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Iroko wood (*Milicia excelsa* C.C. Berg), a good candidate for high-speed rotation-induced wood dowel welding: an assessment of its welding potential and the water resistance of its welded joints

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Abstract

The objective of this study was to determine the explanatory factors for the cold water resistance of welded joints of Iroko wood (*Milicia excelsa* C. C. Berg). The welding parameters considered and measured were grain direction, welding time, pre-drilled-hole depth, and rotation speed on welding temperature. The pull-out resistance of joints immersed in distilled water from 10 °C to 20 °C for five periods (7, 14, 21, 28, and 35 days) was also tested. The results show that the maximum welding temperatures (125 °C and 231 °C) were reached in less than 5s for all the dowelled specimens and obtained with the specimens inserted in the tangential direction, at 2100 rpm and 25 mm hole depth. The maximum value of the pull-out strength (3.28 MPa) was obtained with specimens inserted in the radial direction, at 1050 rpm and 20 mm hole depth. However, no significant difference was found between this result and those obtained with specimens inserted in the tangential direction, at 2100 rpm and 25 mm hole depth and bonded with PVAc. Despite the drastic decrease in pull-out strength of the specimens immersed in cold water within each group compared to the G1 reference group, some welded joints showed good maximum pull-out strength, greater than 2 MPa, and no failure after 5 weeks in cold water. MALDI-TOF analysis reveals the presence of inhibitory oligomers of the stilbene class at (379 Da = no Na⁺, and at 402 Da with Na⁺) chlorophorin (C₂₄H₂₈O₄), and geranyl-trihydroxy-stilbene (364 Da) which remain insensitive to water. In addition, the presence and slow leaching at (381 Da no Na⁺) of geranyl tetrahydroxy-stilbene, at 380 Da of cudraxanthone I (C₂₃H₂₄O₆), and at (377 Da) of neocyclomorusin (C₂₅H₂₄O₇) is an additional reason to justify the water stability of the Iroko welded joints. In conclusion, Iroko wood is a good candidate for the wood welding technique.

Keywords: wood welding, Iroko wood (*Milicia excelsa* C.C. Berg), pull-out strength, water resistance.

1- Introduction

Dowel insertion techniques, with or without adhesives, are common and remain the prerogative of furniture and construction professionals [1]. Recent years have seen the development of the wood welding technique based on temperature-induced softening until the wood components melt and the formation of a composite of entangled fibers embedded in a matrix of molten wood intercellular material, such as lignin and hemicelluloses, at the interface between the two joined wood surfaces [2-5]. It represents, to date, a technological breakthrough in wood joining in terms of joint time and environmental friendliness [6-9].

Previous studies show that mechanical friction by linear vibration and the high-speed rotation of wood dowels are used to produce strong joints, meeting the requirements of structural specifications in furniture and construction [5,10]. Nevertheless, these works to explain the adhesion theory and try to overcome the poor performance of the welded joints under wet conditions have remained the major concern in wood welding technology to date [11-14].

Chemical cross-linking reactions have been demonstrated by CP-MAS ¹³C-NMR. In particular, it is shown that they have little correlation with the strength of the welded joint during the very short welding period, but become more important after the welding period [5,15]. Similarly, gases emitted during wood welding have been determined by Py-GC/MS and gas chromatography coupled with a thermal conductivity detector and a flame ionization detector (GC-TCD/FID) where it was clearly established that thermal melting degrades hemicelluloses and affects the lignin polymer through depolymerization [5,1,16]. In contrast, pyrolytic gas chromatography-mass spectrometry (Py-GC/MS), attenuated total reflection Fourier transform infrared spectroscopy (ATR-FTIR), and X-ray photoelectron spectroscopy (XPS) have been used to explain thermochemical changes during wood welding. In addition, X-ray microdensitometry has been used to confirm and visualize at the microscopic level the densification of the welded interface [12,7,14,17].

