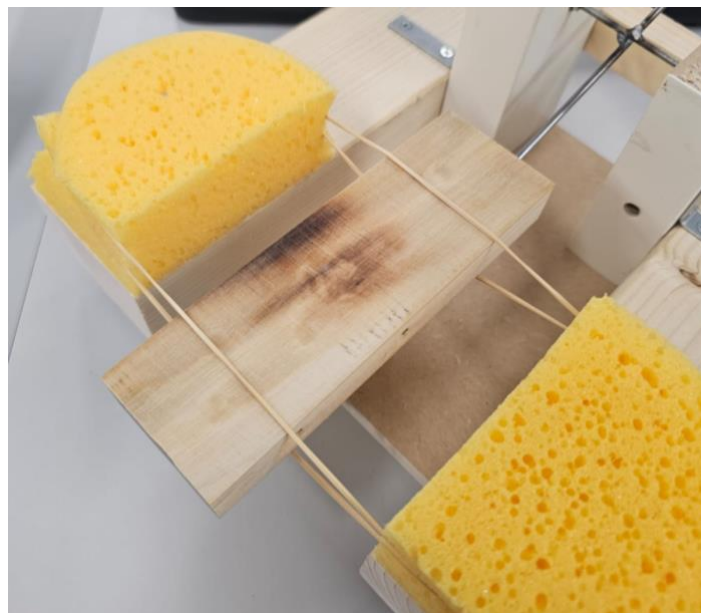


Figure E.3. Intermediate setup. Elastic bands added but foam blocks still in contact with the specimen sides, subsequently corrected.

The foam blocks were replaced by elastic bands stretched between nails fixed to the baseboard at the nodal point positions. Figure E.4 shows the final setup, which fully adopts the elastic band cradles at the nodal points.

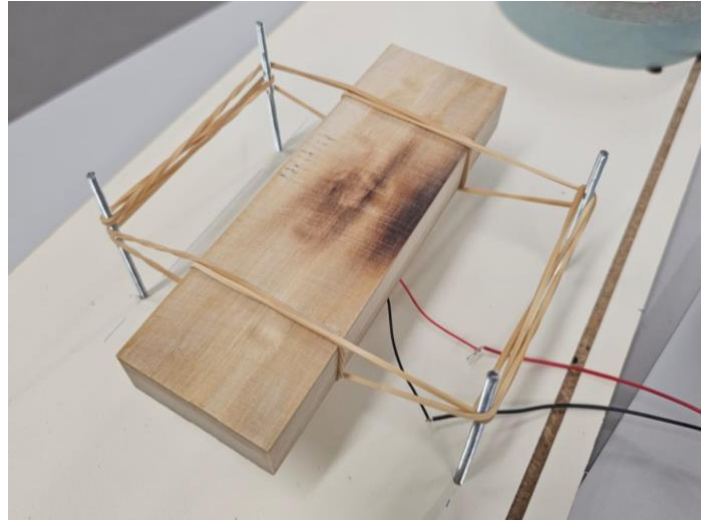


Figure E.4. Improved setup. Elastic band cradles at the nodal points (33.6 mm from each end), specimen floating freely, piezo wires routed without tension.

For a 150 mm specimen, the nodal points of the first flexural mode occur at 22.4% of the length from each end^{[44][45][46]}, giving positions of 33.6 mm from each end, the configuration required by ASTM E1876 Section 6.2. The specimen rests in two transverse elastic band cradles at these positions, which have much lower stiffness and smaller contact area than foam. This change removes the boundary condition error of the initial setup. The striking position was moved from the top face at mid span to the end face (as shown in Figure E.2), which excites the first flexural mode most efficiently.

E.5 Signal Analysis

E.5.1 Recording chain

The piezo disc fed a high impedance instrument input on an audio interface, recorded in GarageBand at 44,100 Hz.

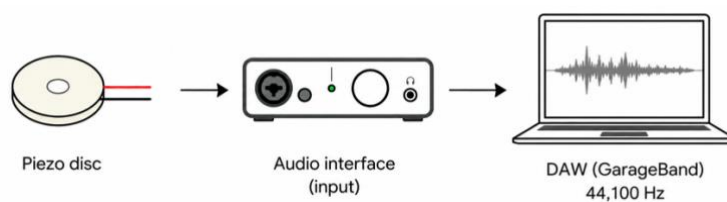


Figure E.5. The recording chain used for the tap tone measurements: a piezo disc contact sensor feeding the instrument input of an audio interface, recorded in GarageBand at 44,100 Hz.

E.5.2 Signal analysis parameters

Each recording was analysed with the following pipeline, stated here for reproducibility. A 4th order high pass filter at 80 Hz removed handling and other artefacts like contact noises. A one second segment from the tap onset was transformed with a Hanning window, giving a frequency resolution of about 1 Hz. The magnitude spectrum was lightly smoothed with a filter (Savitzky Golay - window length 31, polynomial order 3) before peaks were located.

The first flexural resonance was identified as the dominant peak in the frequency band predicted from the specimen geometry and stiffness, which for a 150 x 46 x 20 mm blank of this material falls near 3.5 to 5 kHz. Below about 600 Hz the spectra contain a cluster of peaks from the suspension and the piezo contact, which are not bending modes, so the flexural peak is chosen on physical grounds rather than simply as the tallest peak in the spectrum.

To understand how the material absorbs sound energy and sustains vibration, we analyze three key equations before comparing methods:

- **Acoustic Wave Velocity (v):** The speed at which dynamic mechanical waves propagate through the beam:

$$v = \sqrt{\frac{E}{\rho}}$$

where E is dynamic stiffness and ρ is density. Higher wave velocity indicates faster transmission of acoustic energy through the material.

- **Quality Factor (Q) & Damping Loss Factor (η):** Q represents how "purely" a material rings without losing energy. It is mathematically the inverse of the loss factor η :

$$Q = \frac{f_1}{\Delta f} = \frac{1}{\eta}$$

where f_1 is the resonant frequency and Δf is the frequency width of the resonant peak measured at half its maximum power (-3 dB points). A higher Q (lower η) means less energy is lost per vibration cycle.

- **Reverberation Decay Time (T_{60}):** The estimated time (in seconds) required for a sound vibration to die away by 60 dB (a reduction to 1/1000th of its original amplitude):

$$T_{60} = \frac{3 \ln(10)}{\pi \cdot f_1 \cdot \eta} \approx \frac{2.2}{f_1 \cdot \eta}$$

The damping and the harmonic content were estimated for the exploratory analysis in Section E.8. Each quantity is defined first by its equation, and then explained in plain terms.

These describe how the tap rings. The quality factor Q and the loss factor η measure the damping. A specimen that rings for a long time makes a tall, narrow peak and has a high Q and a low η , while one that dies quickly makes a broad, short peak with a low Q and a high η . The decay time T_{60} is the same idea seen in time rather than in the spectrum: how long the ring lasts.

