INFLUENCE OF CHEMICAL TREATMENT ON THE STRUCTURAL PROPERTIES AND DURABILITY OF LOCALLY AVAILABLE BAMBOO AS A SUSTAINABLE CONSTRUCTION MATERIAL

PEC FUNDED PROJECT

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Completed research project in accordance with PEC funding

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APPROVAL SHEET

It is certified that the contents of the research project titled “Influence of Chemical Treatment on the Structural Properties and Durability of Locally Available Bamboo as a Sustainable Construction Material” submitted by Maryam Tariq have been found satisfactory.

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ABSTRACT

The paper aims to investigate the effectiveness of acid-based chemical treatment on the durability, physio-chemical, structural, and thermal properties of bamboo as a sustainable construction material. The study specifically focuses on the use of acetic acid and zinc chloride as the chemical modifiers to compare their effectiveness with the control samples. The results indicate that the chemical treatment of acetic acid yields optimized results by reducing water absorption to 9% and swelling to 56%, 21%, and 12% in terms of length, width, and thickness respectively. Furthermore, the flexure, tensile, and shear strengths of the acetic acid treated samples show significant improvement by 40%, 11%, and 31% respectively, while the compressive strength compromises by 11%. To determine the mechanism behind these improvements, the effect of esterification on the carbonyl/hydroxyl absorbance ratio is analyzed using FTIR, which shows an increase in cellulose crystallinity as determined by XRD. Conclusively, the research has significant implications for green construction as it demonstrates the potential of acid-based chemical treatment to improve the performance of bamboo, a sustainable construction material.

Keywords:

Bamboo, Chemical treatment, Sustainable construction material, Acetic acid, Physio-chemical properties

1 INTRODUCTION

Sustainable Development, defined as the simultaneous pursuit of economic, social, and environmental goals for creating a better future [1]. Sustainable construction aims to mitigate its substantial carbon footprint while fostering environmental sustainability, community well-being, and biodiversity [2].

As part of a global effort to reduce CO_2 relevant to construction and building industry, bamboo is recognized as a structural alternative and seismically resistant material [3-4]. Bamboo is a versatile building material with excellent load-bearing capabilities [5]. The suitability of bamboo as a sustainable construction material has been extensively investigated by researchers such as K. M. Siddique et. al [6] and Wagemann et. al [7] and they highlighted the physical characteristics of various species of bamboo including Bambusa tulda, Dendrocalamus strictus, Dendrocalamus hamiltonii, Arundinaria falcata and Bambusa bamboo. With its exceptional tensile and compressive strengths, comparable to steel and concrete respectively [8-9], bamboo has emerged as a promising alternative to conventional building materials. Bamboo has fast growth rate as compared to wood. However, the utilization of bamboo in pristine condition for construction purposes is prone to severe durability concerns over the designed service period.

Bamboo requires treatment to enhance its resistance to fungal and insect damage [10] and when chemically preserved, it can last up to 40 years [12-13]. In order to ensure sustainability, eco-friendly preservatives are preferred. However, common bamboo preservatives such as copper, arsenic, and chromium pose a significant environmental risk via leaching which causes water pollution [13]. Alkali treatment using NaOH has been proved to enhance the hydrophilic property and improve the adherence of natural fiber matrix in composites [15-16]. Heat and smoke treatments improve the dimensional stability but they weaken the structural strength and cause environmental pollution [16-17]. Zinc chloride-silicone oil pretreatment has been employed to reduce hygroscopicity and increase dimensional stability in wood [18]. $ZnCl_2$ was found to be an effective fungicide and fire retardant [19]. The use of 5% acetic acid solutions has also been explored to prevent degradation caused by rot fungi in palm wood [20].

Gauss et al. [21] performed the chemical alteration on bamboo by employing citric acid treatment reduced bamboo tensile strength by 30% but slightly improved bending and compression strengths, while acetic acid and zinc chloride treatments are considered for bamboo preservation, with their effects on properties yet to be studied.

To the best of our knowledge, this present study evaluates the physicochemical characteristics, durability, and mechanical properties of bamboo with environmental-friendly chemical (acid) treatment under ambient conditions for its potential utilization in green construction. In summary, bamboo has emerged as a promising sustainable building material, with its exceptional durability and mechanical strengths obtained after chemical treatment.

2 MATERIALS AND METHODS

2.1 Materials and preparation of samples

The bamboo specie used for this study was taken from Tehsil Chunian, District Kasur 55220, Punjab, Pakistan (31° 5' 22" North, 74° 24' 39").

Full grown bamboo culm of more than 3 years was cut into bottom, middle, and top sections according to the ISO 22157-1 [22] using fine wood saw. Samples were collected from internodes due to the nodal section potentially being a point of weakness. The harvested bamboo was dried under shade for 4 weeks to examine their physio-.chemical properties and mechanical characteristics [23-24].