New chemical structures of plant extracts are used in wood technology and medicine. To improve the durability and preservation of the physical properties of wood, the work of Bessike et al.[18] improved the attack resistance of wood biodeterioration agents based on *Jatropha curcas* seed oil and plant resins. MALDI results showed that the developed solution contained saturated fatty acids from Aiele (*Canarium schweinfurthii*, Engl.) resin and oleic, linoleic, stearic and palmitic acids from *Jatropha curcas*. These saturated fatty acids include 2-methyl-5-propan-2-yl cyclohexa-1,3-diene, 1-methyl-4-propan-2-yl cycl Hept-2-ene [4.1.0]. They also found that the hardener in *Vachellia nilotica* tannin extract reacted with a molecule of 2-[(1 S)- 4-methyl cyclohex-3-en-1-yl] propan-2-ol, one of the main components of Aiele resin, to produce catechin oligomers. Similarly, in an effort to contribute to the cold water resistance of treated beech, Eyinga et al.[7] showed that Padauk extracts contain a significant amount of aromatic methoxy groups (OCH₃) which leach slowly in cold water, such as santalin B (C₃₄H₂₈O₁₀) at 596 Da and santalin A (C₃₃H₂₆O₁₀) at 583 Da possessing an additional -CH₃ group and a xylan fragment formed by two glucoses and a glucuronic acid side chain (D- Xylp-1-4-β-D-Xylp-1-2-α-D-Me- GlupA) and another xylose- xylose- MeGlucuronic acid-conyferyl alcohol fragment (D-Xylp-1-4-β-D-Xylp-1-2-α-D-Me-GlupA-conyferyl alcohol). Then, Eyinga et al.[6] identified chlorophorin, a highly hydrophobic substance in Iroko powder before and after 30 days of immersion in cold water. Furthermore, cudraxanthone I and geranyltrihydroxystilbene exhibited low hydrophobicity in wet conditions. Oke-Altuntas et al.[19] investigated the cytotoxic, antioxidant, and antimicrobial activities of three compounds isolated from the methanolic extract on the root bark of *Milicia excelsa* Welw. C. C. Berg namely cudraxanthone I (1), neocyclomorusin (2) and (9βH)-3β-acetoxylanosta-7,24- diene (3). The findings of this study presented excellent cytotoxic effects on the growth of human cervical epithelioid carcinoma (HeLa) cell lines (IC₅₀ o 10 μg/mL). In addition, Ouete et al.[20] identified a new flavonoid, 2-(2,4 dihydroxyphenyl)-5-hydroxy-

8,8-dimethyl 4H,8Hpyrano[2,3-f]chromen-4-one (2' hydroxyatalantoflavone) with five known oligomers, including atalantoflavone, neocyclomorusin, 6-geranylnorartocarpetine, cudraxanthone I, and betulinic acid, in the roots bark of *Milicia excelsa* C. C. Berg.

The large-scale development of wood welding technology is still hampered by the low water resistance of welded wood. To find solutions related to its vulnerability, the role of extractive products is increasingly emphasized. In this context, the use of the tropical wood Iroko (*Milicia excelsa* C. C. Berg), rich in polyphenols, in the high-speed welding of wood dowels by rotation, would necessarily explain the dry and wet stability of its welded joints. The objective of this study is to determine the explanatory factors for the cold water resistance of welded joints of Iroko wood (*Milicia excelsa* C. C. Berg). Matrix-assisted laser desorption and time-of-flight ionization (MALDI-TOF/MS) analysis will be used to elucidate the reasons for the cold water resistance of its welded joints.

2- Materials and methods

2.1.Materials

2.1.1. Wood species

Iroko wood, whose scientific name is (*Milicia excelsa* C.C. Berg) is an African species in the Moraceae family, and one of the seven most commercially valuable species commonly used for local furniture and structural applications in Cameroon [19-21] It is a medium-heavy wood with a density of 630-670 kg.m⁻³ at 12% moisture, an estimated extractives content of 12.98 ± 0.90 and a high concentration of polyphenols [6,22]. Their vessels can reach 250 µm in diameter and fibers have a maximum length of 1700 µm and 27 µm of width [23].

2.2.Methods

2.2.1. Preparation of specimens for welding

Wands of 30 x 30 x 400 mm³ and 12 x 12 x 100 mm³ used to make the substrates and dowels, respectively, were machined to the wood grain and then dried to 12 % moisture content. The resulting substrates and dowels were conditioned for seven days in a climatic enclosure at 20° C and 65% RH to reach a constant mass before welding [24,17,25,5]. Six combinations of specimens based on grain orientation (radial and tangential), rotation speed, and hole depth on the substrate were produced for comparative testing of dowel welding parameters [26,1]. Each combination was repeated twenty times. The respective pre-drilling of the 8 x 20 mm² and 8 x 25 mm² holes compared to the 10 x 80 mm² dowel was performed at a speed of 2500 rpm, while welding in the radial and tangential directions was performed at 1050 and 2100 rpm respectively [27,15,6]. Once fusion and bonding were completed, at approximately 5s, the rotation of the dowel was stopped (Figure S1). The equipment used for welding was a drill press (model SERM CP 32 L/SCOA, Cameroon). During the welding process, temperature was monitored using fast-response thermocouple sensors (T1, T2, and T3) placed at three respective locations in the 1-mm-diameter pre-drilled holes located at 1 mm, 5 mm and 15 mm on the top surface of the substrate (Figure 1). A data logger (model OMEGA TC-08) with a frequency of 60 Hz was used to measure the temperature rise of the system. The response speed of the K-type thermocouple sensors was 0.1s. After welding, the wands were cut into 30 x 30 x 40 mm³ specimens and conditioned for 72 hours at 20 °C and 65 % relative humidity prior to pull-out strength testing [6]. Each specimen consisted of a dowel inserted into the substrate. The control wooden dowels were glued together with a polyvinyl acetate (PVAc) adhesive (VINYL forestali Milano, Italy). Before insertion into the substrate, the dowels were covered with a thin layer of PVAc adhesive (20 mm depth). Before pull-out strength tests, the welded specimens were conditioned for 72 hours at 20 °C and 65% RH.

