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Durability, mechanical properties, and fire resistance of wood impregnated with dilute alumino-silicate suspensions at different pH levels

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Abstract

This study evaluates the effects of dilute alumino-silicate suspension (uncured geopolymer dilution) impregnation on *Pinus sylvestris* sapwood, focusing on pH adjustments. Higher concentrations of the alumino-silicate suspensions (3% and 5%) led to a statistically significant improvement in decay resistance, with all treated samples exhibiting mass losses between $2.2 \pm 0.6\%$ and $5.8 \pm 1.6\%$ —approximately half of that observed for the untreated controls ($9.9 \pm 2.4\%$). In contrast, pH adjustments had only a minor effect. The lowest concentration of dilute alumino-silicate suspensions did not significantly enhance decay resistance, although the mass loss was slightly higher than that of the controls. Mechanical tests showed that intermediate concentrations of alumino-silicate suspensions improved the modulus of elasticity (MOE) and modulus of rupture (MOR), while fire resistance tests indicated an improvement in ignition time of up to 5 s at 5% alumino-silicate suspension. The leaching test revealed challenges with the fixation of the dilute alumino-silicate suspensions, resulting in reduced durability after prolonged water exposure. These findings underscore the potential of dilute alumino-silicate suspensions as sustainable wood treatments. However, further optimization of their formulations is required to enhance adhesion and reduce leachability.

Keywords Alumino-silicate polymers, Degradation, Wood mineralization, Wood modification

1 Introduction

The demand for sustainable construction materials is increasing as architects and engineers seek to reduce the environmental footprint of buildings. As an example, in Europe both the supply and demand of wood have been increasing in the recent years [1]. Wood is regarded as an eco-friendly choice in construction due to its sustainability and capacity for carbon sequestration [2]. However, wood is susceptible to decay, degradation and fire, presenting significant challenges for its long-term use as a structural material. Wood durability is a crucial consideration when building, as we need to ensure the longevity



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and performance of the structures, especially in outdoors environments, where decay risk is elevated, with decay fungi being the main factor leading to wood failure in outdoors environments [3].

To overcome these limitations, construction practices must rely not only on proper design [4] but also on wood preservatives that extend the material's service life. Traditional preservatives, however, often contain toxic compounds with harmful effects on human health and the environment, restricting their use. Due to this, the search for less toxic and environmentally friendly alternatives has gained momentum. In recent years, bio-based preservatives have been proposed as alternatives, yet they frequently present high leachability and, in some cases, even higher ecotoxicity than current industrial preservatives [5]. Moreover, organic chemicals used in these formulations do not usually improve mechanical properties [6], nor do they protect the wood from fire [7]. Therefore, new treatments that can enhance wood's resistance to decay and fire, while also improving or maintaining its mechanical performance, are needed to promote more sustainable construction practices.

Geopolymers have emerged as promising candidates for this purpose. These materials, formed by activating alumino-silicate precursors with alkaline solutions [8], have properties comparable to those of Portland cement [9], but with a lower carbon footprint. These inorganic alumino-silicate binders are known for forming dense, ceramic-like matrices upon curing, a characteristic that could be beneficial when applied to porous substrates such as wood. Geopolymers have been combined with wood in composite materials [10, 11], and several studies have demonstrated their potential to improve fire resistance when applied as coatings or paints [12, 13]. However, when used in high concentrations or inappropriate formulations, geopolymers may crack or fail to properly bind to wood substrates as observed by Barbero-López et al. [14]. At lower concentrations, the alumino-silicate suspension (a dilute, uncured geopolymer) can still interact with wood and provide protective effects [14]. Giancaspro et al. [15] incorporated geopolymer-glass paste into sandwich panel structures as a fire-retardant core material, showing effective fire protection performance. Nevertheless, these studies focused primarily on fire resistance and did not assess the potential of dilute alumino-silicate suspensions to enhance mechanical properties or biological durability when impregnated into the wood structure.

The research on biological durability of dilute alumino-silicate suspension-treated wood is very scarce. Barbero-López et al. [14] explored the impregnation of *Pinus sylvestris* L. (Scots pine) sapwood with diluted alumino-silicate suspensions (5–20%) and reported a marked increase in decay resistance—from a natural durability class 4 to conferred durability class 1 based on the EN 350 [16]. Similarly, López-Gómez et al. [17] showed that sequential impregnation with tannins followed by alumino-silicate suspensions reduced mass loss after leaching. Despite their effectiveness, these treatments also presented some limitations, including cracking at higher concentrations and insufficient fixation. The pH of the medium will affect the solubility of the silica, as higher pH will result in higher silica solubility [18, 19] and in shorter chain length silicate structures, as seen in calcium silicate hydrate [20]. The use of surfactants like sodium dodecyl sulphate (SDS) may improve the wetting and penetration of the treatment into the wood structure. However, none of the cited studies in dilute alumino-silicate suspension-treated

wood addressed how the pH of the dilute alumino-silicate suspension formulation might influence its performance.