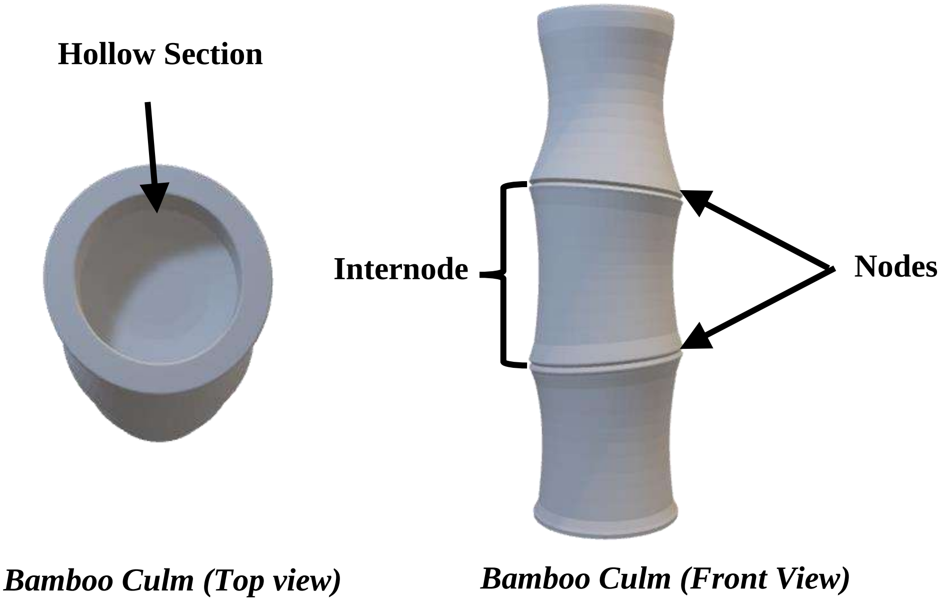

Figure 1. Front and top views of bamboo culm alongside the components

Figure 2: Cutting of bamboo using (a) Wood saw, (b) Telescopic Crosscut and mitre saw, and (c) Wood Chisel Mortizer

Natural fibres have weak interfacial interaction with comparatively hydrophobic polymers due to the presence of hydroxyl and other polar groups. The chemical treatments (described in introduction section) lessen the hydrophilic nature and ability to absorb moisture [15]. Dried samples taken from each section of bamboo were immersed into 5% (v/v) treatment solutions of acetic acid (weak acid) and zinc chloride ($ZnCl_2$) (weak base) under ambient conditions as mentioned in **Table 1.**

Since the surfaces of chemically-treated fibers are rougher than untreated fibers, the effective area of contact is higher. The solution concentration employed for treatment was selected to be 5% (v/v) [25].

Table 1: Treatment and its effects

Samples designation	**Chemicals for Treatment**	**Solution Concentration % (v/v)**	**Solution Absorption (%)**		
-	-	%	Avg.	SD	COV
C-G	Control	-	-	-	-
AA-G	Acetic Acid	5	39.61	1.30	0.03
Z-G	Zinc Chloride	5	24.32	1.60	0.07

2.2 Water absorption and swelling

Bamboo samples with a dimension of 20 x 20 mm (L x W) were obtained from the middle section and subjected to a 10-day leaching process in accordance with AWPA E10:16 instructions [26]. The samples were then submerged in distilled water to measure water absorption (WA) and swelling in width (WS), and thickness (TS), respectively. Readings were taken immediately after removing the sample from water to obtain accurate absorption values. The weight and dimensions were measured using Vernier Calipers with an accuracy of 0.001 g and 0.01 mm, respectively. The water was changed every 24 hours to maintain constant proportions, and readings were taken up to 240 hours. After the completion of the leaching process, the percentage increase in weight and dimensions relative to the initial readings were determined to assess the impact of acid-based chemical treatment.

2.3 Fourier Transformed Infrared (FTIR) spectroscopy

Fourier transform infrared (FTIR) spectroscopy was used to analyze the chemical alterations as a result of pretreatment. The samples were grinded and sieved through 40 mesh size. Afterwards, they were chemically treated using acetic acid and $ZnCl_2$ and finally dried at 60^{o}C. FTIR Spectrometer with Attenuated Total Reflection (ATR) module (Cary 630, Agilent, was used to perform the analysis. For each analysis, 32 scans with a resolution of 4 cm^{-1} were used in the spectral range of 4000-600 cm^{-1}.

2.4 X-ray Diffraction

The treated and untreated samples were scanned between 5^{o} and 50^{o} at 2^{o}/min using an X-ray ^{o}diffractometer (D8, Bruker, operated at a voltage of 40 kV and a current of 40 mA. The samples were prepared via similar procedure which was opted for FTIR analysis. Using the Segal peak height method [27], the crystallinity of cellulose (CrI) of all samples was determined.

2.5 Mechanical behavior

As shown in **Figure 3**, flexure, tension, shear, and compression tests were performed on bamboo samples which were precisely cut according to ISO and ASTM standards. Samples were taken from bottom, middle, and top section of bamboo. Using a digital Vernier caliper with a precision of 0.01 mm, the necessary dimensions of all precisely cut samples were measured. Prior to testing, samples were dried at room temperature for 168 hrs.