2.2.2. Pull-out strength test of the welded joints

The welded dowels were removed from the holes in accordance with ASTM 2006 [28]. A universal type testing machine (Instron H6528 High Wycombe England) was used to test the specimens [29]. Twenty unimmersed specimens were removed from the holes to serve as a reference for the twenty Iroko specimens assigned to each respective period (7, 14, 21, 28, and 35 days) of cold-water immersion. A dowel gripping system inspired by ASTM 2000 [30] was preferred during the tensile test [29]. The dowels were removed from the substrates at a rate of 2 mm.min⁻¹ in accordance with ASTM 2009 [31] to compare the strengths [32,33]. Maximum, mean and standard deviation values of the pull-out strength (Table 4) were calculated for each species. The following equation developed by Belleville [32] was used to calculate the pull-out strength:

$$\delta = F_{\max}/s = F_{\max}/2\pi rh \quad (1)$$

Where δ , F_{\max} , s , r , and h refer to the pull-out strength, maximum shrinkage strength of the dowel, the lateral surface of the hole, dowel radius and dowel insertion depth respectively.

2.2.3. Cold water immersion test

The water resistance test was performed according to the European standard EN14080 [34]. Based on the combinations of optimal welding parameters that can provide good mechanical performance, batches of specimens were formed based on grain direction, rotation speed, and depth of holes on the substrate [1]. The welded specimens were then immersed in distilled water from 10 °C to 20 °C for five consecutive immersion periods: 7, 14, 21, 28, and 35 days, respectively. At the end of each immersion period, the specimens were stored in an oven (Drying Owen 1711442 China) set at 60-70 °C until 12.10 ± 0.09 % moisture content was achieved, and then the dowels were removed from the substrates.

2.2.4. Statistical Analysis

A statistical test was used to analyze the effect of wood dowel welding parameters induced by high-speed rotation on the mechanical properties of the welded specimens. These parameters included rotational speed (1050, 2100 rpm), insertion direction (radial, tangential), and depth of pre-drilled holes (20, 25 mm). The data from the tensile test as well as the test to determine the maximum temperature at the weld interface were also taken into consideration. The test results were subjected to analysis of variance (ANOVA) using R Core Team software [35]. Twenty repetitions per parameter were performed for each experiment.

2.2.5. MALDI-TOF/MS analysis

To identify non-and hydrophobic oligomers in Iroko (*Milicia excelsa* C.C. Berg) wood, Iroko powders were collected by sanding away from the weld bead for unimmersed (0 days) specimens and after 28 days of immersion in cold water respectively. Time-of-flight matrix-assisted desorption laser ionization (MALDI-TOF) analysis was performed by first dissolving 7.5 mg of powder in 1 mL of acetone/water. Then, 3 mL of this solution was added to 3 mL of a 2,5-dihydroxy benzoic acid (DHB) matrix. Dedicated specimen spots on the test plate were first coated with 1.5 mL of a 0.1 M NaCl solution in 2:1 v/v methanol/water as a test activator and pre-dried. Then, 1.5 mL of the specimen solution was placed on its dedicated spot and the plate was dried again. The reference substance used for equipment calibration, up to 2000 Da, was red phosphorus. MALDI-TOF spectra were obtained with a Shimadzu Biotech Axima-Performance mass spectrometer (Kratos Analytical Shimadzu Europe Ltd., Manchester, UK) using a positive polarity linear tuning mode. Measurements were performed by running 800 profiles for both unimmersed and immersed specimens, with two (2) cumulative shots per profile. The accuracy of the spectrum is +1 Da [6].

3. Results and discussion

Figure 2 shows the temperature curves obtained for the six groups' dowelled. It can be clearly seen that the average welding temperatures of the three thermocouples reach values of

124.6 °C in the radial direction at a depth of 20 mm and 231.2 °C in the tangential direction at a depth of 25 mm between 4 and 5 s for the six groups, respectively (Table 1), which is consistent with the findings of Mansouri et al. [36] for rapid dowel rotation welding.

It should be noted that the different profiles showed no decrease in temperature after reaching the maximum temperature. This is strong evidence that all three parameters influence the temperature increase at the weld interface. Similarly, Rodriguez et al.[1] reported the significant influence of rotational speed on soldering performance, followed by species, insertion direction as well as the diameter of the receiving hole rather than the depth of the hole on the substrate. One explanation for this behavior would be the rotational speed-induced friction at the weld interface that increases temperatures up to the softening temperature of amorphous wood polymers, mainly hemicelluloses and lignin [33,32]. In contrast, Sun et al.[16] indicate that differences in the mechanical performance of a wood at the time of welding are primarily the result of differences in the original lignin structures as well as in the welding temperatures determined on a species basis. In addition, we obtained lower temperatures than those found in the literature for species with similar physical-mechanical properties [1], probably due to the location of the thermocouples, the accuracy of the temperature recording module, and the welding conditions [37].