This study aims to fill that research gap by testing dilute alumino-silicate suspension formulations at different pH levels, to evaluate their effects on wood durability. To keep the natural appearance of wood, an important attribute valued by end-users, and ensure a cost-effective treatment, the concentrations of alumino-silicate suspensions were kept low. By impregnating *P. sylvestris* sapwood with these formulations, we assess their performance in terms of decay resistance, mechanical strength, and fire retardancy. Our results contribute to the development of sustainable, non-toxic wood treatments that not only enhance durability but also improve mechanical and fire performance, supporting their implementation in environmentally conscious construction.

2 Materials and methods

2.1 Wood specimens

Pinus sylvestris sapwood was purchased from a local sawmill in Kerimäki (Finland). The sapwood specimens were cut into various sizes based on the requirements of each test: for the decay and leaching tests specimens of $5 \times 10 \times 40 \text{ mm}^3$ were cut; for the mechanical test specimens of $20 \times 20 \times 340 \text{ mm}^3$ were cut; for the fire retardancy test $100 \times 100 \times 20 \text{ mm}^3$ size specimens were cut.

2.2 Formulation and wood impregnation

Metakaolin was used as an aluminosilicate precursor (Metaver® M, Newchem GmbH, Austria). It is a commercial grade calcined kaolin with high purity containing approximately 50–56 wt% SiO_2 and 40–43 wt% Al_2O_3 , with minor impurities of Fe_2O_3 (< 1 wt%) and K_2O (< 2 wt%). The particle size distribution is characterized by $d_{50} < 5 \text{ }\mu\text{m}$ and $d_{90} < 12 \text{ }\mu\text{m}$, with a specific density of about 2.6 g cm^{-3} . This was added as dry powder to an activation solution containing sodium hydroxide (NaOH), sodium silicate (Na_2SiO_3) and water, in an ice bath. The mixture was stirred in a closed plastic container for 24 h with a ratio between Si: Al: Na: H_2O of 4:1:1:17, together with 2% (w/w) sodium dodecyl sulphate (ICN Biomedicals, OH, USA) used as a surfactant. The pH of the alumino-silicate suspension was 11.5. To be used as a wood impregnant, the resulting alumino-silicate mixture was diluted to 1%, 3% and 5% of the original solution, using MilliQ water (Merck KGaA, Darmstadt, Germany). Each diluted alumino-silicate suspension was used to prepare four diluted suspensions with different pH: 8, 9, 10 and 11. The pH was adjusted by adding drops of 0.1 M NaOH until the desired pH value was achieved. In each suspension 30 sapwood specimens for the decay test, 20 sapwood specimens for mechanical tests and 2 replicates for the fire retardancy test were submerged. While submerged, the sapwood specimens were kept at 0.2 bar for 20 min, and the pressure was then increased to 10 bar for 1 h. The whole process was conducted at room temperature. Once the pressure was released, the dilute alumino-silicate suspension-treated wood specimens were taken out of the dilute alumino-silicate suspension and sealed into Ziplock bags and kept 24 h at $40 \text{ }^\circ\text{C}$ and afterwards 14 days at room temperature for curing. The dry mass of the wood specimens dried at $60 \text{ }^\circ\text{C}$ until constant mass was measured. Untreated wood specimens were used as controls.

2.3 Mini-block test for decay resistance

The performance of dilute alumino-silicate suspension-treated wood against decay fungi was tested following a mini-block procedure based on the modified version of EN 113 [21] described in Barbero-López et al. [5]. Growth media containing 4% malt and 2% agar in MilliQ water was prepared, and after autoclaving it (120 °C, 15 min) and under sterile conditions, 30 ml of the growth media were poured in each Petri dish (Ø 90 mm; 20 mm high). One plug (Ø 5.5 mm) of an actively growing *Coniophora puteana* colony (strain BAM 112) was put in the centre of each Petri dish, all the Petri dishes were parafilm and left in a growth chamber (22 ± 2 °C and $60 \pm 5\%$ RH) until the fungal colonies covered the whole surface of the Petri dish. *Coniophora puteana*, purchased from the Federal Institute for Materials Research and Testing (BAM, Berlin, Germany), was chosen for the test as it is one of the most common decay fungi found in wooden buildings in Europe [22]. The sapwood specimens ($5 \times 10 \times 40$ mm³) treated with different dilute alumino-silicate suspension concentrations and pHs, as well as the controls, were weighted after drying at 60 °C, autoclaved, and four randomly chosen specimens were put in each Petri dish (see Fig. 1 as a visual example of the setup). A total of 30 replicates were prepared for each dilute alumino-silicate suspension and pH level, as well as for the untreated controls. An inert plastic mesh was put between the sapwood specimens and the agar to prevent direct contact. The Petri dishes were parafilm and kept in the growth chamber (22 ± 2 °C and $60 \pm 5\%$ RH) for 16 weeks. After that time, the sapwood specimens were taken out of the dish and the mycelium that grew during

