

Modifying the radiation ratio of tonewoods through wood degradation

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Research Article

Keywords: improved radiation ratio, wood degradation, heat treatment, fungal exposure, sodium treatment

Posted Date: April 22nd, 2024

DOI: <https://doi.org/10.21203/rs.3.rs-4280659/v1>

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Additional Declarations: No competing interests reported.

Abstract

This work investigates different wood modification techniques to modify the acoustical properties of tonewoods, in particular the sound radiation ratio (R). The treatments used were heat- and fungal exposure, as well as immersion into NaOH and Na₂SO₃ solution and a combination of the most successful treatments. All initial experiments were performed on pine (*Pinus patula*) due to cost factors, before replicating the best performing treatment on high quality spruce tonewood (*Picea abies*). The main objective was to reduce the hemicellulose content without severely degrading cellulose, which results in a reduction of density, while maintaining, or even improving the elasticity (MOE_L), which results in an increase of R. Overall, the combined heat-fungal and heat-sodium treatments performed best and increased R by up to 20%. Sodium treatment led to the best increases in R, but compromised the wood structure in spruce and the treatment protocol needs to be developed further. Consequently, the most successful wood treatment to improve acoustical properties was determined to be exposure to white rot combined with heat treatment.

1. INTRODUCTION

For centuries luthiers strived to enhance the sound quality of their musical instruments. Some copied the methods and techniques of their predecessors, while others tried new techniques, but the results were not always successful. This endeavour continues today as luthiers are trying to understand why some of the older instruments have a better sound quality. Most of those attempts were directed towards the violin.

Wood used to manufacture instruments is referred to as tonewood, or resonance wood. The quality of the produced sound depends on the elastic properties of the wood and how well it can oscillate. The sound quality of tonewoods can be best described through the radiation ratio (R) which is defined as $R = \sqrt{\text{MOE}/\rho^3}$. A significant difference can be observed between high- (15) - and low- (9) quality soundboards. Some of the famous Stradivari violins have R-values reaching 16 and above, whereas even the best quality modern violins tend to reach a maximum R of 12–15. The reason that old instruments have a much higher R value can only be explained by partial wood degradation, which reduced the density, without affecting the MOE, or speed of sound, too much. Various attempts were made to improve the sound quality of wood through artificial ageing. The ones showing the most promise is heat treatment and fungal degradation (Danihelová et al. 2022; Rang et al. 2016; Zhu et al. 2016). Previous studies have shown that the most important wood characteristics for good sound quality are MOE – which directly affects the speed of sound - and ρ (Zerbst et al. 2018). An increase in the MOE and lowering of ρ results in a higher R value. Soundboards easily transmit vibrations to the edges and are good sound radiators and typically have a low ρ and high MOE with a high sound radiation ratio and tend to resonate lower frequencies much clearer and louder than other wood species (Yoshikawa, 2007 and 2014).

Various attempts were made to improve the sound quality of wood through artificial ageing i.e., heat treatment and fungal degradation (Daniehelová et al., 2022; Rang et al., 2016; Zhu et al., 2017). Previous studies have shown that the most important wood characteristics for good sound quality are MOE – which directly affects the speed of sound - and ρ (Zerbst et al., 2018). An increase in the MOE and lowering of ρ results in a higher R value.

In previous studies it was observed that low and moderate thermal exposures (110°C– 175°C) do not change acoustic properties significantly (Gadd and D'Arcy, 1986; Zerbst et al., 2018). Thermal treatment between 160°C and 220°C was found most suitable to degrade hemicelluloses and lignin, as desired for acoustic changes (Esteves and Pereira, 2009; Výbohová *et al.*, 2018; Zerbst et al., 2018), because at these temperatures the desired density decrease is obtained. At temperatures above 250°C cellulose chains start to degrade, which then also affects the MOE. However, exposure to high temperatures for a short time may prove to be beneficial in improving the acoustic properties and was included in this experiment.

Obataya (2017) studied the effect of artificial hydrothermal ageing on the acoustic properties of wood. Treatment between 1 and 7 days at a RH of 57–64% was found to increase the specific dynamic Young modulus (E'/ρ) and decrease $\tan(\delta)$, which indicates that heating at intermediate RH can improve the acoustical properties.

Schwarze et al. (2008) discovered the presence of fungi, such as *Physisporinus vitreus* and *Xylaria longpipes* in the soundboard of old violins, which led to a decrease in hemicellulose content that might be responsible for the higher radiation ratio. Fungal degradation is a possible approach for the improvement of acoustical properties in wood, as the degradation of polysaccharides, such as hemicelluloses and lignin can have a positive effect on the acoustic properties. Fungi are known to deposit large amounts of organic acids as part of their natural metabolism that accumulate as oxalate salts along their hyphae. These salts form crystalline structures along the hyphae (Cromack et al., 1977), which leads to an increase in c and MOE_L . These findings suggest that extended incubation periods with fungi can improve c up to a point where degradation of the cell wall occurs. It can therefore be concluded that the appropriate fungus capable of secreting a large amount of oxalate salts will improve acoustic properties of wood.