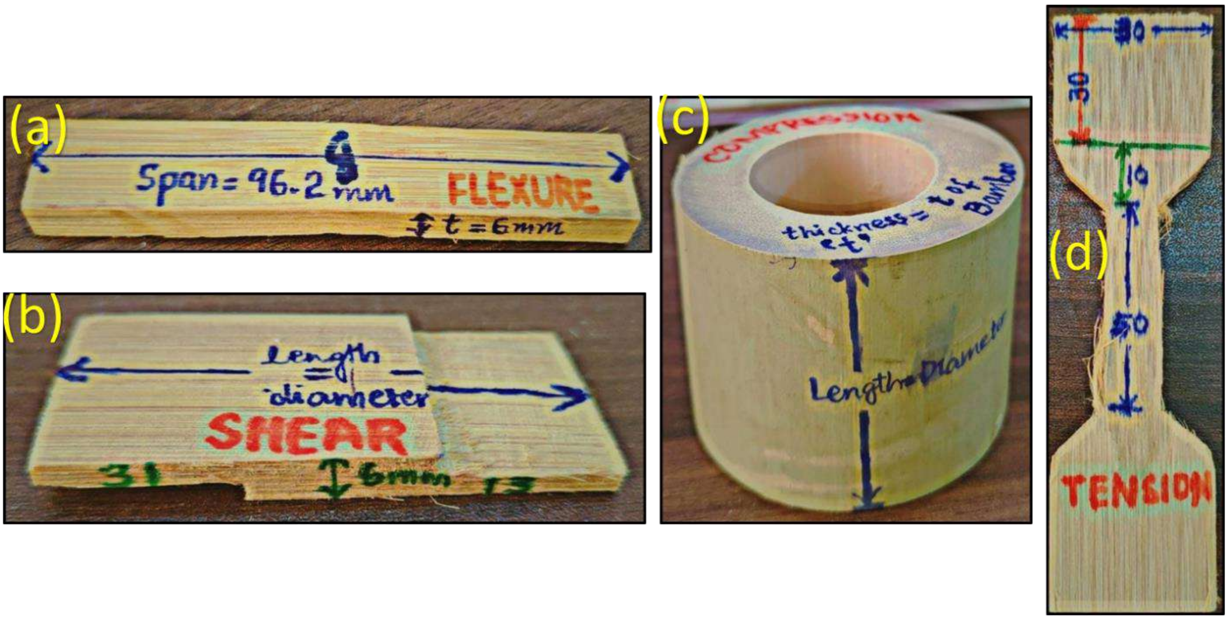

Figure 3: Bamboo samples for (a) Three-point bend test, (b) Shear test, (c) Compression test, and (d) Tension test

2.5.1 Three-point bend test

Bamboo samples, each with a dimension of 96 mm x 15 mm x 6 mm (L x W x T) [28] were employed to get ultimate flexure strength as indicated in **Figure 3.** The testing was performed using an electromechanical universal testing equipment (Shimadzu MWG-50kNA) with a capacity of 50 kN and a displacement rate of 3 mm/min. The modulus of elasticity (MOE), modulus of rupture (MOR), and proportional limit (LOP) were calculated in accordance with ASTM D7264-07.

2.5.2 Tension parallel to fibers

According to ASTM D 3039 [29], the tension test parallel to fibre was conducted. For each bamboo samples, dimensions were maintained at 50 mm x 10 mm x 6 mm (L x W x T). Tests were performed using an electromechanical universal testing machine (Shimadzu MWG-50kNA) with a 50 kN capacity. For each test, a displacement rate of 3.0 mm/min was applied. The longitudinal tensile strength was computed by dividing the peak load with the reduced cross-section area, while the modulus of elasticity was calculated using the strain gauges installed in the apparatus.

2.5.3 Interlaminar Shear

An interlaminar shear test was used to assess the behavior of bamboo samples under shear. The depth of the shear sample was adjusted as per standard [30], resulting in an area of A=L*t (where L and t are length and thickness respectively) in the shear plane due to loading direction at two sites. The length was maintained as per ISO 22157-1 [22], which is equal to the diameter of the sample. When loaded in tension, the shear plane being in the middle of the specimen, it exhibited pure shear. Shear strength was determined by dividing the peak load at failure with the shear area. A 50 kN capacity universal testing machine (Shimadzu MWG-50kNA) was used for all of the interlaminar shear tests, with a displacement speed of 3.0 mm/min.

2.5.4 Compression parallel to fibers

Compression properties parallel to the longitudinal direction was significantly higher than perpendicular to the longitudinal direction [31]**.** To examine the impact of various treatments on compression behavior parallel to the bamboo longitudinal axis, samples with length equal to the diameter of bamboo were taken. The thickness of samples were kept equal to the thickness of bamboo. A 300 kN capacity universal testing machine (Tintus Olsen. Willow grove. PA., U.S.A.) was employed to subject the samples to a cross-head displacement rate of 3 mm/min in accordance with ASTM D143-14[32]. The longitudinal compressive stress was determined by dividing the maximum load by the cross-sectional area of the sample. The ultimate strength and elasticity modulus were computed from the values obtained using strain gauges.

Figure 4: Apparatuses employed for (a) flexure, (b) tension, (c) shear, and (d) compression tests

3 RESULTS AND DISCUSSION

3.1 Treatment Effects

Table 1 provides an overview of the absorption of chemical treatments of varying concentrations on bamboo samples. Three samples were taken from the middle of the bamboo for each treatment. The averages and respective coefficients of variance (COV) were also determined. The solutions (G-C, G-AA, and G-Z) exhibited varying absorption levels, with CH_3COOH showing the highest absorption and resulting in improved contact with the fluid. This might be due to high extent of chemical reaction between –OH groups of cellulose and lignin and acetic acid. This also suggests the higher chemical activity of acetic acid as compared to $ZnCl_2$ and ultimately reduction in chemical resistance [33].