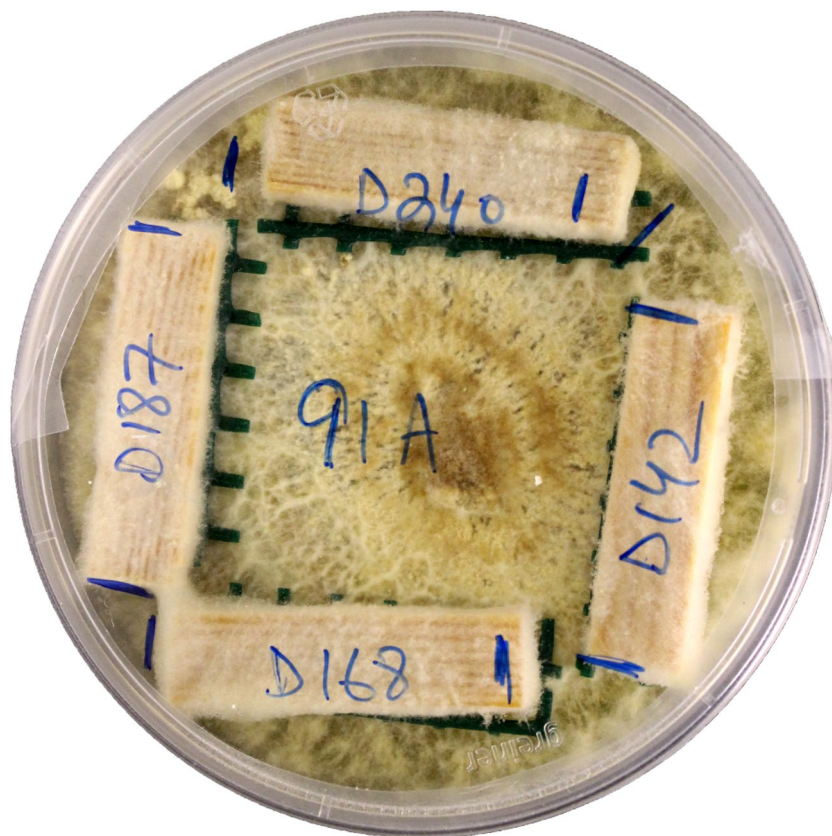


Fig. 1 Setup of the mini-block test used to evaluate the decay resistance of the wood specimens. The specimens, randomly selected, were placed on a mesh over the fully grown *C. puteana* colony. This photo, taken four weeks after the start of the experiment, shows the specimens already covered by mycelium

this time-period was removed from their surfaces using a brush. The wood specimens were dried at 60 °C and their mass was measured to calculate the mass loss caused by *C. puteana*.

2.4 Leaching test and its effects in fungal degradation

For assessing the fixation of alumino-silicate suspensions to wood, a leaching test with a subsequent mini-block test was performed. Additional *P. sylvestris* sapwood specimens ($5 \times 10 \times 40 \text{ mm}^3$) were treated with 5% dilute suspension of alumino-silicate. For each pH (8, 9 and 11) 16 sapwood specimens were impregnated following the same impregnation process as in the mini-block test, and 16 untreated specimens were used as controls. Their mass at 60 °C was measured. Half of the specimens of each pH and controls were exposed to leaching following the EN 84 [23]. Briefly, these sapwood specimens were submerged in a 5:1 (v/v) ratio of Milli-Q water to wood and exposed to a vacuum of 0.1 bar for 20 min. The water was changed after 2, 24 and 48 h, and then additional 7 times within the remaining 12 days, resulting in a total elution time of 14 days in water. After the leaching test, the dry mass of the sapwood specimens at 60 °C was recorded to assess the mass loss caused by the leaching process. The sapwood specimens were then exposed to decay by *C. puteana* in a mini-block test following the same procedure as in the previous mini-block test.

2.5 Mechanical test

The *P. sylvestris* sapwood specimens of $20 \times 20 \times 340 \text{ mm}^3$ previously impregnated and untreated specimens as controls were used in this experiment. For each dilute suspension and pH 20 replicates were used. The wood specimens were conditioned at 20 °C and 65% RH until they reached constant mass. A Zwick Roell 050 materials testing setup was used for the mechanical testing. A three-point bending test was performed to calculate the modulus of elasticity (MOE) following the ISO 13061-4 [24] and modulus of rupture (MOR) following the ISO 13061-3 [25]. The Eqs. (1) and (2) were used to calculate the MOE and MOR as previously done by Marttila et al. [26].

$$MOE = \frac{Pl^3}{4bh^3f} \quad (1)$$

$$MOR = \frac{3P_{max}l}{2bh^2} \quad (2)$$

The mean values of both MOE and MOR were calculated to evaluate the effects of dilute alumino-silicate suspensions in the *P. sylvestris* sapwood.

2.6 Cone calorimetric analysis

The fire resistance of the inorganic polymer-treated wood specimens ($100 \times 100 \times 20 \text{ mm}^3$) was analysed following the ISO 5660-2 Standard Test Method [27], with a cone calorimeter (ConeTool 1; SGS Govmark Ltd., Farmingdale, IL, USA) at a radiant flux of 50 kW/m². The measurement of the heat release rate was conducted by analysing the oxygen consumption and flow rate within the combustion product stream. Two replicates per each dilute suspension and pH were analysed, which is generally sufficient

to identify consistent trends in fire resistance, although not enabling robust statistical analysis.