Wood degrading fungi are typically grouped into white rot and brown rot, depending on the wood components they attack. White rot fungi degrade cellulose, hemicellulose and lignin, while brown rot degrades only hemicellulose and cellulose. The main objective of this study was to decrease the wood density by removing hemicelluloses and part of the lignin, without compromising the strength provided by the cellulose. Therefore, the effect of degradation caused by both brown and white rot fungi was analysed.

Not much research exists dealing with chemical treatment of sodium hydroxide (NaOH) and sodium sulfite (Na_2SO_3) for improvement of acoustical wood properties. The selection of these two compounds

for this study is based the fact that recent studies found high levels (1000 ppm) of Na and other elements (e.g., K, Cl, Ca, Cu and Zn etc.) residing in the cell wall structure of violins made from Stradivari and Guarneri (Taia et al., 2017; Su et al., 2021). A further assumption is that timber companies made use of salt as preservative in the waterways used to move logs, which could have, at some point, had a positive implication on the chemical structure of musical instruments (Gug, 1988). The above findings suggest that some minerals added via chemical or preservative treatment may have been used that improved the acoustical properties of historical musical instruments over time. Studies have found that alkaline treatment increases the crystallinity index of cellulose (Xu et al., 2020), which might result in improved acoustical properties.

Both sodium compounds were found to reduce the density of wood by degrading hemicellulose and lignin, while leaving the cellulose intact (Wachter et al., 2019; Li et al., 2021). Compared to acids (i.e., H_2SO_4), alkaline solutions do not damage the S2-layer, but loosen the middle lamella, where the largest proportion of hemicellulose resides especially, if combined with thermal treatments of 100°C and 120°C. Moreover, the combination of the two compounds was found to degrade hemicellulose more effectively (Maturana et al., 2022; Kim et al., 2020).

The benefits of an increased crystallinity index of the cellulose were shown to improve the acoustical properties of wood (Miao et al., 2021; Wang et al., 2019). This implies that any substance capable of increasing the crystallinity in wood may have a beneficial impact on the vibro-acoustical properties of wood, as soundwaves can move more easily through a crystalline structure than amorphous materials. NaOH was found to improve the crystallinity index of cellulose by selectively removing amorphous hemicellulose (Qi et al., 2023; Barman et al., 2020). However, alkaline treatments may decrease the crystallinity in wood at higher concentrations and longer exposure times (Xu et al., 2020; Nakano, 2010).

The aim of this study is to modify and improve the acoustic properties of wood through various treatments: heat treatment, fungal exposure, UV exposure, sodium hydroxide (NaOH) and sodium sulphate (Na_2SO_3) treatment. These treatments are expected to decrease the hemicelluloses, lignin and extractive content and therefore the density of wood, without significantly altering the MOE and therefore improve R.

2. MATERIALS AND METHODS

2.1 Wood

Radially cut pine (*Pinus patula*) samples were used to determine the most suitable treatment, which was then repeated on tonewood spruce. The wood was cut from the sapwood part of boards originating from mature trees. Density, moisture content (MC) and the speed of sound (c) were measured before and after treatment. Sample sizes were 150 x 55 x 20mm for heat treatment, 60 x 20 x 15mm for fungal exposure, and 60 x 40 x 20mm for sodium, treatment. The sample sizes were different to accommodate the different exposure environments. For the sodium and fungal exposure samples smaller samples are

required to ensure full saturation / coverage. All samples were stored for at least one month in a conditioning room at 65% RH and 20°C, before analysis and all measurements were performed at least in triplicate.

High quality spruce (*Picea abies*) tonewood was obtained from a luthier in Pretoria, South Africa (Hannes Jacobs) and used to determine if the successful changes in acoustical properties of the optimum treatment could be transferred between wood species.

2.2 Treatment methods

Thermal treatment was performed in an oven at temperatures of 160, 180, 200, 230 and 250 °C for times ranging from 5 minutes to several hours. For temperatures above 200°C, the wood blocks were wrapped in aluminum foil to prevent surface discolouration and charring. The experimental procedure was as follows: 160–200°C for 1 to 8 h, 230°C for 10-, 30 min and 1 h and 250°C at 5-, 15-, 30 min and 1 h. The high temperatures were chosen to ensure that hemicellulose degradation took place.

Sixteen samples were exposed to brown rot (*Laetiporus sulphureus*) and white rot (*Schizophyllum commune*), respectively. To keep the fungus alive, the samples were placed in closed plastic containers with paper towels, which were wetted on a weekly basis. To obtain a successful spread rate, separate pine samples were pre-exposed for 8 months to start the fungal activity. The pre-exposed samples were then placed together with the treatment samples and left for incubation of 1, 2, 6 and 20 weeks. Five samples were removed for each exposure time, the fungus was scraped off and the wood was carefully dried in an oven at 40°C for 24 h.

For chemical treatment in saline solution, samples were fully submerged in NaOH and Na₂SO₃ for 8, 24, 48, 72, 120 and 168 h. Four samples were removed for each exposure time and washed in distilled water for 24 h to remove any excess NaOH and Na₂SO₃, before drying in an oven at 100°C for 24 h. Samples were also exposed to a combined NaOH + Na₂SO₃ solution for 8, 24, 48 and 72 h.

After treatment all samples were stored in a conditioning room for 2 weeks before measuring their acoustical properties to ensure that the physical changes are not just temporary. All measurements were performed at least in triplicate.