Statistical analysis reveals a significant effect of welding time, rotation speed, and the interaction between welding time and grain direction (Table 2). The highest average pull-out strength values (2.88 and 2.54 MPa) were obtained with groups G1 and G4, inserted at 1050 rpm in the radial and tangential direction, respectively (Table 3). In addition, specimens from group (G5) also provided a fairly good pull-out strength (2.53 MPa) close to that of specimens from groups (G1 and G4). This strength can be justified in light of the literature [27,32] a dowel rotation speed close to 1000 rpm provides a sufficient softening temperature of the wood polymers to allow good strength of the welded joint. Furthermore, Kanazawa et al.[15]

show that as soon as the depth of the pre-drilled hole is greater than 15 mm, almost all the conditions used improve the strength of the weld. This means that the contact area of the dowel with the welded interface is a determining factor. The larger this area, the higher the strength, regardless of the application conditions used [15,38,24]. In addition, ^{13}C NMR analysis confirms that cross-linking of lignin with carbohydrate-derived furfural is more pronounced in the pre-drilled hole of the substrate than on the dowel when the ratio of the pre-drilled hole to the dowel diameter is high [32,4]. This is also evidenced by the densification of the contact area on X-ray [5]. Another aspect affecting the pull-out strength might be the presence of oily extractives which limit the friction temperature at the weld line, as reported in the literature for *Tectona grandis* [26]. Anatomically, large wood rays of Iroko wood which are commonly 4-10 seriate [23], possibly also limited insertion tangentially of the dowels on the substrate, producing more charring. This could potentially explain the interaction between the welding time and the grain direction (Table 2). A comparison of the pull-out strength results for the six different dowelled combinations also shows that our results are similar to those obtained with other species that have a similar density [26]. A pairwise Wilcoxon test was performed, and Homogeneity groups were found to determine whether there was a significant difference between the combinations. Our results showed (Table 3) no significant difference in the values obtained between the best-welded joints (Group 1) and PVAc-glued controls joints.

Table 4 shows the water contents and pull-out strengths of the welded joints when dry and after 35 days of immersion in cold water. Similarly, Figure 3 shows the average, maximum, and standard deviation of the pull-out strengths obtained for the six combinations of dowelled specimens (G1 to G6). Varying the welding parameters such as grain orientation, pre-drilled hole depth, and dowel rotation speed yields results comparable to those of the PVAc bonded specimens (G7). It should be noted that the failure zones of these different

specimens in these tests were a priori located at the welded interface for the welded specimens and at the dowel and substrate level for the PVAc bonded specimens. Furthermore, when the optimal welding parameters are taken individually as parameters that have a significant effect on pull-out strength, it is clear that the pull-out strength of the specimens immersed in cold water decreased significantly within each group (Figure 3) compared to the reference group G1 consisting of the specimens not immersed in cold water. In contrast, we found no significant correlation of this loss of strength between the five groups (G2, G3, G4, G5, and G6) consisting of specimens immersed in cold water (10 °C to 20 °C), respectively. This behavior could be explained by the cellular structure of the wood, as the higher and more constant the density concentration of wood at the welded interface, the better the mechanical performance of the joint, followed by the marked difference in wood density between the initial and final wood [24]. In terms of orientation, this wood heterogeneity is a limiting factor in achieving high local compression ratios during the welding process [24]. This result is in agreement with the findings of Kanazawa et al [15], Belleville et al [32], Rodriguez et al [1]. An additional explanation for this behavior could also be the chemical composition of Iroko wood. Ganier et al [10], Eyinga et al [6] show that the water resistance of a joint is strongly correlated with the type and amount of extractives it contains. It should also be noted that some Iroko welded joints also showed microcracks after the cold water immersion test. This phenomenon could certainly be explained by the absorption phenomenon, which shows the influence of structure strongly correlated with the size and percentage of several wood tissues, such as vessels, axial parenchyma, fibers, and rays, which are the main water flow paths in the wood, as shown by Manga et al. [39,40], Fonyuy et al [41], on the case of sapelli (*Entandrophragma cylindricum*), sipo (*Entandrophragma utile*), kosipo (*Entandrophragma candollei*), tali (*Erythrophleum suaveolens*) and Bilinga (*Nauclea diderrichii*) respectively.