3.2 Water Absorption and Swelling

Chemically modifying lignocellulosic materials, such as bamboo, is a crucial step towards improving their dimensional stability by reducing water absorption and swelling. Due to its porous nature and high concentration of hydroxyl groups, bamboo readily absorbs water through hydrogen bonding, which can lead to swelling and other detrimental effects [34-35].

Tables 2 and 3 display the results of investigating the impact of acetic acid and zinc chloride chemical treatments on the water absorption and swelling of bamboo samples. The statistically variations in water absorption and swelling provide the impact of chemical on bamboo. Initially for first 48hrs WA was high and increased rapidly to 12.5%, 8.5% and 10.8% for all the three conditions respectively and likewise for the swelling. After 240 hours, an acetic acid-treated bamboo showed a substantial 13% reduction in water absorption (WA) compared to the reference sample, while zinc chloride-treated bamboo had only a minimal 3.5% decrease in WA.

By measuring the thickness and width in the centre of the sample, this study monitored the changes in dimensions due to swelling. Volumetric variations were not considered due to the inherent curvature of the samples. The results, presented in Table 5, show that the samples treated with zinc chloride (Z-G) exhibited significant changes in dimensions compared to the control group (C-G). After 240 hours, swelling based on thickness was reduced by 12% and 10% in case of AA-G and Z-G treated samples, respectively. Moreover, results showed that the reductions in swelling based on width in case of AA-G and Z-G were 21% and 15% respectively.

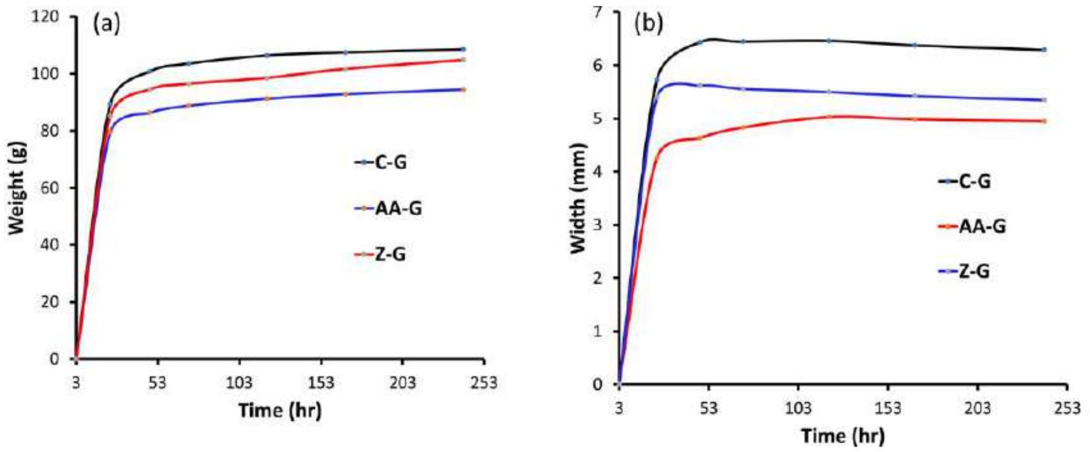

Figure 5. Variations in (a) water absorption and (b) swelling potential of bamboo samples

Table 2. Water Absorption (%) of acetic acid and $ZnCl_2$ treated bamboo samples (AA-G and Z-G) as compared to the reference sample (C-G)

n=9

	24 h		48 h		120 h		240 h		240 h
Sample	**Avg**	**COV**	**Avg**	**COV**	**Avg**	**COV**	**Avg**	**COV**	**Water Reduction (%)**
C-G	89.55	0.23	100.74	0.09	106.38	0.04	108.50	0.07	-
AA-G	79.55	0.16	86.35	0.08	91.30	0.08	94.48	0.08	-12.92
Z-G	85.18	0.04	94.42	0.03	98.52	0.03	104.76	0.01	-3.45

Table 3. Evaluation of swelling potential for treated conditions

		24 h		48 h		120 h		240 h		240 h
Parameter	**Sample**	**Avg**	**COV**	**Avg**	**COV**	**Avg**	**COV**	**Avg**	**COV**	**Swelling Reduction (%)**
Width	C-G	5.73	0.04	6.43	0.06	6.46	0.02	6.29	0.08	-
	AA-G	4.26	0.09	4.63	0.08	5.03	0.03	4.95	0.03	-21.2
	Z-G	5.40	0.08	5.62	0.04	5.50	0.09	5.35	0.04	-14.9
Thickness	C-G	12.72	0.06	13.12	0.03	14.41	0.07	14.40	0.09	-
	AA-G	13.18	0.07	12.58	0.09	12.68	0.02	12.95	0.10	-12.0
	Z-G	12.75	0.05	13.05	0.1	12.75	0.06	12.95	0.08	-10.1