2.3 Measurement of physical properties

The speed of sound (*c*) was determined with a Lucchi meter, which determines the time an ultrasound pulse requires to travel from the emitter to the receiver to determine *c* in m/s. *C* was measured along the grain at three different locations for each piece of wood. The length and MC of the wood need to be input into the instrument beforehand to obtain correct values for *c*. The average of the three measurements along each sample was used to calculate *R*.

To determine the MC, 5 pieces were cut from each board and the MC determined with the equation:

$$MC (\%) = 100 * (m - m_0) / m$$

The density was determined before and after each treatment after conditioning the samples for 2 weeks at 20°C and 65% RH by weighing the sample and calculating the volume.

R was calculated according to its definition by Schelleng (1982):

$$R = c / \rho$$

Bucur (1987) showed that the specific dynamic Young modulus (MOE/ρ) can be derived from ultrasonic speed of sound measurements and MOE_L was accordingly determined by:

$$MOE_Y = c * \rho$$

2.4 Combined treatment approach

The treatments that showed the largest improvement in R - in this case treatment with white rot (*S. commune*) and NaOH solution – were combined with the heat treatment that had the largest improvement in R (one hour at 250°C).

The most successful combined treatment was repeated on spruce tonewood, and the wood samples were prepared and treated in the same way as described above.

2.5 Representation of results and statistical analysis

The distribution of data was checked for normality with the *Shapiro-Wilk* test. The statistical analysis result was determined through a *Kruskal-Wallis* test, followed by a post-hoc *Dunn's* test to determine significant differences indicated by different letters. The significance level was $p = 0.05$.

All results are presented as average values with error bars depicting the standard deviation. All graphs were plotted with *OriginLab*.

3. RESULTS AND DISCUSSION

The following graphs show the change in R after treatment. A positive ΔR correlates to an improved value of R, which means that the treatment was successful in decreasing the density without affecting the MOE considerably.

3.1 Heat treatment

Figure 1 shows that lower exposure temperatures slightly reduced R, which is not desirable to improve the acoustic properties. Furthermore, the exposure time did not have any statistically significant effect on ΔR for temperatures below 200 °C. However, the effect of exposure time on R becomes noticeable above 200°C with the largest difference between exposure times at 250°C. The largest improvement in R of 8% was obtained after exposure to 250°C for 1 h.

The improvement in R can be linked to a decrease in ρ while maintaining or increasing MOE, as highlighted in Table 1.

Table 1 changes in ρ , c, MOE_Y and R as function of the exposure temperature. Treatments that reduced ρ and maintained or improved MOE_Y are highlighted

T (°C)	t (h)	$\Delta \rho$ (%)	Δc (%)	$\Delta \text{MOE}_{\text{sd}}$ (%)	ΔR (%)
160	1	-1.22 ± 0.40	-0.76 ± 0.71	-2.71 ± 1.60	0.47 ± 0.67
	2	-1.18 ± 0.54	-1.80 ± 1.65	-4.67 ± 3.44	-0.62 ± 1.54
	6	-1.09 ± 0.55	-1.71 ± 4.07	-6.86 ± 4.30	-0.64 ± 3.63
	8	-1.53 ± 1.74	-2.84 ± 1.38	-7.01 ± 3.58	-1.31 ± 1.85
180	1	-1.13 ± 0.45	-1.74 ± 2.02	-4.51 ± 4.13	-0.62 ± 1.86
	3	-0.87 ± 0.88	-3.02 ± 1.22	-6.75 ± 2.64	-2.16 ± 1.38
	6	-2.34 ± 1.16	-3.63 ± 0.98	-9.28 ± 2.71	-1.32 ± 0.82
	8	-2.25 ± 0.23	-3.28 ± 0.80	-8.56 ± 1.43	-1.05 ± 0.94
200	1	0.01 ± 0.52	-5.60 ± 2.33	-10.84 ± 4.21	-5.60 ± 2.59
	3	-1.04 ± 1.43	-4.44 ± 2.38	-9.56 ± 5.25	-3.44 ± 2.02
	6	-2.44 ± 1.59	-5.54 ± 3.26	-12.81 ± 7.21	-3.20 ± 2.23
	8	-2.57 ± 0.73	-5.74 ± 2.17	-13.37 ± 4.53	-3.26 ± 1.67
230	0.17	-0.09 ± 0.13	-2.52 ± 1.63	-5.04 ± 3.09	-2.42 ± 1.70
	0.5	-1.17 ± 0.31	-2.43 ± 3.73	-5.81 ± 7.30	-1.28 ± 3.68
	1	-3.06 ± 1.58	1.16 ± 0.92	-0.82 ± 1.2	4.38 ± 2.50
	2.5	-3.54 ± 2.24	3.27 ± 0.83	2.90 ± 3.50	7.09 ± 2.17
250	0.08	0.15 ± 0.06	-2.95 ± 1.17	-5.66 ± 2.29	-3.09 ± 1.15
	0.25	0.06 ± 0.41	-1.66 ± 1.41	-3.23 ± 2.57	-1.71 ± 1.67
	0.5	1.70 ± 0.71	0.88 ± 0.79	3.50 ± 1.67	-0.81 ± 1.11
	1	-4.46 ± 0.88	3.21 ± 0.43	1.77 ± 1.17	8.04 ± 1.15

De Roller et al. (2023) report that an increase in exposure temperature and time improves MOE at temperatures above 120°C. However, statistical analysis of our results shows no significant difference for different exposure temperatures and times for temperatures below 200°C, which is similar to what was reported by several other authors (Kučerová et al., 2016; Kocaefe et al., 2008; Zhao et al., 2008; de Jesus et al., 2022; Mania and Skrodzka, 2020).