2.7 Statistical analysis

SPSS 29.0 (IBM Corp., USA) was used to analyse the effects of dilute alumino-silicate suspension concentrations and pH levels on wood properties, including decay resistance and mechanical properties. Tukey's B test was applied post hoc for ANOVA to determine specific group differences at a 95% confidence level. Graphical representations of the data were generated using SigmaPlot 15.0 (Grafti LLC, USA).

3 Results and discussion

3.1 Mini-block test for decay resistance

The results of the mini-block test in Petri dishes indicated that dilute alumino-silicate suspension impregnation led to a statistically significant reduction in the mass loss caused by *C. puteana*. Figure 2a presents the combined effects of concentration and pH, while Fig. 2b and c separate these factors, showing the effects of concentration and pH individually. The dilutions of the alumino-silicate suspension, except at 1%, caused a statistically significant reduction in the *P. sylvestris* sapwood mass loss (Fig. 2b) while the different pH of the dilute alumino-silicate suspensions did not cause any statistically significant effect (Fig. 2c). There was no statistically significant difference between sapwood treated with 3% and 5% alumino-silicate suspensions. Despite not being statistically significant, in both 3% and 5% alumino-silicate suspension treated wood, the mass loss caused by *C. puteana* looks to be lower in higher pH values (Fig. 2a).

The mini-block test results indicate that impregnation of dilute alumino-silicate suspensions enhanced the decay resistance of the *P. sylvestris* sapwood specimens, with the

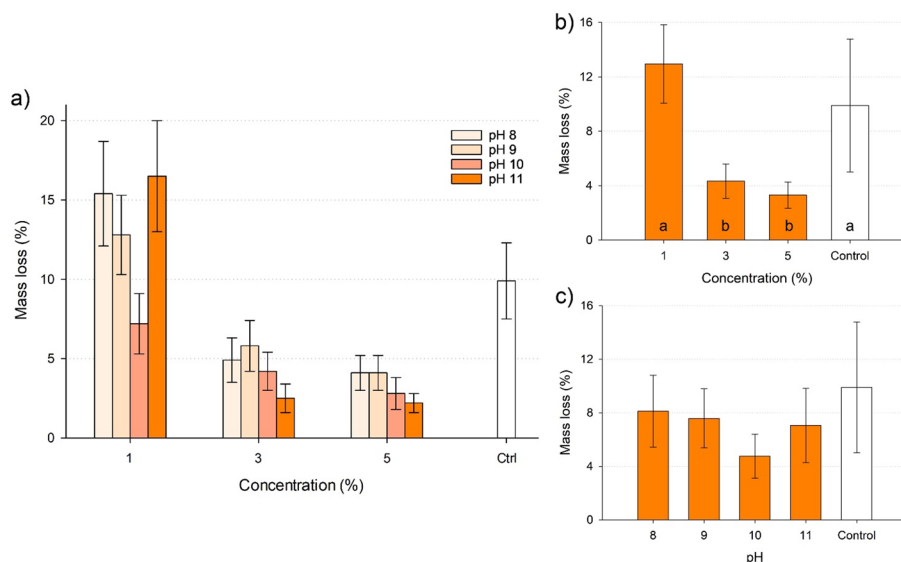


Fig. 2 Mean mass loss (%) caused by the fungus *Coniophora puteana* to the wood specimens treated with dilute alumino-silicate suspensions adjusted to different pH and concentrations. **(a)** Mass loss when both dilution % and pH are taken into consideration, **(b)** mass loss when only concentration of the dilute alumino-silicate suspension is taken into consideration (mean of results at a given concentration), **(c)** mass loss when only pH of the dilute alumino-silicate suspensions is taken into consideration (mean of results at a given pH level). Data are presented as the mean value of mass loss, with a 95% confidence interval standard error. Treatments not sharing the same letter are statistically significantly different, based on Tukey's range test ($p < 0.05$)

enhancement caused by the alumino-silicate suspension's concentration rather than by its pH. Despite the low virulence of *C. puteana*, which did not reach to 20% mass loss in controls, the results show differences which allow clear comparison between the different treatments. The reason behind this lower mass loss caused by *C. puteana* remain unclear but could be caused either by the wood properties (the amount of extractives, etc...), experimental conditions (such as the reduced airflow caused by the parafilm) and fungal factors (vitality of the fungus, etc...). While these explanations are speculative, they help contextualize why the untreated specimens lost less than the 20% mass indicated by the EN 113 [21]. Previous research found no statistically significant variations in mass loss between wood treated with 5, 10 and 20% alumino-silicate suspensions [14], while in our current study we see no variation in 3% and 5% alumino-silicate suspension-treated wood. Only the lowest alumino-silicate suspension tested, 1%, does not reduce the mass loss of wood when compared to untreated controls. In some cases, this concentration even promoted a slight increase in mass loss, likely due to the low effectiveness of such a dilute alumino-silicate suspension combined with the leaching of wood extractives during impregnation [28]. The mass loss caused by *C. puteana* in the paper at hand in 5% alumino-silicate suspension treated specimens are slightly higher than those in Barbero-López et al. [14]. The observed reduction in wood protection may be attributed to the pH adjustments conducted in this study, the addition of sodium dodecyl sulphate in the dilute alumino-silicate suspension formulation, the natural variability of the wood or the differences between metakaolin used and should be studied further for optimizing the alumino-silicate suspension formulation for this end-use.