Why two damping measurement methods are compared:

In theory, measuring damping by analyzing the **peak width in the frequency spectrum** (Half-Power Bandwidth) or by measuring the **time it takes for sound to die out** (Decay Time / T_{60}) should yield identical Q and η values for a clean, long-ringing material.

In our tests, however, these two calculation methods differed by a factor of 2 to 3 (Table E.4). Because the recorded tap sounds were very short (~100 ms) and rapidly faded into background

electrical noise, neither method could capture a perfectly clean ring down. Therefore, damping, T_{60} , and quality factor values are treated as **preliminary indicators** rather than absolute properties.

The harmonic ratio H_2/H_1 measures how strong the first overtone is compared with the fundamental. For a beam free at both ends the overtone sits at 2.76 times the fundamental, a fixed property of the shape rather than of the material. A soft mallet strikes gently and barely excites this overtone, so H_2/H_1 is close to zero in all three recordings and cannot be characterised here.

These are standard results. The full derivations are given in the modal testing and vibration literature^{[44][45]}, the overtone position follows from beam theory^[46], and the decay time form is the one used in room acoustics^[32].

E.6 Results: First Flexural Frequency

The measured first flexural frequencies and the corresponding densities are given in Table E.3, and the three spectra are shown together in Figure E.6.

Material	f_1 (Hz)	Density (kg/m ³)	Note
Hard maple, raw	4,299	710	Benchmark
Yellow poplar, raw	4,635	594	Highest f_1 , lowest density
Yellow poplar, 50%	3,792	942	Lowest f_1 , highest density

Table E.3. Measured first flexural frequency and density for the three materials. Values are from one clean tap per specimen ($n = 1$).

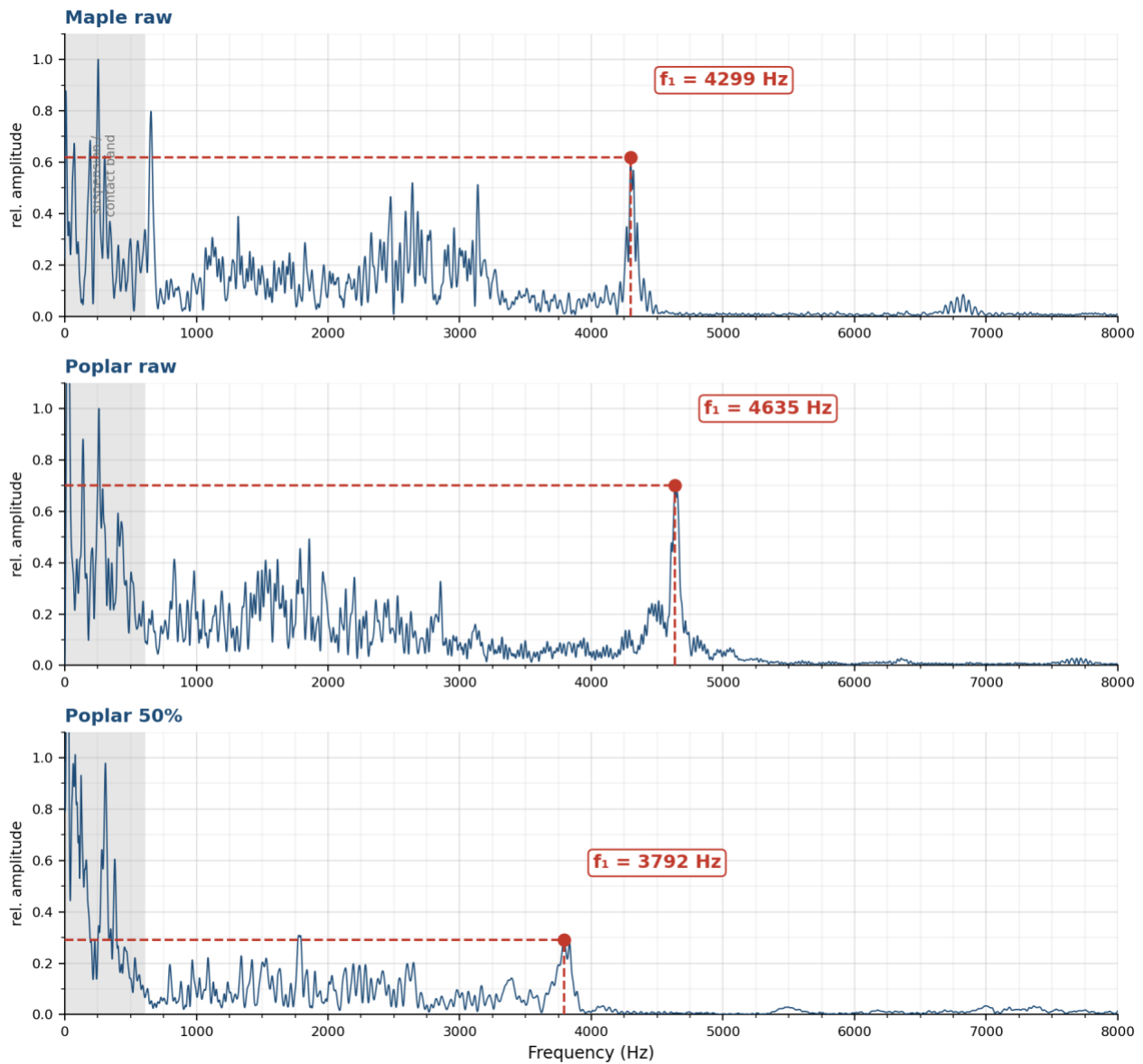


Figure E.6. Tap tone spectra of the three materials, shown as separate panels on identical axis scales, with the first flexural resonance marked on each. The shaded band below about 600 Hz contains suspension and piezo contact peaks, which are not bending modes and are excluded from the frequency identification.

Three points follow directly from Table E.3. Raw poplar has the highest first frequency and the lowest density, which is expected for a light, moderately stiff wood. Poplar 50% has the lowest first frequency, because compression raises its density faster than its stiffness, lowering the specific stiffness that f_1 tracks. Maple sits between the two. The interpretation for the modulus is developed in Section E.9.

E.7 Comparative Summary

Figure E.7 draws the measured properties of the three materials together as a comparative summary. Each axis is scaled to its own maximum across the three materials, so the chart shows the shape of the differences at a glance rather than absolute magnitudes. It is a visual overview of the results, not a trend analysis, since only two compression levels remain in the dataset.