3.3 Mechanical Characteristics

Table 4. Three point bend test of bamboo samples for all analyzed conditions

n=27

Section **-**	**Sample** **-**	**Dimension** **L*w*t (mm^3)**	**Treatment** **-**	**Fmax (COV)** **N**	**σult (COV)** **Mpa**	**MOE (COV)** **Gpa**	**MOR (COV)** **Mpa**	**LOP (COV)** **Mpa**
Bottom	GB-C	96*15*6	Control	399.92 (0.07)	4.42 (0.07)	0.13 (0.09)	51.29 (0.08)	1.33 (0.09)
	GB-A	96*15*6	Acetic acid	563.52 (0.01)	6.25 (0.01)	0.21 (0.03)	77.97 (0.06)	2.99 (0.01)
	GB-Z	96*15*6	Zinc chloride	468.77 (0.01)	5.20 (0.01)	0.20 (0.01)	92.04 (0.01)	2.88 (0.03)
Middle	GM-C	96*15*6	Control	406.39 (0.05)	4.50 (0.06)	0.13 (0.08)	51.43 (0.03)	2.61 (0.06)
	GM-A	96*15*6	Acetic acid	499.87 (0.10)	5.54 (0.03)	0.18 (0.05)	75.51 (0.03)	3.19 (0.09)
	GM-Z	96*15*6	Zinc chloride	478.8 (0.04)	5.31 (0.04)	0.14 (0.03)	64.80 (0.05)	3.15 (0.05)
Top	GT-C	96*15*6	Control	260.63 (0.07)	2.89 (0.07)	0.09 (0.06)	23.83 (0.04)	1.65 (0.01)
	GT-A	96*15*6	Acetic acid	399.06 (0.03)	4.43 (0.03)	0.11 (0.02)	51.93 (0.01)	3.23 (0.01)
	GT-Z	96*15*6	Zinc chloride	342.82 (0.04)	3.80 (0.04)	0.09 (0.03)	43.20 (0.02)	3.16 (0.03)

In assessing the suitability of bamboo as a sustainable construction material, mechanical testing is conducted, followed by examination of the impact of acid-based chemical treatment on its strength in flexure, tension, compression, and shear. ISO 22157 standards are followed, dividing the bamboo into three sections, i.e., bottom, middle, and top. The acetic acid-treated samples exhibit the best results in terms of flexure strength, whereas the untreated middle section initially shows the highest ultimate strength, as indicated in **Table 4**. In tension test, the bottom section demonstrates the highest tensile strength both before and after treatment as mentioned in **Table 5**. The MOE recorded in tension and flexure tests is highest in the bottom reference samples, as well as the MOR. However, the LOP is better in the top section. Results of compression and shear strength tests show an increasing trend from top to bottom for reference samples as shown in **Table 6** and **Table 7** respectively. In case of shear test, the samples with node at the center show decreased strengths of 27% in bottom section and 33% in middle section compared to the control sample. Overall, acetic acid treatment improving strength, except for the compression test as presented in **Table 8**.

Table 5. Summary of Tension Test

n=27

Section	Sample	Dimension	Treatment	Fmax (COV)	σult (COV)	MOE (COV)
-	-	L*w*t (mm^3)	-	N	Mpa	Gpa
Bottom	GB-C	50*10*6	Control	4565.73 (0.01)	73.63 (0.01)	4.07 (0.09)
	GB-A	50*10*6	Acetic acid	5082.44 (0.14)	81.95 (0.14)	3.77 (0.04)
	GB-Z	50*10*6	Zinc chloride	5001.86 (0.14)	81.70 (0.15)	3.86 (0.09)
Middle	GM-C	50*10*6	Control	3587.46 (0.03)	57.69 (0.03)	2.63 (0.04)
	GM-A	50*10*6	Acetic acid	3907.76 (0.10)	62.95 (0.10)	2.06 (0.03)
	GM-Z	50*10*6	Zinc chloride	3782.92 (0.09)	60.95 (0.09)	2.94 (0.07)
Top	GT-C	50*10*6	Control	3516.10 (0.02)	56.68 (0.02)	2.26 (0.17)
	GT-A	50*10*6	Acetic acid	4752.55 (0.09)	76.57 (0.09)	3.58 (0.04)
	GT-Z	50*10*6	Zinc chloride	4309.93 (0.05)	69.50 (0.05)	3.39 (0.19)

Table 6. Summary of Compression test

n=27

Section	Sample	Treatment	∂ult (COV)	MOE (COV)
-	-	-	Mpa	Gpa
Bottom	GB-C	Control	49.40 (0.04)	0.01 (0.07)
	GB-A	Acetic acid	44.00 (0.01)	0.01 (0.06)
	GB-Z	Zinc chloride	39.35 (0)	0.02 (0.0 9)
Middle	GM-C	Control	49.15 (0.01)	0.02 (0.06)
	GM-A	Acetic acid	44.05 (0.01)	0.03 (0.05)
	GM-Z	Zinc chloride	48.25 (0.02)	0.01 (0.10)
Top	GT-C	Control	29.75 (0.12)	0.02 (0.16)
	GT-A	Acetic acid	42.00 (0.08)	0.03 (0.15)
	GT-Z	Zinc chloride	39.85 (0.01)	0.03 (0.13)