The reduced mass loss observed in wood specimens treated with 3% and 5% alumino-silicate suspensions at higher pH levels, though not statistically significant, warrants further investigation. Given that the initial pH of the alumino-silicate suspension was 11.5, the results suggest that adjustment of the pH to more neutral values may reduce the effectiveness of the alumino-silicate suspension as a wood modification treatment. Two possible explanations can be considered. The first is that the adjustment of pH with NaOH not only modified alkalinity but also increased the sodium concentration, potentially raising the Na: Al ratio of the alumino-silicate suspension above 1. As the ratios of constituent elements are known to influence alumino-silicate suspension properties [29, 30], this effect cannot be excluded, although it remains speculative and requires further confirmation. The second is that the pH of the impregnant itself can influence wood durability, since very acidic solutions may degrade some wood components [31], and alkaline impregnants have been reported to improve resistance against brown-rot fungi [32].

Interestingly, at 1% diluted suspension, the performance of the specimens with pH 11 was worse than the rest, in contrast to the findings at 3 and 5%. Since geopolymerization is favoured under alkaline conditions, although the underlying mechanisms are complex and not yet fully understood [33], further research is needed to clarify the performance of dilute alumino-silicate suspensions at pH 11, as this pH would theoretically be expected to provide the best performance for wood treatments. However, the result at 1% suggest that, in practice, the outcome under highly alkaline conditions was less favourable than anticipated.

The reason for the observed reduction in mass loss caused by *C. puteana* was not directly investigated in this study. However, it is likely that the dilute alumino-silicate

suspension acts by forming a physical barrier and filling the wood vessels with inorganic compounds such as aluminum and silica, in a manner similar to silicon polymers used in commercial OrganoWood® [34]. Supporting this idea, treatments with silica–alumina sol combined with fatty alcohol polyoxyethylene ether have been shown to enhance wood durability, mechanical properties, and fire resistance [35]. Despite differences in the products, their shared silica-alumina precursors may be the reason of the antifungal effect observed.

3.2 Leaching test and its effects in fungal degradation

The mini-block test comparing unleached and leached *P. sylvestris* sapwood specimens resulted in a statistically significant higher mass loss caused by the fungus to all leached specimens (Table 1). All the unleached treated sapwood specimens had lower mass loss than the control specimens, even if the difference was not statistically significant. Based on the criteria of EN 350 [16], the durability of unleached 5% alumino-silicate suspension treated sapwood specimens was between 1 and 2, while the controls ranged between 3 and 4. The mass loss of leached specimens was about 20% for all treated specimens, while controls had a mean mass loss of about 15%. The durability class, according to the criteria of EN 350 [16], was between 3 and 4 for all the specimens.

The mass loss differences between leached and unleached dilute alumino-silicate suspension-treated specimens indicated that alumino-silicate suspensions did not fix to wood and leached out from wood during the leaching test. Geopolymers are generally expected to exhibit performance comparable to, or even surpassing, that of Portland cement [8]. As a result, geopolymers are considered as alternatives to Portland cement, as they should solidify creating an amorphous solid, which, when impregnated in wood, should create a stratum around wood or penetrate its pores, adhering effectively and inhibiting fungal decay. The non-formation of a stratum around the wood could be caused because of the low dilutions tested in this experiment. The low concentration of alumino-silicate suspension may also have hindered the geopolymerization. In addition, alternative application methods, such as coating rather than impregnation, should be considered, as previously reported for cement-coated wood [36]. Additionally, geopolymers have been reported to mineralize and harden wood cell walls [37]; however, this likely did not occur in our specimens, as mineralization is expected to prevent fungal decay [38], which was not the case in our samples after leaching. Additionally, it also aimed avoiding a substantial increase in wood production costs. Still, the low adhesion of the dilute alumino-silicate suspension to the wood may be due to a formulation that has not yet been fully optimized.

Table 1 Comparison of the mass loss caused by the decay fungus *Coniophora Puteana* to the control and dilute alumino-silicate suspension-impregnated specimens before and after leaching. Results are presented as mean value $\pm$ standard error ($N=8$)

Treatment	pH	Unleached mass loss (%)	Durability class (unleached)	Leached mass loss (%)	Durability class (leached)
Control	-	13.7 $\pm$ 5.2 ^{ab}	3–4	15.3 $\pm$ 2.6 ^{ab}	3–4
5%	8	5.8 $\pm$ 0.9 ^a	1–2	21.3 $\pm$ 3.0 ^b	4
5%	9	5.6 $\pm$ 1.4 ^a	1–2	22.5 $\pm$ 2.7 ^b	4
5%	11	3.9 $\pm$ 1.0 ^a	1	17.4 $\pm$ 2.8 ^b	3–4

Treatments not sharing the same letter differ statistically significantly, based on tukey's range test ($p < 0.05$)

The dilute alumino-silicate suspension-treated specimens exhibited decay resistance when unleached, but their resistance diminished after leaching. The durability class of the unleached specimens ranged from 1 to 2, while the leached specimens exhibited a durability class of 3 to 4, like that of the control specimens. These findings agree with López-Gómez et al. [17], which found that dilute alumino-silicate suspension were effective against fungal decay but also leached out from wood. As the performance of alumino-silicate suspensions may vary depending on their formulation, additional formulations should be tested to understand how these affect their adhesion and leachability. The addition of sodium dodecyl sulphate in the formulation may also be the reason behind the low binding of dilute alumino-silicate suspensions to wood, by increasing the alumino-silicate suspension's hydrophilicity, which may increase water retention during curing and lead to leaching of alumino-silicate suspension components from the wood surface during drying.