In the Figure 4, the peaks of the MALDI-TOF spectra clearly show that resveratrol = 3,5,4'-trihydroxystilbene (250 Da) of chemical formula $C_{14}H_{12}O_3$, a potent antioxidant of the flavonoids class acting as a substantial barrier against attacks, is strongly affected on contact with water. This would explain the very significant loss of color of Iroko wood in humid conditions. Conversely, stilbene = multiprotonated 1,2-Diphenylethene (256 Da) (calculated $253 + 3 H^+$) dissolves slowly. Moreover, some inhibitory oligomers of the stilbene class such as chlorophorin = 5-[(1E)-2-(2,4-Dihydroxyphenyl)ethenyl]-2-[(2E)-3,7-dimethyl-2,6-octadien-1-yl]-1,3-benzenediol (379 Da = no Na^+ , and 402 Da with Na^+), and geranyl trihydroxy stilbene (364 Da) remain insensitive to water [6]. This behavior could be explained by the strong hydrophobicity of these compounds, which justifies their slow or zero leaching in contact with moisture and are responsible for the dimensional stability of Iroko wood. Geranyl-tetrahydroxy-stilbene (381 Da no Na^+), cudraxanthone I = 5,9,11-trihydroxy-3,3-dimethyl-8-(2-methylbut-3-en-2-yl)pyrano [3,2-a]xanthene-12-one (380 Da), and neocyclomorusin = 11,20-dihydroxy-16-(2-hydroxypropan-2-yl)-7,7-dimethyl-2,8,17-trioxapentacyclo [12.9.0.03,12.04,9.018,23] tricos-1(14),3(12),4(9),5,10,18(23),19,21-octaen-13-one (377 Da) are three antioxidants generally present in Iroko wood roots bark and their content decreases by about half after 28 days of immersion in cold water. This could be due to the harmful impact of free radicals responsible for the degradation of the wood structure. Free radicals are the products of basic cellular metabolism. They consist of atoms or molecules whose outer shell contains unpaired electrons. This odd number of electrons makes them unstable and very reactive and encourages them to capture electrons from other molecules to gain stability. By stealing electrons from them, they in turn transform these substances into free radicals, creating a chain reaction that can oxidize and damage cells, tissues and organs [19,20].

4. Conclusion

The welding potential of wood dowels induced by high-speed rotation and the water resistance of welded wood joints were investigated on Iroko wood. Welding parameters such as grain direction, welding time, pre-drilled hole depth, and rotation speed were measured over the welding temperature. At the same time, a series of PVAc-bonded specimens was made to serve as a reference for the welded specimens in the mechanical tensile test. The main results show that the specimens that were not immersed in water exhibited a maximum pull-out strength (3.28 MPa) comparable to that of the PVAc-bound joints (3.87 MPa). In addition, there was a drastic decrease in the pull-out strength of the specimens immersed in cold water within each group compared to the reference group G1 consisting of the specimens not immersed in cold water. In contrast, we found no significant correlation of this loss of strength between the five groups (G2, G3, G4, G5, and G6) consisting of specimens immersed in cold water (10 °C to 20 °C), respectively. MALDI-TOF results confirm this differential behavior between groups through the presence of inhibitory oligomers of the stilbene class at (379 Da = without Na⁺, and at 402 Da with Na⁺) chlorophorin (C₂₄H₂₈O₄), and geranyl-trihydroxy-stilbene (364 Da) which remain insensitive to water. In addition, the presence and slow leaching at (381 Da without Na⁺) of geranyl tetrahydroxy-stilbene, at 380 Da of cudraxanthone I (C₂₃H₂₄O₆), and at (377 Da) of neocyclomorusin (C₂₅H₂₄O₇) is an additional reason for this behavior. Based on this result, the chemical composition of Iroko may be sufficient to impart some natural water durability to its welded joints, although this aspect deserves further study.

Credit authorship contribution statement

Jalin Jalin Eyinga Biwôlé: Data analysis, GIMP 2.10.32 software, ChemDraw software, R Core Team software, Writing – original draft, Review and editing. **Achille Bernard Biwolé:** Conceptualization, Project administration, Resources, Supervision, Validation. **Joseph Zobo Mfomo:** Formal analysis, Supervision, Validation. **Antonio Pizzi:** Conceptualization, Project

administration, Resources, Supervision, MALDI-TOF interpretation, Validation. **Cesar Segovia**: Formal analysis, Resources, Validation. **Dieudonné Abessolo**: Formal analysis, Resources. **Benoît Ndiwe**: Formal analysis, Supervision. **Evariste Fedoung Fongzossie**: Formal analysis, Supervision, Validation. **Atangana Ateba**: Conceptualization, Project administration, Resources, Supervision, Validation. **Pierre-Jean Meausoone**: Supervision, Resources, Validation.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Figure list