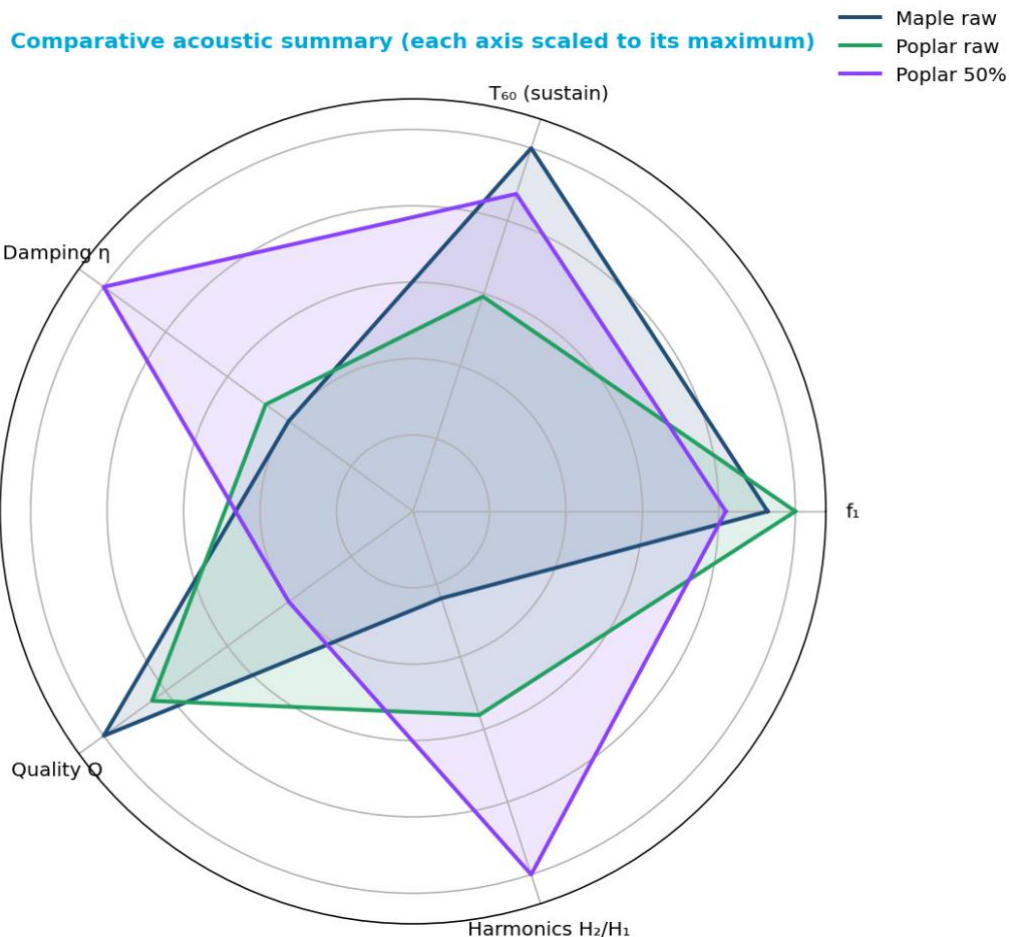


Figure E.7. Comparative summary of the three materials across first frequency, sustain (T_{60}), damping, quality factor, and harmonic content. Each axis is normalised to its maximum. The sustain, damping, quality, and harmonic axes use the preliminary values discussed in Section E.8 and should be read as indicative. Acoustic velocity is not shown, because at fixed geometry it is proportional to the first frequency and would duplicate that axis.

The overview shows the trade the compression makes. Poplar 50% sits lowest on first frequency and quality factor and highest on damping and harmonic content, reflecting its greater density and internal friction. Maple has the highest quality factor and the longest sustain, and raw poplar has the highest first frequency. This matches the numerical results and gives a quick read of where each material sits.

E.8 Exploratory Damping and Harmonic Analysis

The damping and harmonic content are presented here as a preliminary, exploratory analysis. They are reported because they are informative, but they are not put forward as settled measurements, for two reasons stated plainly at the start so the reader can weigh them accordingly.

- **Short recordings.** Each tap rings for only about 100 ms before decaying into noise, which is a short window for a damping measurement. When the damping is estimated two standard ways, the half power bandwidth and the decay time, the results differ by roughly twofold to threefold, so the absolute values are uncertain.

- **Weak overtones.** The first flexural overtone is close to the noise floor in all three spectra. The harmonic ratios are therefore near the limit of what can be measured and are indicative only.

With those caveats stated, Table E.4 gives the preliminary values from both methods.

Material	Q (half power)	Q (decay)	η (half power)	η (decay)	H_2/H_1
Hard maple, raw	119	70	0.008	0.014	~0
Yellow poplar, raw	101	44	0.010	0.023	~0.01
Yellow poplar, 50%	48	54	0.021	0.019	~0.02

Table E.4. Preliminary damping and harmonic values, from single taps by two methods. The disagreement between the two Q and η columns is itself the measure of their uncertainty. H_2/H_1 values are near the noise floor. These figures are indicative and should not be quoted as absolute damping properties.

The measurements place maple as the least damped and longest ringing of the three, consistent with its reputation as a sustaining tonewood, while the relative damping of the two poplars is not resolved by these recordings and the effect of densification on damping cannot be settled here. The absolute size of that difference is not resolved by these recordings, and there is scope left for future work with longer recordings and a firmer, calibrated striker.

E.9 Cross Check with the Bending Modulus

Because all specimens share the same geometry, the first frequency gives an independent estimate of the modulus that can be compared with the value measured directly in three point bending. From $f_1 \propto \sqrt{E/\rho}$, and anchoring on the measured maple properties, the inferred Poplar 50% modulus is:

$$E_{\text{Poplar 50\%}} = E_{\text{maple}} \times (f_{1,\text{Poplar 50\%}} / f_{1,\text{maple}})^2 \times (\rho_{\text{Poplar 50\%}} / \rho_{\text{maple}})$$

$$= 13.23 \times (3792 / 4299)^2 \times (942 / 710) = 13.66 \text{ GPa}$$

The directly measured static modulus of Poplar 50% is 12.23 GPa, so the acoustic estimate of 13.66 GPa sits about 12% above it. This is the physically expected direction. A modulus measured dynamically, from a fast vibration, is consistently higher than one measured in a slow static bend, because the static test includes a small amount of time dependent give that the tap does not. The maple shows the same effect: its first frequency implies a dynamic modulus of roughly 15.7 GPa against a static 13.23 GPa. So the two methods agree in ranking and sit in the expected relationship, which supports the bending result rather than contradicting it.

Note. The absolute dynamic modulus values are computed from a simple beam relation that does not correct for shear, which is not negligible for a bar this thick relative to its length. They are therefore indicative. The cross check itself relies on the ratio of frequencies at identical geometry, where that correction largely cancels, so the 12% agreement is more robust than the absolute figures.