3.3 Mechanical durability related to alumino-silicate suspension dosing and pH

The impregnation of dilute alumino-silicate suspension into wood had a statistically significant effect on the MOE of the sapwood specimens (Fig. 3). Figure 3a presents the combined effects of concentration and pH, whereas Fig. 3b and c show the individual effects of concentration and pH, respectively. The concentration had an statistically significant effect on the MOE (Fig. 3b), as the specimens treated with 3% dilute alumino-silicate suspension had higher MOE than the remaining treatments and controls, while the pH of the alumino-silicate suspension did not have an statistically significant effect on the MOE (Fig. 3c).

The results of MOR indicate a statistically significant effect of the treatment concentration and pH (Fig. 4). Figure 4a presents the combined effects of concentration and pH, whereas Fig. 4b and c show the individual effects of concentration and pH, respectively.

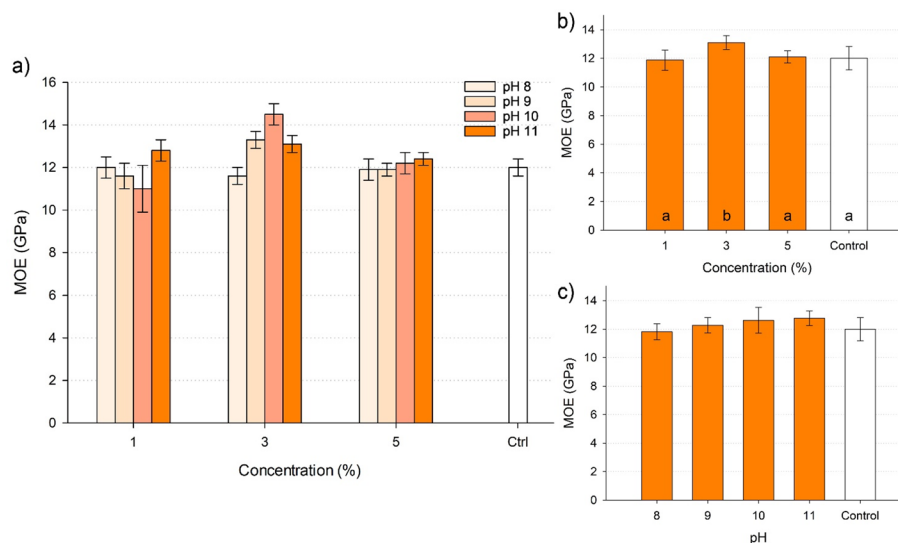


Fig. 3 Mean modulus of elasticity, MOE (GPa) of the wood specimens treated with dilute alumino-silicate suspensions adjusted to different pH and concentrations. **(a)** The MOE when both concentration and pH are taken into consideration. **(b)** The MOE when only concentration of the dilute alumino-silicate suspension is taken into consideration. **(c)** The MOE when only pH of the dilute alumino-silicate suspension is taken into consideration. Data are presented as the mean value of mass loss, with a 95% confidence interval standard error. Treatments not sharing the same letter differ significantly ($p < 0.05$, Tukey's test)