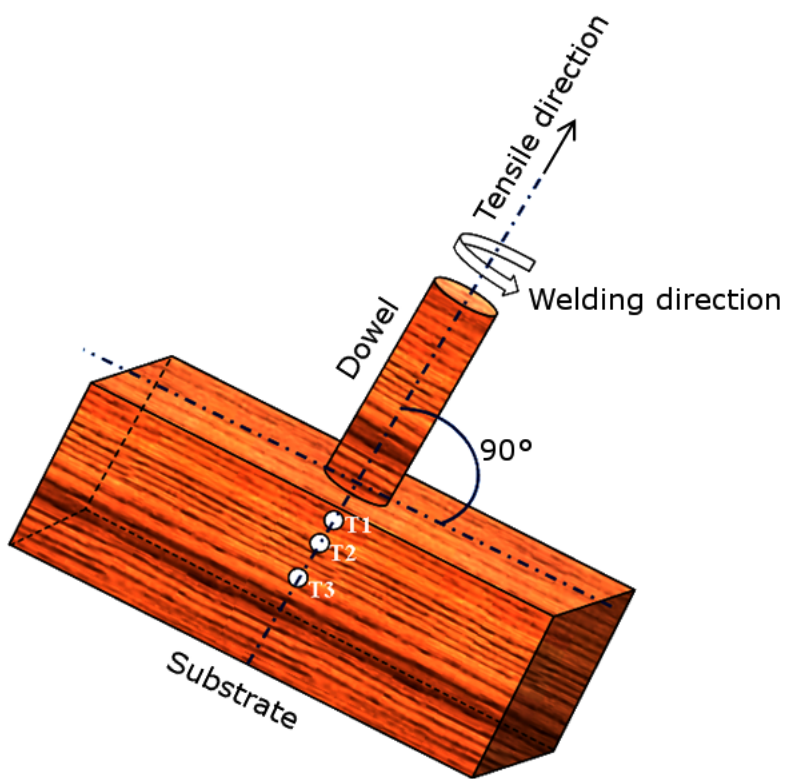
Figure 1: Location of thermocouples on the substrate for temperatures measurement during the welding process. T1, T2, T3 correspond to the thermocouple 1, 2, and 3, respectively.

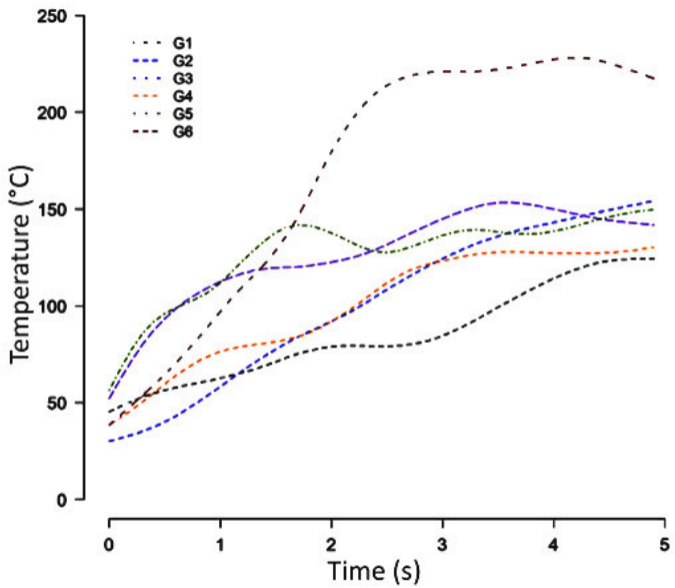
Figure 2: Temperature profiles obtained during the welding process for the six specimen combinations dowelled (G1 to G6) by varying the welding parameters: grain orientation, pre-drilled hole depth and dowel rotation speed.

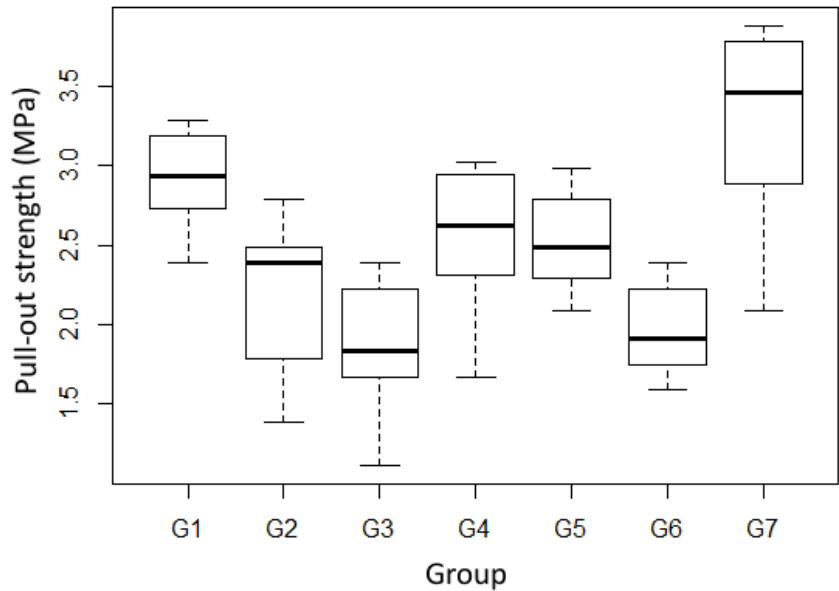
Figure 3: Distribution of average and maximum pull-out strength of the seven groups: G1 specimens tested dry; G2-G6 specimens immersed for 7, 14, 21, 28, and 35 days of immersion in cold water; G7 specimens bonded with PVAc.