The main cause for the increase in R is a reduction in density as extractives and hemicelluloses are removed as volatile components during thermal treatment, which results in a mass loss (Holeček et al., 2017; Tumen et al., 2010; de Jesus et al., 2022; Zatloukal et al., 2021; Akgül et al., 2007; Wang et al., 2022). The increase in MOE_Y is caused by the increased crystallisation of hemicellulose and cellulose, which was also found by other authors (de Jesus et al. 2022; Zatloukal et al. 2021; Akgül et al. 2007).

The best thermal treatment of 250°C for 1 h was repeated on spruce to ensure that the results can be translated between wood species. The increase in R was somewhat smaller for spruce than for pine, but

with and average $\Delta R = 5.89\%$ still noteworthy.

3.2 Fungal degradation

White rot showed a much faster spread rate than the brown rot after 20 weeks of incubation and both brown (*L. sulphureus*) and white rot (*S. commune*) samples showed a significant reduction in ρ with an increase in exposure time, which translates into an increase in R , as can be seen in Fig. 2.

The changes in c , ρ , MOE_Y and R are highlighted in Table 2 (brown rot) and 3 (white rot).

Table 2
The average change in ρ , c , MOE_Y and R of pine incubated with brown rot (*L. sulphureus*) with standard deviations

t (weeks)	$\Delta \rho$ (%)	Δc (%)	ΔMOE_L (%)	ΔR (%)
1	-0.35 ± 0.11	1.03 ± 0.64	1.73 ± 1.33	1.38 ± 0.61
2	-0.53 ± 0.36	-1.17 ± 1.63	-2.81 ± 3.43	-0.65 ± 1.44
6	-1.21 ± 0.08	1.94 ± 0.91	2.67 ± 1.85	3.19 ± 0.90
20	-1.01 ± 0.98	5.43 ± 1.48	10.06 ± 3.40	6.51 ± 1.73

Table 3
The average change in ρ , c , MOE_L and R of pine incubated with white rot (*S. commune*) with standard deviations.

t (weeks)	$\Delta \rho$ (%)	Δc (%)	ΔMOE_L (%)	ΔR (%)
1	-0.38 ± 0.07	2.02 ± 1.24	3.69 ± 2.51	2.41 ± 1.26
2	-0.37 ± 0.08	0.28 ± 1.21	0.2 ± 2.42	0.66 ± 1.24
6	-1.32 ± 0.11	2.61 ± 1.90	3.92 ± 3.76	3.98 ± 2.00
20	-3.50 ± 1.10	7.15 ± 1.78	10.79 ± 3.06	11.05 ± 2.81

After 20 weeks of exposure, brown and white rot reduced ρ by about 1% and 3.5%, respectively, which lead to an increase in R of about 6% and 11%. The treatment successfully reduced ρ without negatively affecting MOE , which allows the conclusion that the fungi degraded predominantly lignin and hemicelluloses without compromising cellulose.

The results show that fungal degradation can indeed improve ρ . The density loss caused by the two fungi was similar, but brown rot had a slower spread rate compared white rot. Significant changes in ρ , MOE_Y and R occurred after an exposure time of 6 weeks, which was deemed to be a more feasible time to improve tonewood than 20 weeks. Therefore, the fungal treatment of spruce with to white rot was repeated with an exposure time of 6 weeks. Unfortunately, R in spruce increased only slightly by 0.31%, which is similar to what others have reported (Rennenberg et al., 2008). This indicates that degradation

did take place in spruce to some degree and that longer exposure times may be needed to obtain a more significant reduction in density.

The lower increase in R in spruce can be explained by the fact that the tonewood has been seasoned for a very long time and reached a very stable conformation, which made it more difficult for the fungi to penetrate the wood. Furthermore, *S. commune* may not be the most suitable white rot fungus to decrease the density in spruce and another species may yield better results.

3.3 NaOH and Na₂SO₃ treatments

Figure 3 highlights the changes in R after treatment with the two sodium solutions and a combination of both solutions. Generally, the NaOH solution had a more positive effect on R compared to the Na₂SO₃ solution, or the combination.

Initially both the 0.2 M NaOH and Na₂SO₃ solution significantly decreased R, which is undesirable. On average, the NaOH solution resulted in positive ΔR values between 2 and 4% for all exposure times and independent of the concentration. The Na₂SO₃ solution showed lower increases in R and no clear trend, which concentration yields better results. This shows clearly that a NaOH solution is more effective in improving R for exposure times up to about 160 h, after which ΔR starts to decrease. It can be assumed that higher exposure times damage the cell wall structure, resulting in a decrease of structural integrity and therefore MOE and R.

The density reduction was found to be significantly greater at higher concentration and longer exposure time for both sodium treatments. Zimmermann et al. (2007) explained that increased NaOH concentration degrades hemicellulose, and that mannose is the most vulnerable to NaOH. This was confirmed by various other studies (Zhang et al. 2016, Zhao et al. 2008 and Barman et al. 2020).