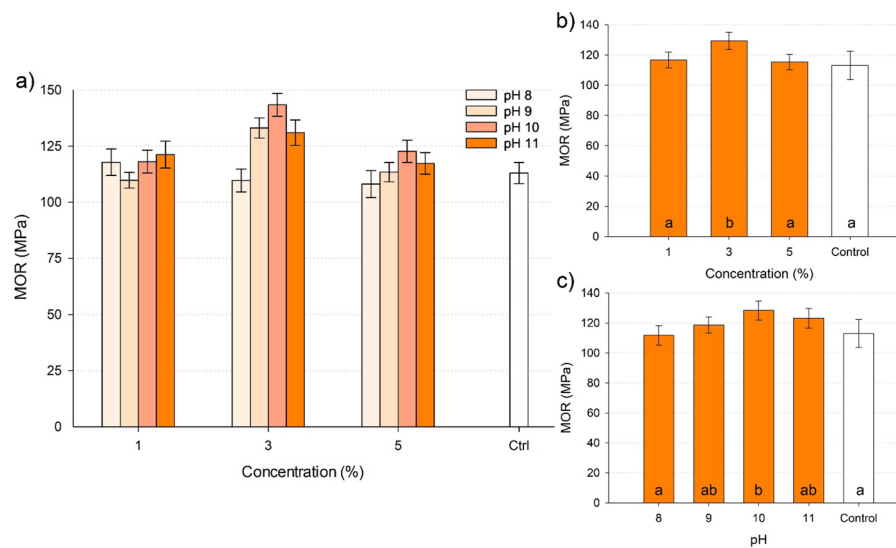


Fig. 4 Mean modulus of rupture, MOR (MPa) of the wood specimens treated with dilute alumino-silicate suspension adjusted to different pH and concentrations. **(a)** The MOR when both concentration and pH are taken into consideration. **(b)** The MOR when only concentration of the dilute alumino-silicate suspension is taken into consideration. **(c)** The MOR when only pH of the dilute alumino-silicate suspension is taken into consideration. Data are presented as the mean value of mass loss, with a 95% confidence interval standard error. Treatments not sharing the same letter differ statistically significantly, based on Tukey's range test ($p < 0.05$)

Similarly to MOE, the MOR values of 3% alumino-silicate suspension treated wood are statistically significantly higher than the rest of the treatments (Fig. 4b). The pH of the alumino-silicate suspension had also an effect, as specimens treated with dilute alumino-silicate suspension with pH 10 had a higher MOR value than the controls and the specimens treated with dilute alumino-silicate suspension at pH 8 (Fig. 4c).

The mechanical properties of treated wood, both MOE and MOR, exhibited unexpected trends as the 3% dilute alumino-silicate suspension had a significantly higher MOE and MOR than controls, but 1% and 5% did not show any significant differences from control specimens. Despite the statistical significance, the observed changes may result from the natural variability of wood, as there is no clear trend in the concentration to indicate that increasing or decreasing concentrations would impact the mechanical properties. The pH also had a statistically significant effect on the MOR of the samples, as samples treated with pH 10 dilute alumino-silicate suspension differed statistically significantly from controls. While the natural variability of the wood may also have affected these results, the NaOH used to adjust the pH could also have affected the effectiveness, as geopolymers' mechanical properties vary depending on their constituents' ratios [29, 30]. As a result of this, those solutions with lower pH showed a slightly reduced performance. Similar to the trend observed in mass loss caused by *C. puteana*, samples treated with a 1% alumino-silicate suspension and pH 11 showed a slightly higher MOE compared with pH 8, 9, and 10, which had a decreasing trend with increasing pH. This unexpected result highlights the need of further research, as theoretically, it should be the best pH for geopolymerization. Interestingly, while both MOE and MOR were influenced by the concentration of alumino-silicate suspension, only MOR showed a significant effect of pH, with pH 10 producing statistically higher MOR compared to the other treatments and controls. A previous study by Fu et al. [39] found that heat treatment of pine wood caused MOE fluctuations, while caused a MOR decrease, indicating that

Table 2 Mean values $\pm$ standard error of the cone calorimetric analysis performed to control and dilute alumino-silicate suspension-impregnated wood specimens ($N = 2$)

Specimen	pH	Time to ignition (s)	Mean heat release rate (kW/m ²)	Peak heat release (kW/m ²)	mass loss (%)	Total smoke (m ² /m ²)
Control		15.5 $\pm$ 0.5	117.9 $\pm$ 2.6	184.0 $\pm$ 8.2	47.0 $\pm$ 0.2	184.7 $\pm$ 16.2
1%	8	16.0 $\pm$ 4.0	106.3 $\pm$ 6.3	180.2 $\pm$ 1.5	63.2 $\pm$ 19.1	358.8 $\pm$ 177.5
	9	16.0 $\pm$ 2.0	115.25 $\pm$ 0.1	180.9 $\pm$ 3.6	48.6 $\pm$ 2.1	209.5 $\pm$ 9.6
	10	18.0 $\pm$ 2.0	114.4 $\pm$ 8.0	204.4 $\pm$ 3.5	65.6 $\pm$ 15.9	474.2 $\pm$ 210.6
	11	16.5 $\pm$ 2.5	110.0 $\pm$ 11.4	176.9 $\pm$ 4.5	66.9 $\pm$ 15.2	344.5 $\pm$ 139.5
3%	8	21.0 $\pm$ 1.0	112.5 $\pm$ 2.5	183.4 $\pm$ 4.4	47.2 $\pm$ 1.6	206.0 $\pm$ 23.2
	9	15.0 $\pm$ 3.0	118.4 $\pm$ 2.7	186.2 $\pm$ 5.3	49.8 $\pm$ 0.4	279.0 $\pm$ 22.0
	10	20.0 $\pm$ 3.0	146.6 $\pm$ 34.7	179.0 $\pm$ 2.3	46.5 $\pm$ 0.2	147.6 $\pm$ 4.8
	11	21.0 $\pm$ 1.0	105.3 $\pm$ 3.8	213.0 $\pm$ 27.9	63.1 $\pm$ 16.0	356.0 $\pm$ 162.2
5%	8	18.0 $\pm$ 1.0	114.8 $\pm$ 2.7	191.8 $\pm$ 8.2	49.2 $\pm$ 0.5	191.8 $\pm$ 11.5
	9	17.5 $\pm$ 1.5	113.3 $\pm$ 3.9	179.9 $\pm$ 2.7	48.8 $\pm$ 0.7	173.7 $\pm$ 11.1
	10	20.5 $\pm$ 0.5	108.8 $\pm$ 1.5	182.7 $\pm$ 12.9	47.2 $\pm$ 0.6	177.3 $\pm$ 24.7
	11	20.5 $\pm$ 1.5	115.7 $\pm$ 5.1	183.5 $\pm$ 9.9	49.4 $\pm$ 1.9	254.7 $\pm$ 31.6

some treatments can affect differently both MOR and MOE, as it happened to the dilute alumino-silicate suspension treated wood.