E.10 Limitations

#	Limitation	Impact
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1	Single tap per specimen	f_1 is a repeatable property, so one clean tap is a fair estimate, but there is no standard deviation. Replication is recommended.
2	Adapted, non standard setup	Elastic band suspension and a soft mallet depart from ASTM E1876. Comparisons at identical geometry remain valid; absolute damping values do not.
3	Preliminary damping and harmonics	Short recordings and a soft mallet mean Q , η , and H_2/H_1 are indicative only (Section C.8). Longer recordings and a firmer striker are needed to measure them properly.
4	Moisture not matched for Poplar 50%	The raw materials were both at 8% moisture content, but the processed Poplar 50% was actively dried and its moisture was not measured, so comparisons involving it are suggestive (Section C.3.3).
5	Absolute dynamic modulus uncorrected for shear	The bar is thick relative to its length, so absolute dynamic modulus values are indicative; the frequency ratio cross check is more robust. The full set of limitations is collected in Table E.5.

Table E.5. Limitations of the current acoustic dataset.

E.11 Discussion and Conclusions

The acoustic testing gives one firm result and one useful cross check, with a preliminary look at damping.

- **First flexural frequency is measured cleanly.** Maple 4,299 Hz, raw poplar 4,635 Hz, and Poplar 50% 3,792 Hz. Poplar 50% rings lowest because compression raises its density faster than its stiffness.
- **The modulus cross check supports the bending result.** The first frequency infers a Poplar 50% modulus of 13.66 GPa, about 12% above the directly measured 12.23 GPa, in the expected dynamic above static direction. The acoustic and bending methods therefore agree that Poplar 50% is close to maple in stiffness.
- **Damping is explored, not settled.** Raw maple appears the least damped and Poplar 50% more damped, but the absolute values are not resolved by single short taps, and harmonic content cannot be characterised with a soft mallet. Both need better recordings.
- **Comparisons involving Poplar 50% are suggestive.** The processed material could not be conditioned to the 8% moisture of the raw blanks at workshop scale, so its comparisons should be read with that caveat.
- **Spruce is not part of the acoustic dataset.** It was excluded on mechanical grounds after brittle fracture under Janka indentation, documented in the Janka report.

Appendix F. Exploratory Acoustic Re-Characterisation: Reading the Tonewood Chart Against Published Data with Re-Analysed Measurements

This chapter is written as a process rather than a single result. The acoustic characterisation went through two distinct approaches, and the earlier one is kept here on purpose. It is not discarded, because the way it failed is what pointed to the corrected method, and that reasoning is itself a finding. The structure is therefore: the starting assumption and where it broke, the research into what governs tone, the deconstruction of a commercial tonewood chart against published data, the two candidate methods for measuring the speed of sound, and finally the corrected measurements on raw poplar, maple and Poplar 50%. The limitations of the first acoustic test are documented separately in Appendix B.

F.1 The starting assumption and where it broke

The first approach treated specific stiffness, the modulus of elasticity divided by density (E/ρ), as a proxy for tone. The reasoning was that specific stiffness sets the speed of sound in a bar, and the speed of sound is a recognised acoustic descriptor, so a wood with a higher specific stiffness should be the brighter, livelier material.

This broke on a simple internal check. When the candidate woods were placed on a specific stiffness axis, they fell into bands that did not line up with their known tonal character. Maple, universally treated as a bright wood, sat lower in specific stiffness than several woods that luthiers call warm. Mahogany and the light, soft woods such as basswood and yellow poplar carried a higher specific stiffness than maple, not a lower one, because their low density outruns their modest stiffness. If specific stiffness were the direct driver of brightness, basswood would be brighter than maple, which runs against the way these woods are described in the player and tone-chart literature. The proxy predicted the wrong order.

The conclusion was that specific stiffness, and by extension the bare speed of sound, does not appear to be the direct driver of perceived tone. It is more plausibly one input among several, and for a solid body it may not be the dominant one. That negative result is what motivated the rest of the chapter.

F.2 What governs tone: the parameter set

A review of the instrument acoustics literature identifies a small set of mechanical and vibrational parameters that together describe the vibrational behaviour of a wood, each derived from just two measured quantities, the modulus of elasticity and the density.

- The speed of sound, $c = \sqrt{E/\rho}$, sets the pitch of the wood's own resonances.
- The acoustic impedance, $Z = \rho c$, describes how stiffly the material anchors and transfers vibration, which for a solid body governs how firmly it loads the string.
- The radiation ratio, $R = c/\rho$, is the classic soundboard figure of merit and describes how efficiently a wood converts vibration into radiated sound; it rewards light, stiff material and falls steeply with density.
- The damping, expressed as the loss factor η or its reciprocal the quality factor Q , sets how quickly vibrational energy is lost, and because the upper partials fade first, it is the parameter most directly tied to brightness and to note clarity.
- Harmonic content ratios describe overtone richness.

The standard references for these relationships are Wegst^[13], Brémaud et al.^{[47][48]} and the Ono and Norimoto damping model^[49].

The important structural point is that brightness and crispness are two different questions. Brightness is a spectral property, how much high frequency content survives, and it is governed mainly by damping. Crispness is a temporal property, how sharply a note starts and how cleanly it is defined, and it is governed by how quickly the material delivers energy, which is impedance and radiation for the attack and damping for the decay.

F.2.1 The radiation coefficient and damping: the underlying physics

The radiation coefficient

The radiation coefficient R can be speculated as the material figure of merit for a tonewood. It is the radiated sound power a material delivers per unit of vibrational energy put into it, for plates tuned to the same pitch. It is a material index, not a property of a finished instrument. Its modern use traces to Wegst's review *Wood for Sound*^[13]. It is defined as $R = c / \rho$, which on substituting $c = \sqrt{E/\rho}$ becomes $\sqrt{E / \rho^{3/2}}$, so it rewards stiffness and penalises density steeply. The physical meaning the literature attaches to it is the potential average loudness and radiating efficiency of the material: how much sound a plate returns for a given energy input from the strings^[13]. A high R material, being light and stiff, radiates readily and responds to small inputs, which is why low density, high stiffness woods such as spruce score highly and are chosen for soundboards^[13].

This is confirmed quantitatively in recent open access work by Kim et al.^[50], who measure the same quantity, calling it the acoustic constant $A = c / \rho$, and state plainly that high elasticity and low density improve the acoustic properties, that a higher A enables greater sound radiation and projection, and that species of lower density typically show a high A , the key characteristic of instrument woods. In their measurements soft maple sat at an A of about 7.2 and lighter alder at about 9.1, and every treatment that lowered density raised A , with a strong inverse correlation between density and A ^[50]. On this evidence the radiation coefficient appears to bear more on loudness, projection and responsiveness, the crispness of response, than on treble colour as such.

Damping

Damping is a genuinely separate material property. The loss factor $\tan \delta$ is the tangent of the phase angle by which strain lags stress in a viscoelastic material.