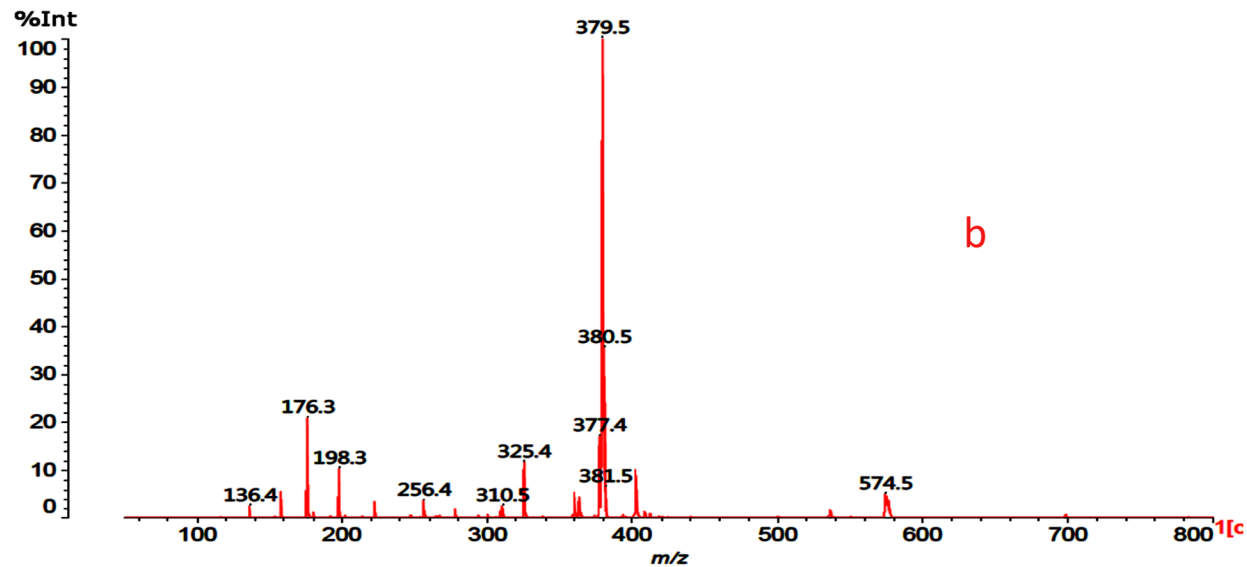
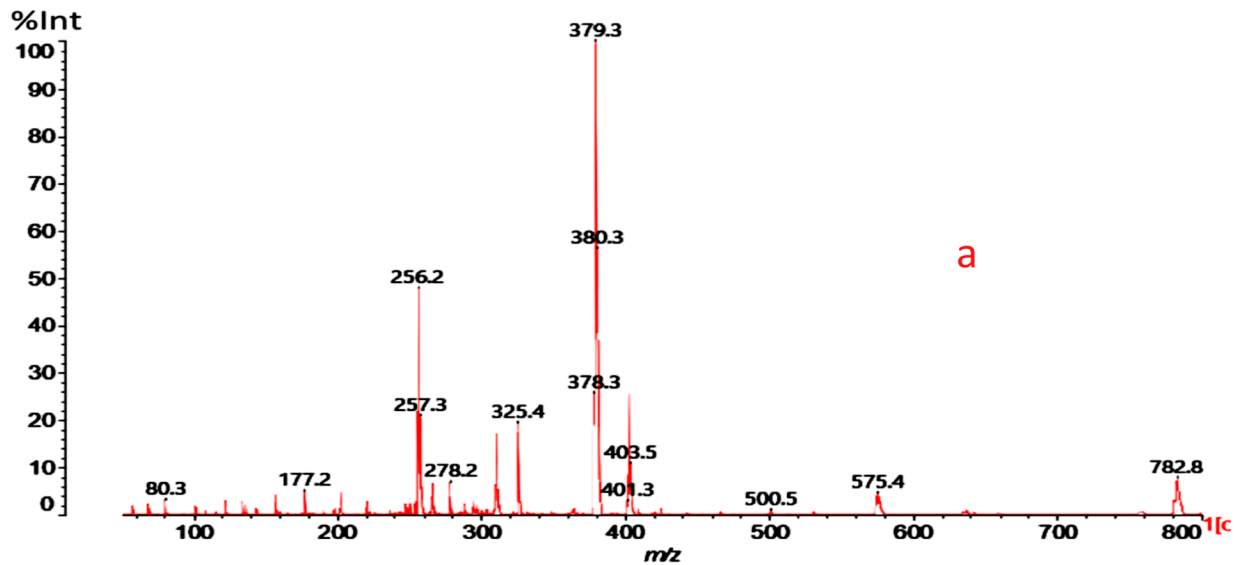
Figure 4: MALDI-TOF spectra of powders collected from the welded specimens: (a) Iroko unimmersed, (b) Iroko immersed in cold water for 28 days.