3.4 Cone calorimetric analysis to assess the fire-retardancy performance of dilute alumino-silicate suspension treatment

The results of the fire resistance test indicate that time to ignition increased in few seconds in those specimens treated with higher dilute alumino-silicate suspension concentration, but no effect of the pH was observed (Table 2). The mean and peak heat release rates were not affected by the treatments, while results of the mass loss were variable but indicate no statistically significant effect of the treatments' concentration or pH. The total smoke was higher for many of the specimens than in controls in many of the samples, however, high standard errors indicate high variability in many of the samples.

The higher time to ignition of dilute alumino-silicate suspension-treated wood specimens agrees with previous findings on dilute alumino-silicate suspension impregnated and coated wood [12, 14], while the remaining variables measured in the cone calorimetry test did not indicate any relevant changes from the control specimens, agreeing with previous findings [14]. The pH variance did not have any effect on the fire resistance of the wood specimens. Our results agree with previous findings that indicate that calcium chloride and disodium hydrogen phosphate improve fire resistance of Mongolian *P. sylvestris* [40], and the addition of mineral fillers improved the fire resistance of wood polypropylene composites [41].

In this study, the impregnation process was carried out under carefully controlled conditions. Nonetheless, it is important to highlight that the alumino-silicate suspension tends to sediment over time, which may influence its distribution within the wood specimens if this are not located always exactly on the same way. Although the specimens were kept always fully submerged in the dilute alumino-silicate suspension during impregnation, minor movements during the process cannot be entirely excluded, and this may have contributed to part of the variability observed. While these factors did not compromise the overall outcomes, they highlight the need for further investigating the most promising treatment approaches, such as impregnation, coating, or dipping, for the application of alumino-silicate suspensions to wood.

The alumino-silicate suspension formulation included SDS as a surfactant, as it can enhance wetting and penetration of the treatment into the wood structure. Although this study did not include a direct comparison with formulations without SDS, the inclusion of this additive represents a key difference from previous studies in the field [14, 17], which did not employ surfactants. The improved suspension homogeneity and more uniform distribution observed in the present work compared with earlier reports may be partially attributed to the presence of SDS, which likely reduced particle agglomeration and facilitated better contact between the reactive species and the wood substrate. Nevertheless, the specific contribution of SDS to the overall performance remains to be clarified, and future research directly comparing formulations with and without SDS would help to elucidate its precise role.

4 Conclusions

This study demonstrates the preliminary potential of wood impregnation with dilute alumino-silicate suspension as an alternative to traditional wood preservatives, showing some improvement in decay resistance under non-leaching conditions, particularly at higher concentrations. Despite the relatively high number of replicates, some lower concentrations still showed high variability, which can be attributed to the natural variability of wood and biological durability testing. The pH adjustments appeared to have minimal impact, although the effects are difficult to separate from the increase in sodium ion concentration caused by the addition of NaOH. A 3% dilute alumino-silicate suspension impregnation led to a statistically significant improvement in the mechanical properties, with increases in MOE and MOR of 1.1 GPa and 16 MPa, respectively, compared to the controls; however, higher concentrations showed no further improvement, suggesting that the observed effect may not be directly attributable to the treatment. Slight gains in fire resistance were observed in ignition time. However, leaching tests revealed challenges with alumino-silicate suspension fixation, resulting in reduced durability, from durability class 1–2 to 3–4 after water exposure, highlighting the need for formulation optimization to enhance adhesion and minimize leachability. These findings highlight the emerging interest in using dilute alumino-silicate suspension-treated wood to combine biological protection with improved mechanical properties, though evidence remains limited and further studies are required to confirm long-term benefits. With further refinement, alumino-silicate suspension-based treatments could offer a non-toxic solution for extending wood service life in moisture-prone or fire-sensitive environments. Continued research should optimize formulations to enhance long-term durability and fire retardancy, supporting the development of next-generation sustainable building materials.

Supplementary Information

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Supplementary Material 1

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Author contributions

A.B.L. and A.H. made the conceptualization and experimental research. A.B.L. prepared the main manuscript text. A.H. secured the funding and resources. P.K. Supported the conceptualization and research and provided material resources. All authors reviewed the manuscript.

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Data availability

The data required to reproduce the above findings will be made available on reasonable request.

Declarations

Ethics approval and consent to participate

Not applicable.

Consent for publication

Not applicable.

Competing interests

The authors declare no competing interests.

Declaration of generative AI and AI-assisted technologies in the writing process

During the preparation of this work, the authors used ChatGPT to improve grammar and enhance the flow of the text. After using this tool, the authors reviewed and edited the content as needed and take full responsibility for the final version of the published article.

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