Table 7. Summary of Shear test

n=27

Section	Sample	Node	Treatment	Fmax (COV)	∂ult (COV)
-	-	-	-	N	Mpa
Bottom	GB-C		Control	6927.71 (0.07)	38.405 (0.07)
	GB-C-N	Centre	Control	5053.07 (0.03)	28.01 (0.04)
	GB-A		Acetic acid	9437.87 (0.02)	52.23 (0.03)
	GB-A-N	Centre	Acetic acid	7031.71 (0.05	39.06 (0.07)
	GB-Z		Zinc chloride	7152.81 (0.03)	39.725 (0.03)
Middle	GM-C		Control	5143.813 (0.01)	28.45 (0.09)
	GM-C-N	Centre	Control	3437.59 (0.07)	19.08 (0.07)
	GM-A		Acetic acid	4975.49 (0.09)	27.6 (0.09)
	GM-Z		Zinc chloride	8430.42 (0.08)	46.8 (0.08)
	GM-Z-N	Centre	Zinc chloride	5050.05 (0.05)	28.05 (0.05)
Top	GT-C		Control	4298.68 (0.08)	23.91 (0.08)
	GT-A		Acetic acid	6046.72 (0.02)	34 (0.05)
	GT-A-N	Centre	Acetic acid	3344.94 (0.05)	19 (0.09)
	GT-Z		Zinc chloride	3994.88 (0.11)	22.5 (0.11)

Table 8. Summary of overall percentage increase in strength of treated samples wrt controlled samples

		% increase in strength wrt GB-C			
Section	**Sample**	**Bending**	**Tesion**	**Compression**	**Shear**
Bottom	GB-A	41.40	11.31	-10.93	36.00
	GB-Z	17.65	10.97	-20.34	3.44
Middle	GB-A	22.22	9.12	-10.38	-2.99
	GB-Z	20.69	5.65	-1.83	64.50
Top	GB-A	53.29	35.09	41.18	42.20
	GB-Z	31.49	22.63	33.95	-5.90

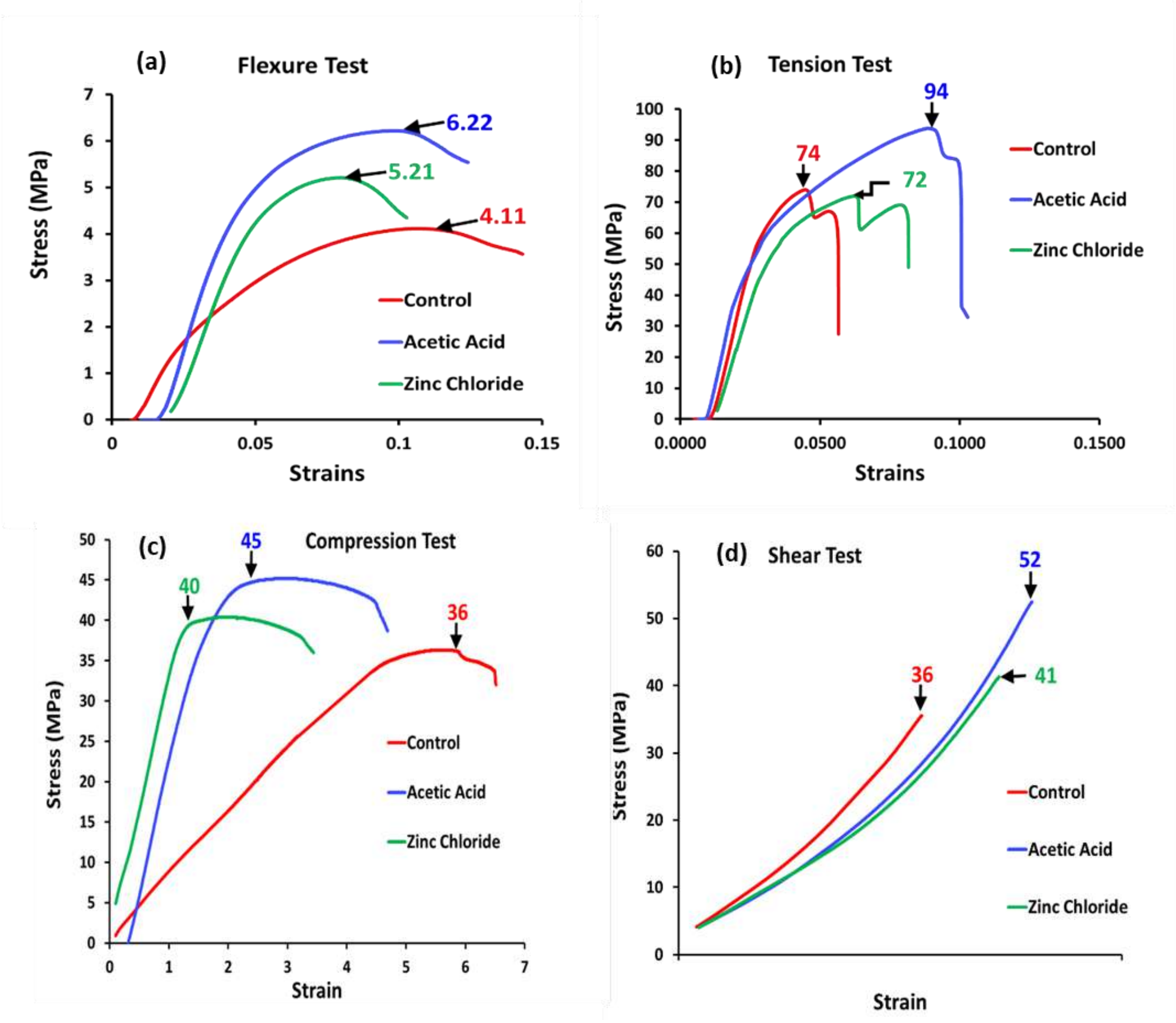

Figure 6: Stress-strain response of all treated bamboo samples in flexure (a), tension (b), compression (c) and shear (d) from bottom section

3.4 Fourier Transformed Infrared (FTIR) spectroscopy

Fourier Transformed Infrared (FTIR) Spectroscopy was performed to investigate the effects of chemical treatment on chemical composition in bamboo fibers, which will be valuable for optimizing its use as a construction material. The spectra shown in **Figure 7** were normalized using the maximum absorbance for all analyzed conditions. The main functional groups were identified and summarized in **Table 11**.