Writing the complex modulus as $E^* = E' + iE''$, where E' is the energy stored and returned each cycle and E'' is the energy dissipated, $\tan \delta = E'' / E'$, and the fraction of vibrational energy lost per cycle is $2\pi \tan \delta$. For light damping it is the same number as the loss factor η , the reciprocal of the quality factor $1/Q$, and the normalised half power bandwidth $\Delta f / f_0$ from which it is measured in Section F.5^{[44][45]}. Unlike the tap frequency, it is a material constant at a given frequency and moisture content rather than a property of the specimen geometry, which is what makes it comparable across species. Brémaud et al.^[47] measured the loss factor $\tan \delta$ across 94 wood types from 76 species and confirmed the standard Ono and Norimoto relationship^[49], $\tan \delta = 10^{-A} (E/\rho)^{-B}$, in which damping falls as the specific modulus E/ρ rises. Crucially, that relationship explains only about 57 percent of the variation, the remainder being driven by extractives and moisture^[47], so damping is not merely a restatement of stiffness. The tonal link is explicit: violin top plate woods lie in the middle to low range of $\tan \delta$, and very low damping is required of a material that must ring for a long time^[47].

The mechanism connecting damping to brightness is that internal friction in the cell walls dissipates vibrational energy as heat, through viscoelastic hysteresis in the cell wall polymers (the lignin and hemicellulose matrix does not unload along the same stress strain path it loaded on, so the loop encloses an area and that area is the energy converted to heat each cycle), giving fast decay in high

damping wood and slow decay in low damping wood. Radiation is a separate loss channel, energy leaving the body as sound rather than as heat, and low damping wood also radiates more efficiently^[51]; a measured tap Q lumps internal friction, radiation and support losses together, which is why boundary conditions matter so much to the value obtained. Listening tests summarised by the same source report that players consistently prefer high and medium Q instruments and that no one prefers low Q, with spruce singled out because it combines low density, high stiffness and low damping^[51].

Why damping is likely to govern brightness

The step from damping controls decay to damping controls brightness rests on one broadly accepted point of acoustics. Even where the loss factor is treated as frequency independent, which the tap tone testing in this work found to be broadly correct across modes, a high partial completes more cycles per second than the fundamental, so at the same fractional loss per cycle it loses its energy faster in real time. Decay time in seconds is inversely proportional to frequency, and radiation losses also grow with frequency, so the upper partials always fade first and the tone darkens as the note rings out. A low damping wood lets those upper partials survive longer, which the ear reads as bright and clear; a high damping wood strips them quickly, which reads as warm and dark. Brightness can therefore be read as a statement about how long the treble content survives, with damping as the property most closely tied to it.

Acoustic conversion efficiency

The two combine into a single figure of merit, the acoustic conversion efficiency, $ACE = R / \tan \delta$, equivalently the radiation constant times the quality factor Q, written by Kim et al. as $A \times Q$ ^[50]. That number rewards exactly the pairing this work is concerned with: a high radiation coefficient together with low damping gives the loud, bright, responsive and sustaining instrument, and it is the best single comparator already listed in the test plan. Poplar 50% sits low on both inputs, about 64 percent of maple on R and, in the first foam supported measurements, roughly double maple's damping, so its ACE falls on both counts. It should be read together with the corrected measurement of Section F.5, where the clean rig revised the damping gap down to about a quarter above maple, making the penalty milder than the first figures implied, though still in the same direction.

Caveats for a guitar neck

Two caveats qualify all of this for the present application. First, almost all of the evidence is drawn from soundboard and acoustic instrument research, where the wood radiates the sound directly^{[13][47][50][51]}. The application here is a solid body electric guitar neck, where the pickups sense the string rather than radiated wood sound. The wood is not therefore acoustically silent: it is what the string is anchored to, and the neck and body form the boundary the string terminates into, so their stiffness and damping feed back into how the string itself vibrates and decays. The influence is real but indirect, which is why the perceptual weight of R and $\tan \delta$ is genuinely contested for this case, and they should be framed as material acoustic descriptors rather than guaranteed audible outcomes. Second, the radiation coefficient's link to loudness is itself only a potential^[51], because real instrument loudness depends heavily on body, bracing and construction, and some dense soundboards are famously loud despite a low R. The material properties set the tendency, not the verdict.

F.3 Deconstructing the tonewood chart against published data

To test which parameters actually move with the perceptual axes, the woods on a commercial electric guitar tonewood chart (Figure 5.1, warm to bright horizontally, muddy to crisp vertically) were looked up in the USDA Wood Handbook^[14]. Density at twelve percent moisture and the modulus of elasticity were taken from Table 5-3b, and the derived acoustic parameters were computed from those two

inputs. Table F.1 lists the ten of the twelve chart woods that appear in the handbook; koa and korina are not tabulated and are omitted. Measured Hard Maple, Yellow Poplar (Uncompressed) and Poplar 50% is also included in the table.