Unfortunately, the sodium treatment could not be replicated on spruce, as it led to cracks and honeycombing in the wood after drying. This may be caused by the fact that the NaOH did not penetrate the spruce wood well – probably because the wood was very well seasoned, which caused uneven drying after sodium treatment that led to cracking of the surface.

3.4 Combined treatments

The most promising treatments to improve R were the fungal treatment with white rot for 6 weeks, heat treatment at 250°C for 1 h and sodium treatment with 0.2 M NaOH treatment for 120 h. These were combined to see if the combination would improve R even further and heat treatment of 250°C for 1 h was applied to the samples previously exposed to fungal treatment and sodium treatment, respectively. Table 4 highlights the changes in R for pine and spruce for the combined treatments and the results from the best performing individual treatments.

Table 4
Improvement in R after heat-, fungal- and sodium treatment, as well as combined treatments

Wood Type	Treatment	Exposure time	ΔR (%)
Pine	white rot	6 weeks	3.98 ± 2.00
Pine	white rot + heat	6 weeks, 1 h	13.34 ± 2.80
Pine	0.2 M NaOH	120 h	5.84 ± 0.93
Pine	0.2 M NaOH + heat	120h, 1 h	19.83 ± 2.36
Spruce	white rot	6 weeks	0.31 ± 0.58
Spruce	white rot + heat	6 weeks, 1 h	5.45 ± 3.13
Spruce	0.2 M NaOH	120 h	N/A
Spruce	0.2 M NaOH + heat	120 h, 1 h	N/A

The combined fungal / heat treatment showed a significant increase in R of more than 10% in pine wood compared to fungal exposure alone, which is a significant improvement. In spruce the combination increased ΔR from 0.3% for fungal treatment alone, to about 5.5%, which is also a good improvement.

The combined sodium / heat treatment improved R in pine wood to about 20%, which is 14% more than the sodium treatment alone. This shows that sodium treatment followed by heat treatment is highly effective in improving the acoustic properties of pine wood.

The combined sodium / heat treatment could unfortunately not be repeated on spruce, because the sodium solution compromised the wood structure and led to cracking and honey combing. This can probably be explained by the fact that the spruce wood has been well seasoned, which made penetration of the dry and stabilized wood very difficult.

The penetration depth of pine and spruce was determined in a subsequent experiment on larger wood blocks. The penetration depth of the pine wood increased linearly with time, which means that the small sample blocks for the experiment were fully saturated after a few days. On the other hand the penetration depth in spruce remained around 5 mm over a measurement period of 18 days.

The fact that the spruce wood is fairly impenetrable also explains why the fungal treatment of spruce was significantly less effective when compared to pine.

4. CONCLUSIONS

The aim of the study was to investigate different treatment techniques to improve the sound radiation coefficient (R), which can be accomplished by reducing the density (ρ) and increasing or maintaining the dynamic Young modulus MOE_Y . Treatments were tested on more easily available pine wood and successful treatments were repeated on high-value spruce tonewood.

Fungal, heat and sodium treatment all improved R significantly. A combination of heat treatment with NaOH or fungal treatment resulted in the largest improvement in R. Unfortunately, the NaOH treatment could not be replicated on spruce, because it compromised the wood structure. Wood treatment in sodium solution to improve acoustic properties of tonewood were subsequently not regarded as feasible. Combined thermal and fungal (white rot) treatment showed the most promise and could successfully modify the acoustical properties of spruce with similar – although lower - results to pine. Thermal treatment improved in R in pine and spruce by 8.04% and 5.89%, respectively. White rot improved the R of pine by 3.98% after 6 weeks exposure and 11.05% after 20 weeks exposure. Experiments on spruce were repeated with a more practical time of 6 weeks exposure, which led to an increase in R of 0.31%. The combined heat/fungal treatment improved R in pine by 13.34%, while the combined heat/sodium treatment led to a ΔR of 19.83%. The combined heat/fungal treatment in spruce improved R by 5.45%.

In all cases it could be shown that R increased, because the density was decreased without affecting the MOE_y negatively. This can be explained by the fact that the degraded components were predominantly hemicelluloses and extractives and the cellulose remained intact. Fungal- and sodium treatment have the additional effect of increasing the crystallinity of cellulose, as discussed above, which positively affects the MOE_y .

For future work, it is suggested to identify a more suitable white rot to degrade spruce and increase spread and decay uniformity. Especially for tonewoods, it may be advisable to treat the wood shortly after harvesting and before seasoning. An alternative order of the combined treatments i.e., first heat treating the wood then submerging it in NaOH or subjecting it to fungal exposure could also be tested.

DECLARATIONS

Author Contribution

K. Nefdt: performed all experimental work, interpreted and presented results, wrote first version of manuscript
M Meincken: Project conception and funding, guidance through experiments, substantial editing of manuscript

Acknowledgement

This work was supported by the National Research Foundation (NRF) through grant no. 141950. Fungi were supplied by the Department for Plant Pathology, Stellenbosch University.