Main functional groups found in bamboo samples between 3400 cm^{-1} and 800 cm^{-1} are summarized in Table 10. The samples exhibited peak intensities at 3419 cm^{-1} for the stretching of the —OH functional group and at 2900 cm^{-1} for the stretching of the —CH functional group [41].

Figure 7 shows main peaks observed in bamboo samples. The existence of ester bonds, as indicated by the 1733 cm^{-1} band corresponding to the C=O stretching of the —COOH functional group, was the dominant spectral change observed. The presence of multiple functional groups in the bamboo samples was evidenced by the spectral region ranging from 1600 to 800 cm^{-1}, which included the —OH stretching of lignin reacting with acetic acid and the C-H deformation vibrations of the acetyl groups. In addition, changes in the intensity of the hydroxyl stretching vibrations at 3344 cm^{-1} were attributed to the formation of zinc acetate. The hydroxyl absorption peak in the $ZnCl_2$ group showed a significantly higher intensity compared to the untreated group [20].

Absorption ratios of FTIR spectra were compared to gain an understanding of the chemical changes that occurred during the chemical treatment process [42]. **Table 12** presents the peak intensity ratios between 1739 cm^{-1} and other relevant peaks for various functional groups. The ratio analysis contributes to understand chemical modifications during a certain process [36]. A comparison of the peak intensity ratios of the bamboo treated with acetic acid to the reference and zinc chloride indicates the occurrence of acetylation, as characterized by an increase in the C=O stretching vibration. When the carbonyl group is compared to the hydroxyl peak at 3334 cm^{-1}, the ratio increases noticeably, indicating that an esterification process is consuming some of the available hydroxyls. The ratio of the 2917 cm^{-1} (C=H, CH_2) and 1323 cm^{-1} (phenol group of cellulose) peaks exhibits the similar behaviour, and can be used to assess the degree of esterification of cellulose [37]. The formation of zinc acetate was further confirmed by the observation of higher peak intensities at 2917 and 3334 cm^{-1}, due to the —OH stretching. When zinc chloride is dissolved in water, it undergoes hydrolysis to produce zinc ions and an acidic solution. The impregnation of wood with this solution may have increased the degradation of moisture-absorbing groups in the wood [18].

Other appealing changes can be detected by looking at the peak ratios in Table 11. The ratios of cellulose and hemicellulose peaks, I1383/I1323 and I909/I1323, (where 1383 cm^{-1} correlates to C—H deformation in cellulose and hemicellulose, 1323 cm1 to O—H, phenol group in cellulose, and 896 cm1 to C—H deformation in cellulose), increased somewhat in acetic acid-treated samples, implying structural alterations in cellulose and hemicellulose. These chemical alterations indicate the increase in tensile strength of bamboo treated with acetic acid and somewhat decrease in zinc chloride.

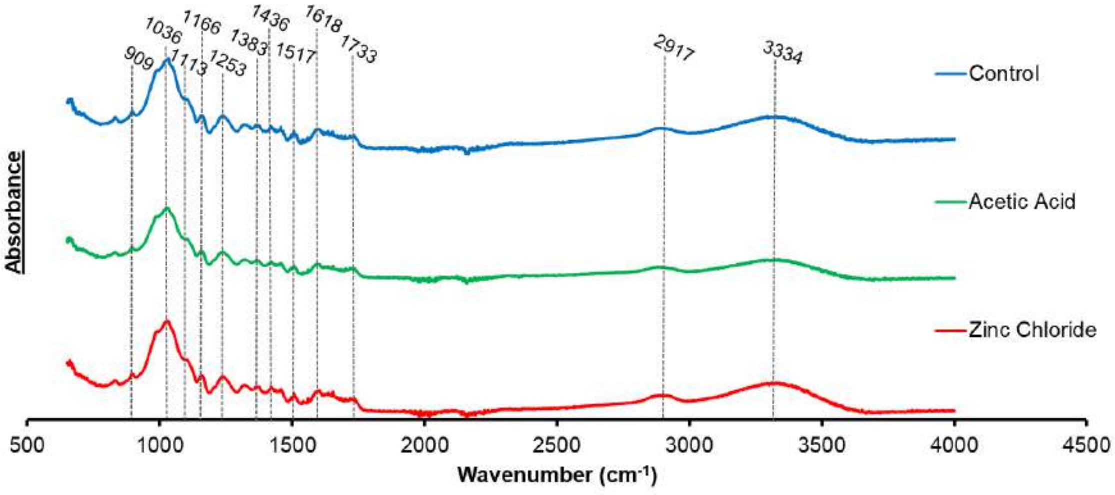

Figure 7: FTIR Spectrum of Bamboo for all analyzed conditions

Table 9. An overview of primary functional groups present in samples of wood and bamboo [38 21]