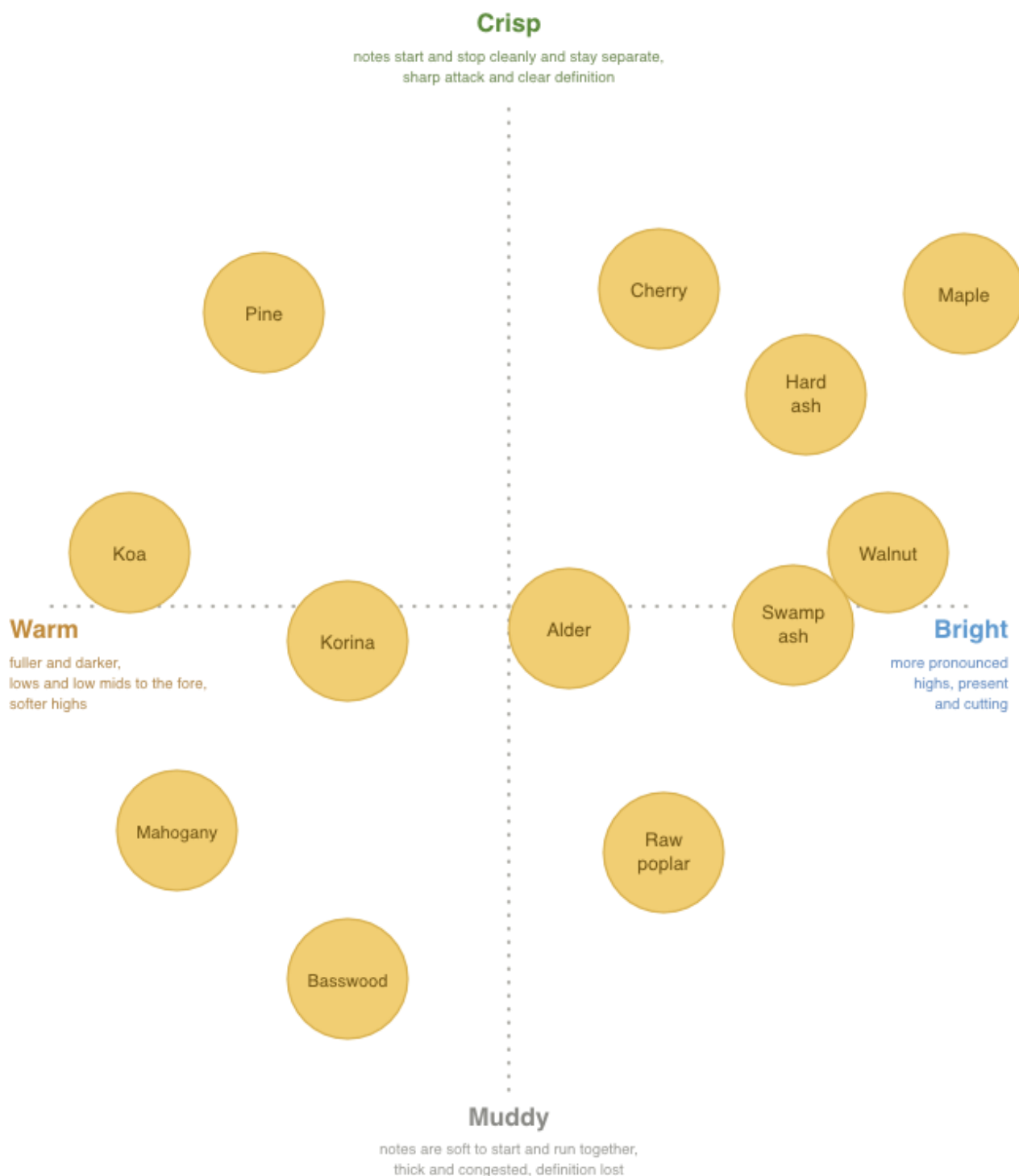


Figure 5.1 (repeated from Section 5.2). The perceptual tonewood map, warm to bright across and crisp to muddy up the side, with common electric guitar woods placed from player and luthier descriptions.^{[33] [34] [35]} The map shown here is not a reproduction of a published chart: it was redrawn by the author, traced from and informed by the tonewood map in the *Andertons Music Co. electric guitar tonewood guide*^[33], which cannot be used directly in this thesis.

Wood	Density, ρ (kg/m ³)	Modulus of elasticity, E (GPa)	Speed of sound, c (m/s)	Specific stiffness, E/ ρ (MJ/kg)	Radiation ratio, R (m ⁴ /(kg·s))	Acoustic impedance, Z (MPa·s/m)
Maple (hard)	706	12.62	4229	17.88	5.99	2.98
Hard ash (white)	672	12	4225	17.85	6.29	2.84
Walnut (black)	616	11.58	4336	18.8	7.04	2.67
Cherry (black)	560	10.27	4283	18.34	7.65	2.4
Swamp ash (black)	549	11.03	4483	20.1	8.17	2.46
Mahogany (Swietenia)	504	10.34	4530	20.52	8.99	2.28
Poplar (yellow)	470	10.89	4812	23.16	10.23	2.26
Alder (red)	459	9.51	4552	20.72	9.91	2.09
Basswood	414	10.07	4929	24.29	11.89	2.04
Pine (E. white)	392	8.55	4670	21.81	11.91	1.83
Maple (measured)	710	13.23	4316	18.63	6.08	3.06
Raw poplar (measured)	594	12.67	4618	21.32	7.77	2.74
Poplar 50% (measured)	942	12.23	3603	12.98	3.83	3.39

Table F.1 USDA Wood Handbook density and stiffness for the tonewood chart species, with derived speed of sound c , specific stiffness E/ρ , radiation ratio R and acoustic impedance Z . Units are given in the column headings.

The three shaded rows are the measured blanks from this work rather than handbook species: densities are measured, the maple and Poplar 50% moduli are the three point bending results, and the raw poplar modulus is inferred from its tap frequency ratio to maple at matched geometry. Derived quantities in these rows follow the same formulae as the handbook rows.

Each wood was then placed on the chart's two axes, and the correlation of every parameter with each axis was computed. The correlation strength runs from +1, meaning the parameter climbs perfectly as you go right or up, through 0, meaning no link, to -1, meaning it falls as you go right or up. The result, summarised in Table F.2, is clear and in one respect counterintuitive.

Parameter	Correlation with BRIGHT (left to right)	Correlation with CRISP (bottom to top)
Density, ρ (kg/m ³)	+0.83 (rises)	+0.54 (rises)
Modulus of elasticity, E (GPa)	+0.79 (rises)	+0.21 (weak)
Acoustic impedance, $Z = \rho c$ (MPa·s/m)	+0.83 (rises)	+0.43 (rises)
Speed of sound, c (m/s)	-0.68 (falls)	-0.77 (falls)
Specific stiffness, E/ ρ (MJ/kg)	-0.68 (falls)	-0.77 (falls)
Radiation ratio, $R = c/\rho$ (m ⁴ /(kg·s))	-0.80 (falls)	-0.56 (falls)

Table F.2 Correlation of each parameter with the two perceptual axes. Positive means the parameter rises toward bright or crisp; negative means it falls.

The warm to bright axis is a mass and stiffness axis. Density, stiffness and acoustic impedance all rise together toward the bright side; the dense, hard woods such as maple and ash are the bright ones, and the light, soft woods such as basswood and mahogany are the warm ones. With data taken from published tonewood comparisons considered here, density and impedance give a more plausible first-order description of the warm to bright axis ordering than specific stiffness alone. The muddy to crisp axis is the same family but appears weaker, and it is only partly explained by the handbook data, because its real driver is damping, which the handbook does not tabulate.

The counterintuitive part supports the reading put forward in Section F.1. Specific stiffness, the bare speed of sound and the radiation ratio all run backwards on this chart: they are highest for the warm, light woods and lowest for the bright, dense ones. The very quantity the first approach used as a brightness proxy is anti correlated with brightness for solid bodies. The reason is that these are solid body electric woods, where the body barely radiates sound, so the soundboard figure of merit is likely to carry little weight, and perceived brightness plausibly tracks how the body loads the string, which is mass and impedance.

F.4 Measuring the speed of sound: two methods

Two routes to the speed of sound were considered. The engineering route computes it from the static modulus and density, $c = \sqrt{E/\rho}$, using the three point bending result. The acoustic route, following the luthier tap tone method informed by the paper- L. Jost [\[52\]](#), excites the first longitudinal mode of a bar and reads its frequency f from an FFT, giving $c = 2Lf$, from which a dynamic modulus follows as $E = \rho c^2$. The physical basis of this method, and the simple tabletop experiment on which it rests, are drawn from [\[52\]](#).

The two are the same physics but not interchangeable in practice. The static route uses a bending modulus, which reads slightly low because of shear and machine compliance, so it is a lower bound. The tap route requires the longitudinal mode specifically, excited by tapping the end of the bar with the sensor at the far end and the piece held at its centre, where the longitudinal mode has its node. It cannot be applied to a bending resonance.