Data availability

all data is publicly available

Author declarations

No conflicts of interest exist

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Figures

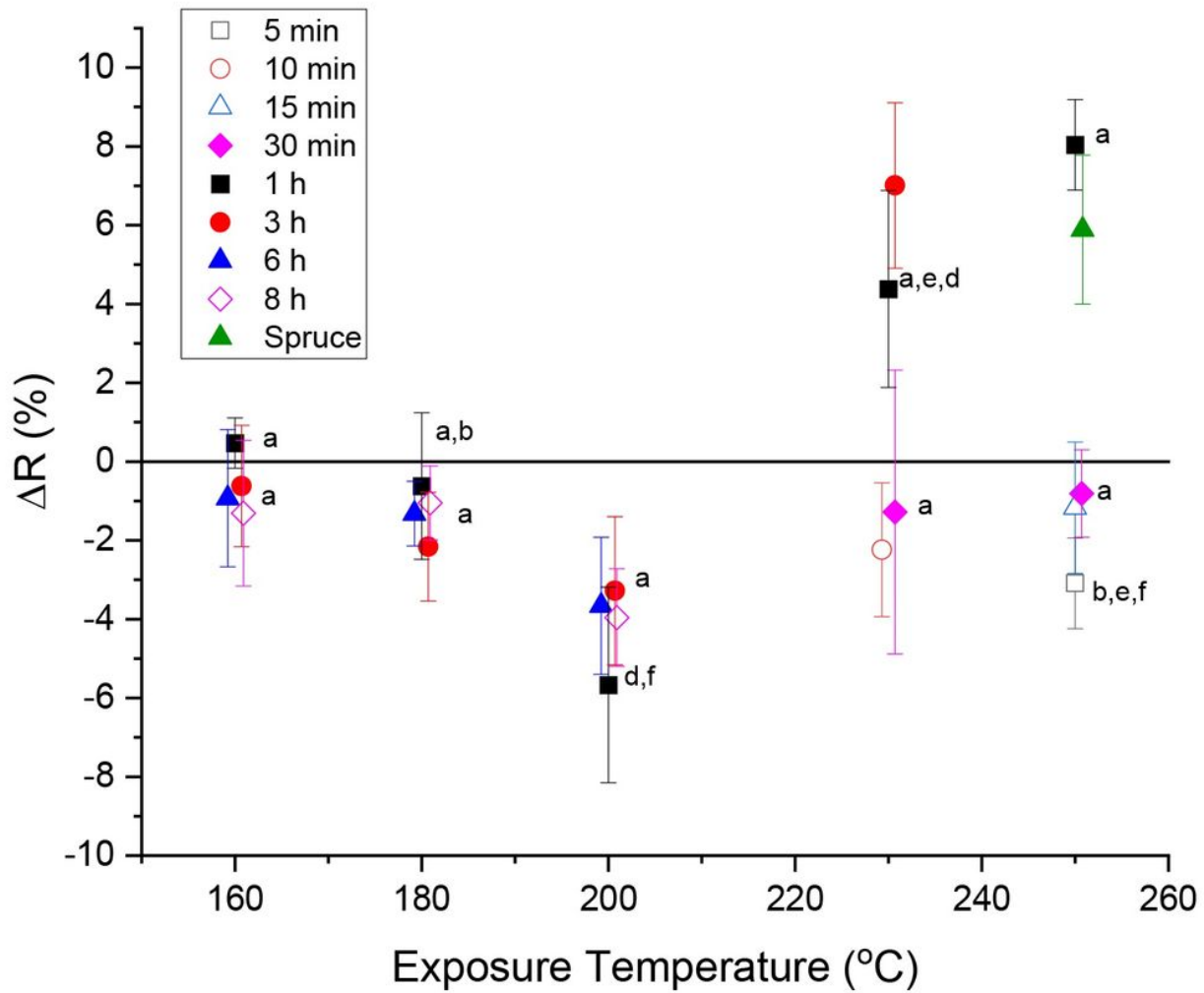


Figure 1

Relative change in R due to heat treatment as a function of exposure temperature for different exposure times for pine and spruce. Different letters indicate statistically significant differences