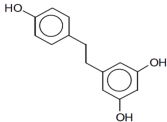
Figure 5: Chemical structures of oligomers identified by MALDI-TOF analysis at 0 and after 28 days of immersion in the cold water of Iroko wood welded joints.



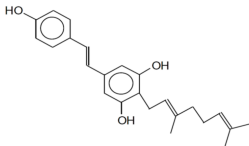




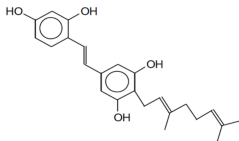




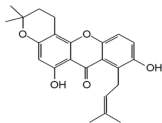
256 Da with Na⁺, stilbene
multiprotonated
(calculated 253 + 3 H⁺)



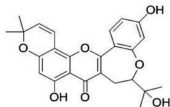
377 Da = no Na⁺,
geranyltrihydroxystilbene



379 Da = no Na⁺, and 402 Da
with Na⁺, chlorophorin



380 Da = no Na⁺,
cudraxanthone I



Neocyclomorusin
176 Da

Table 1. Maximum experimental values of welding temperatures obtained for the six specimens combinations studied (G1 to G6) by varying the following welding parameters: grain orientation, pre-drilled hole depth, and dowels rotational speed.

Group	Grain direction (R,T)	Rotational speed (rpm)	Hole depth on the substrate (mm)	Mean temperature (°C) ±SD	Maximum temperature (°C)
G1	Radial	1050	20	99 ± 38	125
G2	Tangential	1050	20	65 ± 27	154
G3	Radial	1050	25	86 ± 42	155
G4	Tangential	1050	25	140 ± 53	132
G5	Radial	2100	25	86 ± 51	149
G6	Tangential	2100	25	105 ± 49	231

Table 2. Result of the analysis of variance testing the effect of welding parameters (grain orientation, welding time, pre-drilled hole depth, and rotational speed) on the pull-out strength of the welded joints.

Source of variation	Mean square	F-value	Pr.>F ^a
Welding time	3.614	24.366	<0.0001***
Hole depth	0.982	6.621	0.0129*
Rotational speed	0.257	1.734	0.1934
Grain direction	0.111	0.748	0.3910
Welding time x Grain direction	2.748	18.527	<0.0001***
Residuals	0.148		

* Asterisk indicates significance at $\alpha = 0.05$. *** very significant. * moderately significant

Table 3. Average values of the pull-out strengths obtained for the six specimens combinations studied (G1 to G6) by varying welding parameters: grain orientation, pre-drilled hole depth, and dowels rotational speed and on the specimens PVAc glued (G7). Each value was calculated on 20 replicates used for measurement. SD means Standard deviation.

Group	Insertion direction	Rotational speed (rpm)	Hole depth on the substrate (mm)	Pull-out strength (MPa)		Homogeneity group
				Mean	±SD	
G1	Radial	1050	20	2.88	0.32	A
G2	Tangential	1050	20	2.21	0.47	B
G3	Radial	1050	25	1.85	0.43	BC
G4	Tangential	1050	25	2.54	0.47	ABD
G5	Radial	2100	25	2.53	0.32	ABD
G6	Tangential	2100	25	1.98	0.38	BCDE
G7	-	-	20	3.23	0.64	ABDF

Note : The homogeneity of the groups makes it possible to compare two by two the degree of influence of each group of specimens on their mechanical performance.

Table 4. Average values of moisture contents after immersion in cold water for specimens in groups G2, G3, G4, G5, and G6. The moisture contents were reduced to 12.10 ± 0.09 % moisture before the tensile test. The average value was calculated over 20 replicates used for the measurement. SD means standard deviation.

Immersion time in water (days)	Moisture content (%)		Pull-out strength (MPa)		
	Mean	±SD	Mean	±SD	Max
Unimmersed (0 day)	12.10	0.09	2.88	0.32	3.28
Immersed (7 days)	14.31	0.65	2.21	0.47	2.78
Immersed (14 days)	15.75	0.67	1.85	0.43	2.38
Immersed (21 days)	16.62	0.37	2.54	0.47	3.02
Immersed (28 days)	19.81	1.18	2.53	0.32	2.98
Immersed (35 days)	21.91	0.21	1.98	0.38	2.31
Glued	12.10	0.09	3.23	0.64	3.87