This distinction resolved a persistent confusion. The tap frequencies recorded in the first acoustic test were flexural resonances, measured with the sample suspended at its bending nodes (22.4 percent from each end) and the sensor at the centre antinode. That configuration is ideal for the bending mode but blind to the longitudinal one, so it can never yield a $c = 2Lf$ value; the piezo sits at the exact position where longitudinal motion is zero. Furthermore, the neck scale blanks are stubby, with a span to thickness ratio near 7.5, far below the slender bar assumption, so the bending frequency cannot be converted into a reliable modulus either. The tap test as configured is therefore valid for damping and for comparing bending frequencies between identical blanks, but not for an absolute speed of sound. For absolute values the density and static modulus route is retained, giving $c \approx 3600$ m/s for Poplar 50% and $c \approx 4300$ m/s for maple.

F.5 The corrected measurement and results

The same recordings were re-analysed at a 131072 point FFT so that the resonance peak is resolved to better than half a hertz. No new taps were made. The finer resolution changed which peak is identified as the first flexural mode for the two poplar specimens: at the original resolution, and after the Savitzky Golay smoothing applied to it, the resonance in the 3.5 to 5 kHz band presented as a single broad maximum, and the value read from it was not in every case the true fundamental. The revised frequencies below therefore supersede the earlier ones as readings of the same recordings, and the earlier values are best understood as peak identification errors rather than as a second, disagreeing measurement. Because the geometry is identical, the ratio of tap frequencies is the ratio

of specific stiffness, and hence of speed of sound, with the geometry cancelling. The damping was taken from the half power width of the peak. Table F.3 gives the result.

That reading is supported by the pattern of the revisions themselves. Maple, the sharpest and least damped peak of the three at $Q = 61$, moved by 1 Hz, from 4,299 to 4,298 Hz. Raw poplar, at $Q = 50$, moved by 39 Hz. Poplar 50%, the broadest peak at $Q = 48$, moved by 111 Hz. The size of the revision scales inversely with peak sharpness, which is what peak identification error on a broad resonance predicts, and the two poplar values moved in opposite directions, which rules out a systematic bias in the analysis chain.

Sample	Density, ρ (kg/m ³)	Tap frequency, f (Hz)	Quality factor, Q (–)	Loss factor, η (–)	Relative speed of sound, c (maple = 1.00)	Relative radiation ratio, R (maple = 1.00)
Raw poplar	594	4596	50	0.0198	1.07	1.28
Maple	710	4298	61	0.0165	1.00	1.00
Poplar 50%	942	3903	48	0.021	0.91	0.68

Table F.3 Measured acoustic parameters, same rig, same size, re-analysed from the original tap recordings at 131072 point FFT resolution. Relative speed and radiation ratio normalised to maple = 1.00; damping η and Q from the –3 dB half power width of the tap peak.

Three observations follow, and together they call into question the impression left by the first test.

First, damping is low for all three and densification barely changes it: raw poplar 0.0198, Poplar 50% 0.0210, a rise of only about six percent for a fifty percent compression, and Poplar 50 percent sits only about a quarter above maple's 0.0165. This is far below the near two to one gap the first test reported, a gap most likely attributable to its foam supports rather than to a property of the wood. On damping, densified poplar sits close to maple.

Second, the relative speed shows raw poplar slightly faster than maple and densification lowering it by about fifteen percent, leaving Poplar 50% at ninety one percent of maple, close but a little slower.

Third, the radiation ratio is the parameter that trails most: raw poplar sits above maple, but densification brings it down to sixty eight percent of maple, largely because the density nearly doubled while the stiffness barely rose.

The through line appears to be that the acoustic cost of densification runs mainly through density. Density drives the radiation ratio down and pulls the speed down, while the damping, the parameter that would actually make the wood sound dull, stays low. Densified poplar appears to retain maple like internal damping, and on these measurements the main remaining acoustic gap to maple is excess mass.

One further consequence follows for the stiffness estimate. Because the three blanks share geometry, the ratio of first flexural frequencies gives a dynamic modulus for Poplar 50% when anchored on the measured maple static modulus and the measured densities: $E = 13.23 \times (3903 / 4298)^2 \times (942 / 710) = 14.48$ GPa. This supersedes the 13.66 GPa given in Section 4.5.1, which was computed from the superseded 3,792 Hz reading. The revised figure sits about 18 percent above the directly measured static value of 12.23 GPa, rather than the 12 percent previously reported. The direction is unchanged and still the expected one, since a modulus inferred from a fast vibration reads higher than one from a slow static bend, but the margin is now wider. For the reason set out in Section F.4 the absolute value should be read as indicative only: blanks are too stubby for the slender bar assumption and no shear correction has been applied. The frequency ratio at matched geometry remains the more robust quantity, and on the revised reading it continues to place Poplar

50% close to maple in bending stiffness, which is the conclusion the bending test independently supports.

F.6 Interpretation and process implication

The structural side of this is captured by the impedance and stiffness map (Figure F.1), which places the three measured blanks against the USDA reference woods: densification pushes poplar up and to the right, into the dense, stiff region near maple. The tone side is captured by the radiation ratio against damping plot (Figure F.2), where the densification path runs almost straight down, radiation lost while damping stays put.