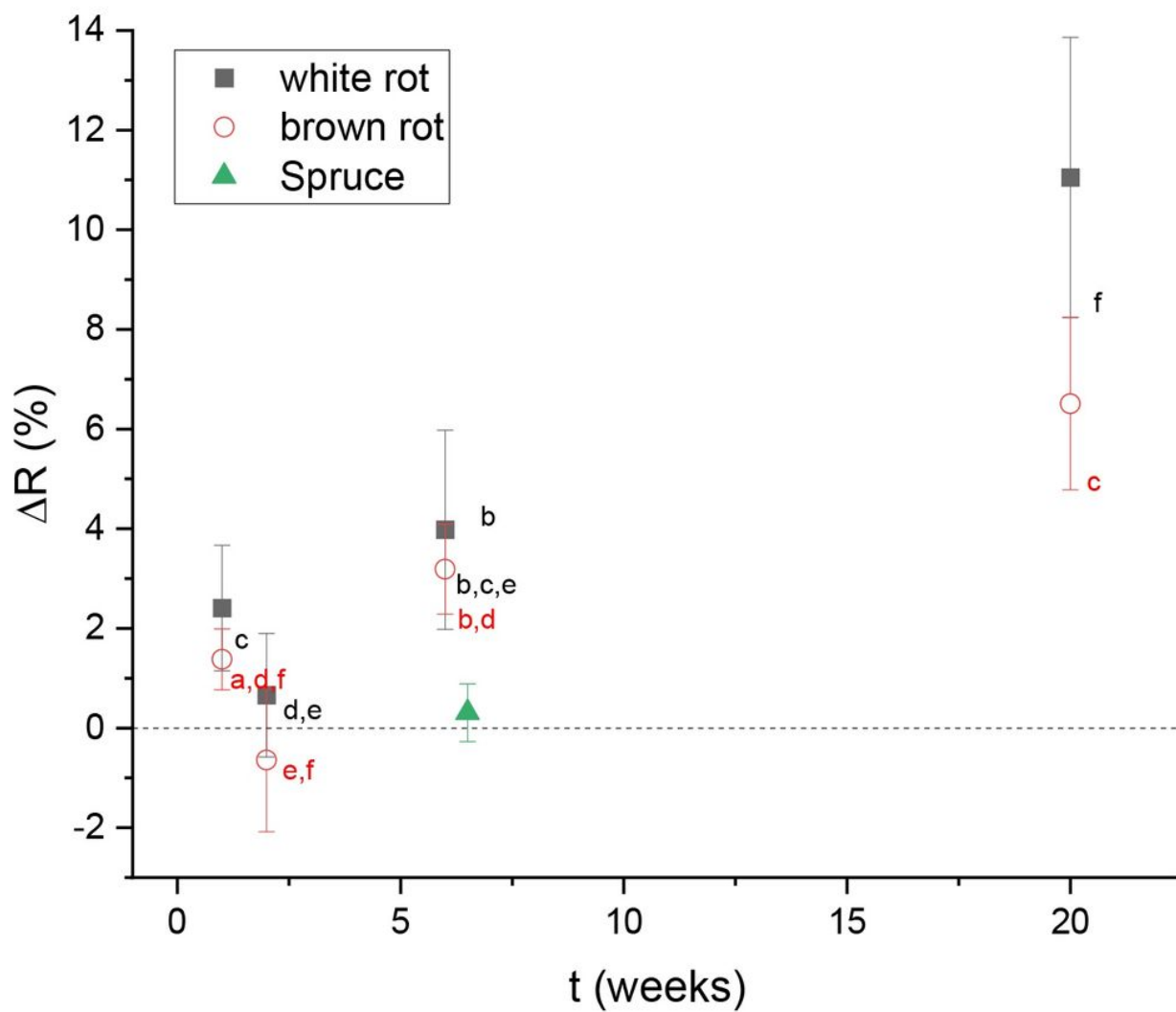


Figure 2

Relative change in R due to fungal degradation as a function of exposure time for pine and spruce. Different letters indicate statistically significant differences