Wavelength (cm^{-1})	Functional group	Assignment
3334	−OH	Present in water and wood/bamboo components
2917	C=H,–CH2–	Stretching of the methyl and methylene groups, hydrocarbon chains
1739	–COOH (C=O)	free carbonyl groups, Stretching of acetyl or carboxylic acid (hemicelluloses)
1618	C=C	Aromatic ring (lignin)
1517	C=C	Aromatic ring (lignin), stronger guaiacyl element than syringyl
1465	C–H	Asymmetric bending in CH3 (lignin)
1436	CH2	Aromatic skeletal vibrations (lignin) and CH deformation in plane (cellulose)
1383	C–H	C–H deformation in cellulose and hemicellulose
1323	O–H	phenol group (cellulose)
1253	CO	Guaiacyl ring breathing with CO-stretching (lignin and hemicelluloses), esters
1166	C– O– C	Carbohydrate
1113	C –H	Guaiacyl and syringyl (lignin)
1036	C – O, C – H	Primary alcohol, guaiacyl (lignin)
909	C– H	C H deformation in cellulose

Table 10. Peak intensity ratio for varying functional groups [21]

	Ratio of Peak intensity for varying functional groups				
Sample	I(1739/3334)	I(1739/2917)	I(1739/1323)	I(1383/1323)	I(909/1323)
C-G	0.53	0.72	0.64	0.98	1.35
AA-G	0.64	0.92	0.64	0.98	1.47
Z-G	0.57	0.85	0.59	0.95	1.32

3.5 X-ray Diffraction

The influence of treatment on the crystalline structure of bamboo was analyzed. The XRD pattern was examined, and the intensity ratios of the diffraction peaks were calculated to determine the crystallinity index (CrI) of cellulose using the Segal method [21]. The XRD spectra (**Fig. 5**) demonstrates that all diffractograms exhibited clear peaks at $2\Theta = 16^{o}$, 22.1^{o} and 35^{o} which are indicative of the typical cellulose I form [39-40]. The XRD analysis of bamboo fibers in the $ZnCl_2$ group showed two overlapping weak diffraction peaks at 15° and

16.3° [17]. This observation suggests that the primary crystal structure of the bamboo fibers impregnated with $ZnCl_2$ solution was retained, although the intensity of the diffraction peaks varied significantly. The CrI is shown at the top of each XRD diffraction pattern, and the results indicated that the specimens treated with acetic acid exhibited increased mechanical properties and highest CrI of 66.29%, while the bamboo specimens treated with zinc chloride displayed the lowest mechanical strengths and correspondingly, the lowest CrI of 47.22%. This decrease in crystallinity is likely a result of the degradation of the amorphous regions of cellulose and microfibers in the solidification area under the influence of acid [41].

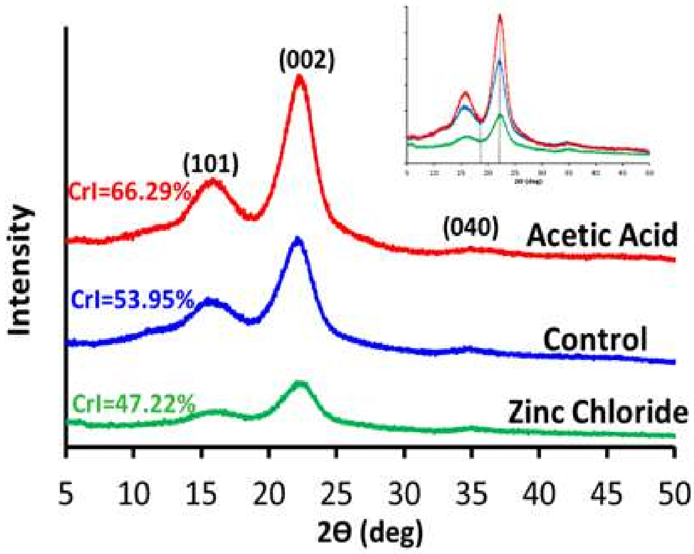

Figure 8: X-ray diffraction patterns of all investigated conditions. The XRD graph highlights the cellulose 1 crystallinity index determined using the (101), (002) and (040) planes of the Ib crystal structure, as illustrated in the inset.

4 CONCLUSION

The research has demonstrated that acetic acid treatment can effectively improve the durability, physio-chemical, structural, and thermal properties of bamboo as a sustainable construction material. The treatment reduced water absorption and swelling while increasing flexure, tensile, and shear strengths by 40%, 11%, and 31% respectively, with only a compromise in compressive strength by 11%. The FTIR and XRD analyses revealed an increase in cellulose crystallinity as the mechanism behind the improvement in mechanical properties. The findings suggest that acid-based chemical treatment, specifically with acetic acid, offers an environmentally friendly and effective way to improve the performance of bamboo for construction applications. These results have important implications for the development of more eco-friendly buildings, as bamboo can be used in a wider range of sustainable building projects.

These results have important implications for researchers, manufacturers, and stakeholders in the bamboo industry, as acid-based chemical treatment offers an environmentally friendly and effective way to improve the properties of bamboo for construction applications. By enhancing its mechanical properties and durability, bamboo can be used in a wider range of sustainable building projects, contributing to the development of more eco-friendly buildings. Overall, this study adds valuable knowledge to the existing body of research on sustainable construction materials and demonstrates the potential of acid-based chemical treatment as an effective technique for improving the performance of bamboo.

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