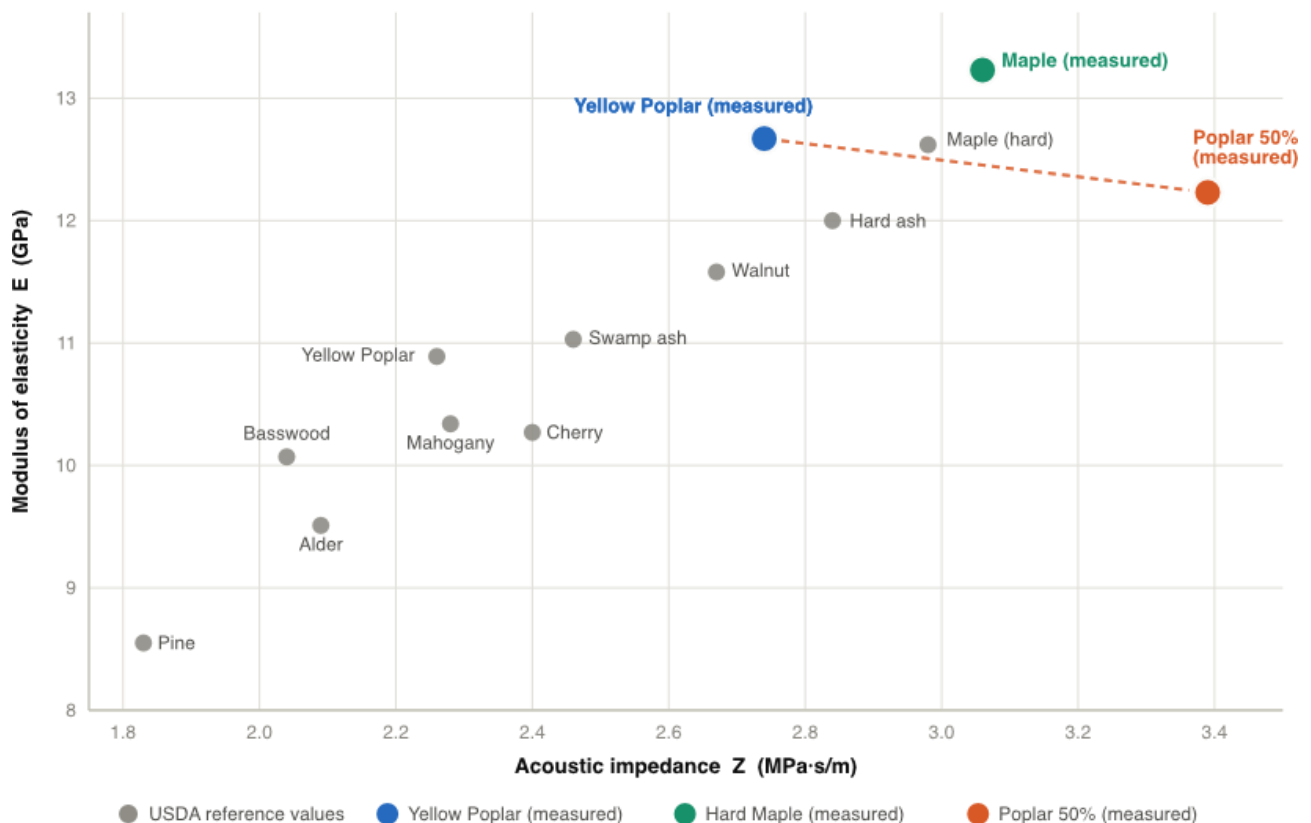


Figure F.1 Impedance versus stiffness. Reference woods (USDA) in grey; the three measured blanks highlighted, with the measured densification arrow from Yellow Poplar to Poplar 50%.

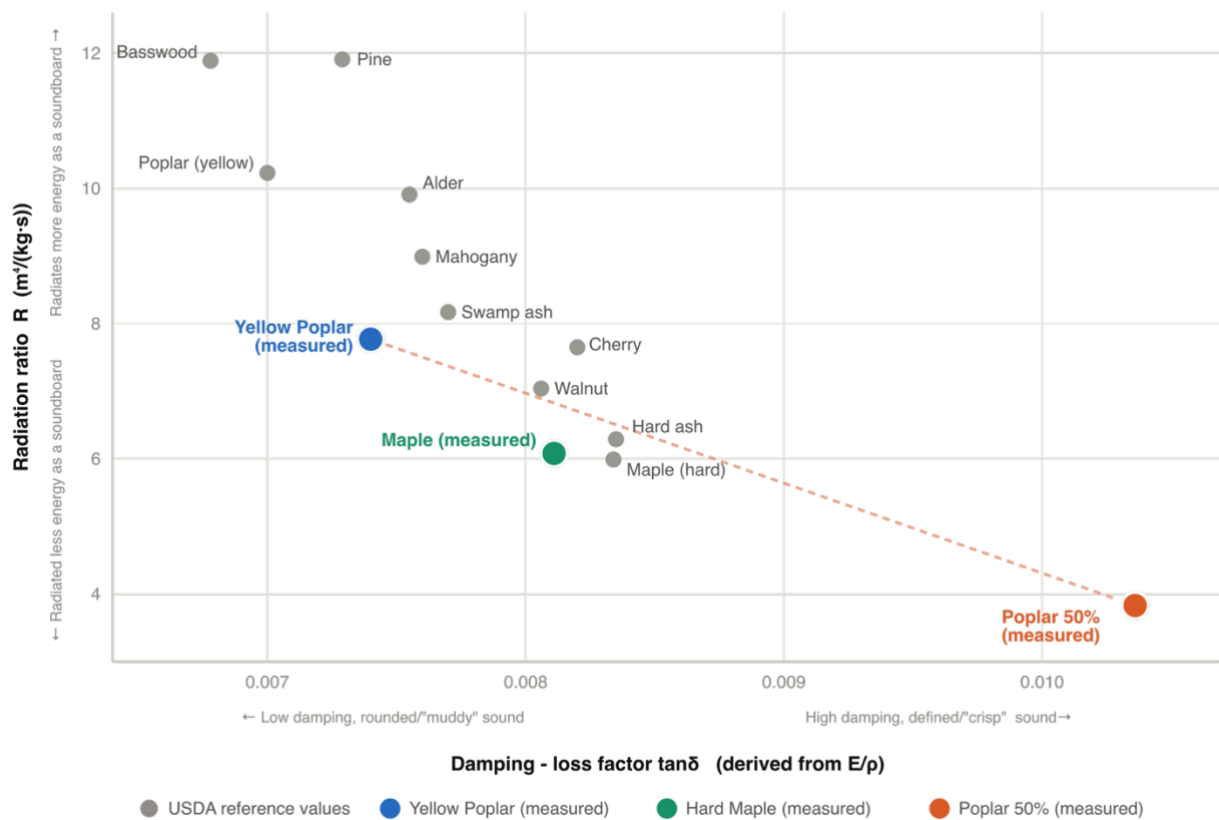


Figure F.2 Radiation ratio versus damping (measured, same rig). Densification drops the radiation ratio and increases damping.

Placed back on the perceptual chart itself (Figure F.3), the measured Poplar 50% lands in the bright, crisp region near maple, not in the warm, muddy zone where generic poplar sits, because it is dense and hard and its damping is low (indicative, not validated).



Figure F.3 The tonewood chart with the measured blanks placed by data: brighter to the right with higher impedance, crisper upward with higher Q. Measured Poplar 50 percent lands in the upper right quadrant, a distinct difference from Raw Poplar (indicative, not validated).

Because the whole acoustic penalty is excess density rather than damping, the process implication is direct. Reducing the compression from fifty percent toward about a third would bring the density back down from 942 toward maple's 710 while, on the evidence here, leaving the already low damping untouched and recovering much of the lost speed and radiation. This reinforces the compression window recommendation developed elsewhere in this work and is now supported by measured acoustics rather than inference.

F.7 Relationship to the earlier acoustic work

The first acoustic test is retained in the thesis as the initial characterisation attempt. Its ranking of conditions remains internally valid, but first flexural frequencies and the absolute damping values are superseded by the corrected measurement, and its use of specific stiffness as a tone proxy is corrected by Section F.3. The specific methodological faults, the foam boundary damping, the flexural versus longitudinal confusion, the coarse FFT resolution and the stubby specimen geometry, are documented with their corrections in Appendix B, which functions as a standalone correction note to the original acoustic report.

Note. The acoustic parameters, comparisons and placements developed in this appendix are speculative. They are built on published data and studies, on handbook values for the reference species and on material figures of merit drawn from the instrument acoustics literature, and they have not been experimentally validated in this thesis. The measured tap tone and bending results anchor the density and stiffness figures, but the tonal readings that follow from them, the positions on the perceptual chart and the inferred consequences for a finished neck remain indicative rather than demonstrated, and require the listening and instrument level validation set out in the recommendations.