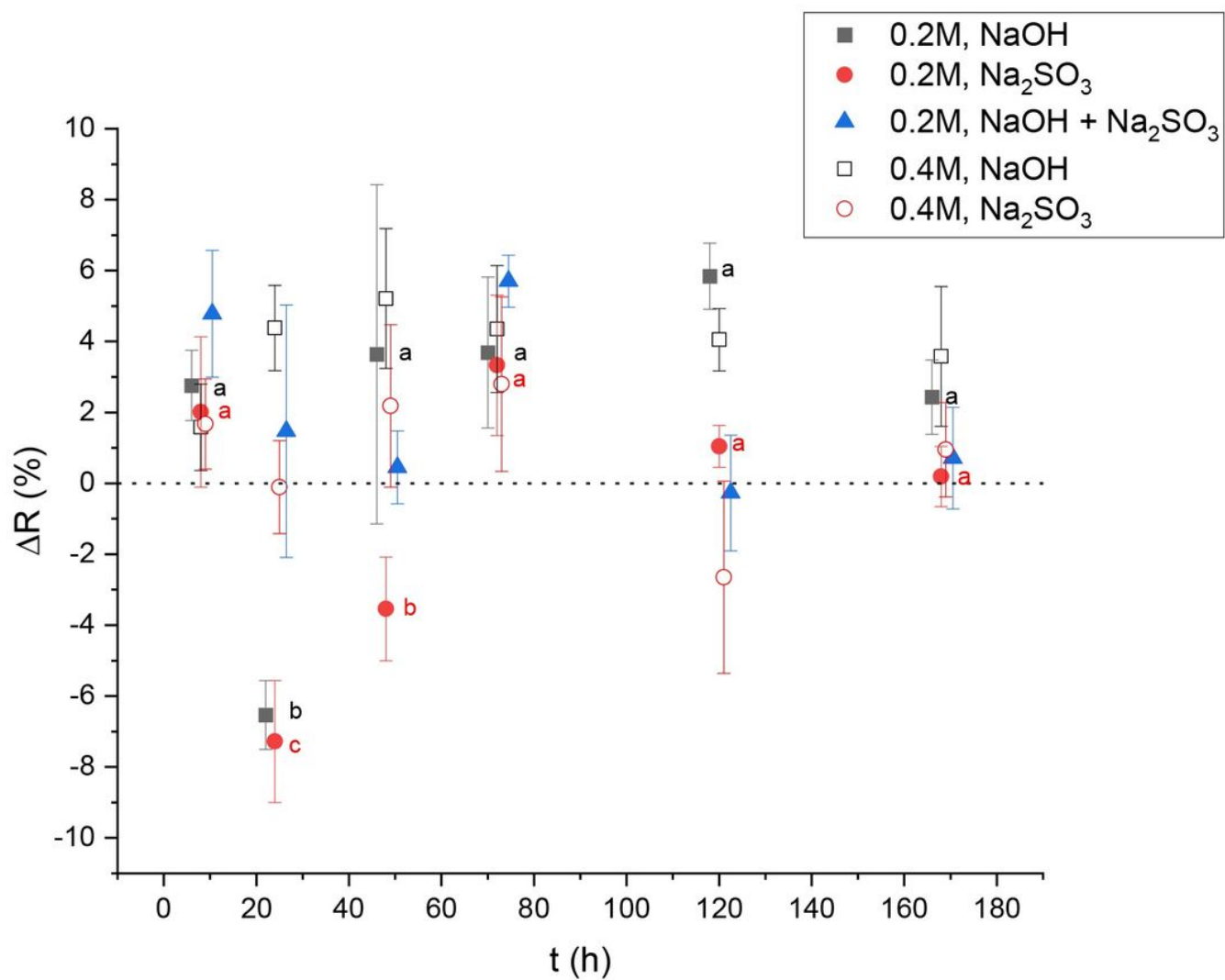


Figure 3

Relative change in R as a function of exposure time for sodium treatments.

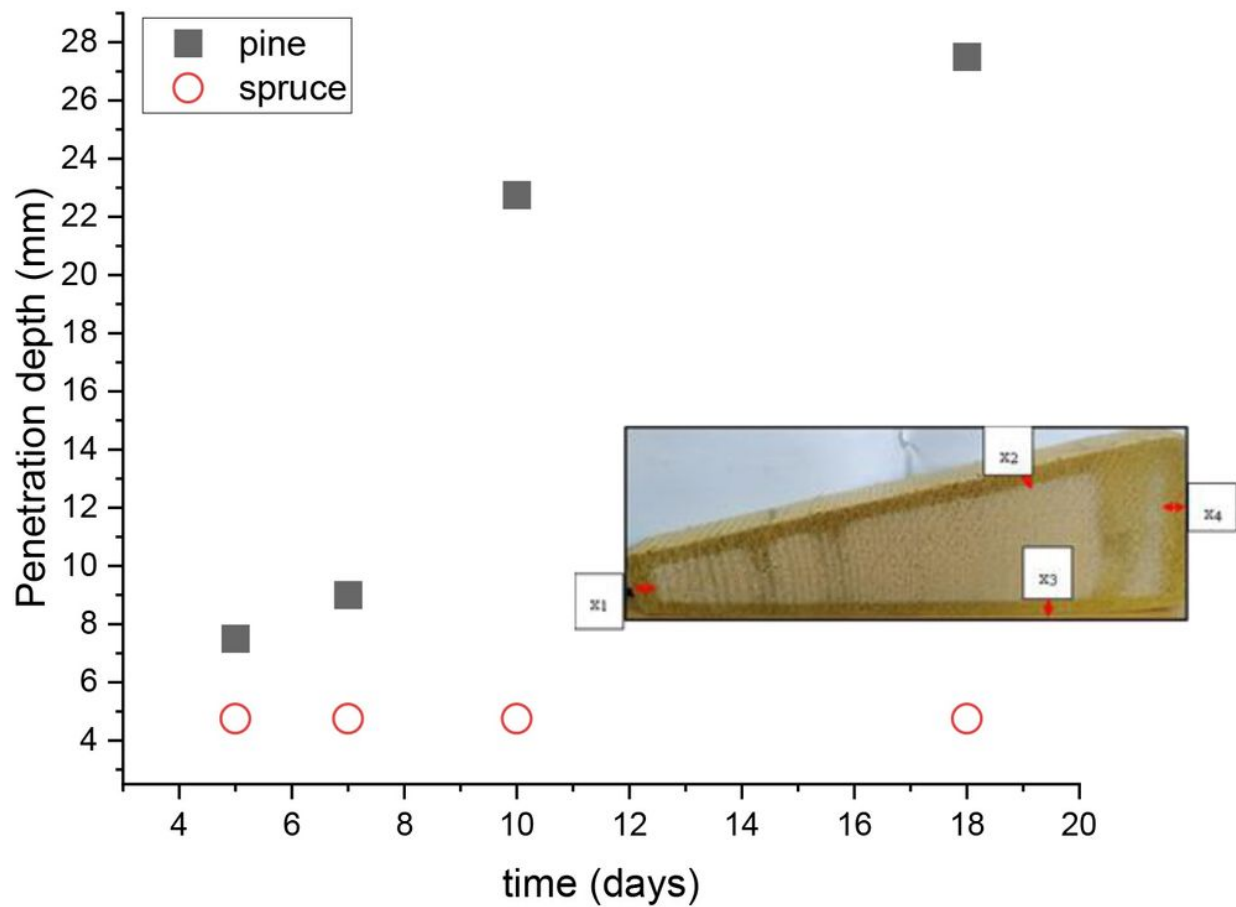


Figure 4

Penetration depth of NaOH into pine and spruce wood as a function of time. The insert shows a spruce wood block (as supplied from the luthier – the wedge shape is the starting dimension for the violin top plate)