Production and Evaluation of Cement-Bonded Composites Board Made from Banana Pseudo Stem

Adebola S. AKOLADE[1*], Precious A. OLAOMOTITO[2], Abibat Y. ADEBIYI[3], Oluwatunmise P. ABOLARIN[4], Opeyemi I. ADETUNJI[5], Kola OGEDENGBE[6]

[1*,2,3,4,6]Department of Civil Engineering, Lead City University, Ibadan, Oyo State, Nigeria
[5]Department of Civil Engineering, University of Ibadan, Ibadan, Nigeria

[1*]akolade.adebola@lcu.edu.ng, [2]olaomotito.precious@lcu.edu.ng, [3]abibat.adebiyi@lcu.edu.ng, [4]abolarin.oluwatunmise@lcu.edu.ng, [5]oi.adetunji@ui.edu.ng, [6]ogedengbe.kolawole@lcu.edu.ng

Abstract

This study examined the viability of producing cement-bonded composites board incorporating banana pseudo-stem fibre and varying percentages of chemical additives. Mechanical and physical properties such as density, flexural strength, modulus of rupture (MOR), modulus of elasticity (MOE), and compressive strength were evaluated to determine the optimal composition for construction materials. The results showed that density values ranged 1.418 g/cm³ to 1.847 g/cm³, with higher densities correlating to improved mechanical strength. Flexural strength increased with additive content up to 1%, with diminishing returns at 1.5%. Modulus of rupture and elasticity were highest at 1%, suggesting an optimal balance between strength and stiffness. Compressive strength peaked at 1% additive, reaching 567.52 MPa, before declining at 1.5%. In conclusion, it was found that a 1% additive level offers the best mechanical performance across most parameters, making it suitable for structural applications. These findings suggest that banana pseudo-stem fibre can be an effective raw material for sustainable construction composites, with potential applications in lightweight, non-load-bearing structures.

Keywords: *Cement bonded additives, banana pseudo stem, composite board, fibre, lightweight.*

1.0 Introduction

The increasing demand for sustainable building materials is driven by the environmental impacts of conventional construction practices, particularly the reliance on wood-based boards. These materials contribute to deforestation, habitat loss, and significant carbon emissions. The construction industry heavily relies on timber, leading to extensive deforestation and biodiversity loss [1]. The wood industry produces approximately 60 million tons of waste annually, with a significant portion being underutilised [2]. The production and disposal of wood-based materials contribute to greenhouse gas emissions, exacerbating climate change [1]. In contrast, agricultural residues, such as banana pseudo stems, present a viable alternative that can mitigate these issues.

Cement-bonded particleboards (CBPB) are construction materials extensively utilised in both new constructions and the restoration or retrofitting of existing structures [3]. Cement-bonded wood particleboard (CBWP) has been utilised for over a century in various construction applications owing to its remarkable attributes, including toughness, durability, high impact resistance, dimensional stability, low water absorption, thermal insulation, freeze-thaw resistance, fire resistance (in both B1 and A2 classifications), favourable acoustics, resistance to biological degradation (including fungi, insects, termites, and vermin), ease of production, and low manufacturing costs [4, 5]. Cement-bonded wood particle boards provide superior performance in both interior and exterior applications, such as wall cladding, roof sheathing, flooring, fencing, pavement, and sound barriers, without the need for treatment [5, 6].

Recently, there has been a resurgence of interest in cement-bonded particleboards (CBPB), especially with the incorporation of lignocellulosic wastes [7 - 11] or alternative wood species [12, 13] for various applications, including interior walls, external cladding surfaces, ceiling panels, and decorative uses [3, 14]. Among these, agricultural residues used in cement-bonded particles, the banana pseudo stem stands out due to the abundance of banana pseudo stem abundance in banana-producing regions and its typical disposal as waste. Banana plants generate substantial waste, with each ton of bananas producing about four tons of residues, primarily from the pseudo stem [2, 15].

Banana plants (Musa sp.) originate from Asia but thrive in various settings. They are versatile for mixed agriculture and are cultivated extensively in tropical and subtropical regions [3]. Production predominantly occurs in Asia (56%), Latin America (26%), and Africa (15%) [15]. The FAO (2019) reports that it is the predominant global crop, with output increasing from 60 million tonnes in 2000-2002 to 116 million tonnes in 2017-2019 [3, 16]. The production cycle endures merely two years, resulting in a substantial quantity of waste materials generated from this crop. Consequently, the volume of waste generated can be repurposed for the production of CBPB and

other construction materials [3]. Research indicates that banana fibreboards exhibit superior tensile strength and durability compared to traditional materials, making them suitable for construction [17]. Utilising agricultural waste not only reduces environmental impact but also provides a low-cost alternative to conventional building materials [17, 18]. This presents an opportunity to ascertain banana pseudo stems into a valuable resource for construction materials, potentially offering both environmental and economic benefits.

In regions where bananas are cultivated extensively, such as parts of Africa, Asia, and Latin America, the cultivation of banana results in significant volumes of biodegradable waste. Utilising banana pseudo stem as a component in cement-bonded composites presents a sustainable solution to agricultural waste management and environmental pollution. This approach not only justifies an abundant resource but also enhances the properties of construction materials, promoting eco-friendly practices in the building industry. Utilising banana pseudo stem in cement-bonded composites leads to waste valorisation, as it converts agricultural waste into valuable construction materials, reducing the volume of biomass discarded or left to decompose [3]. It decreases dependence on wood and synthetic inputs, contributing to forest conservation and sustainable resource use. It minimizes methane emissions from decomposing stems and prevents potential water pollution from leachates and it encourages rural development by creating value-added products from locally available materials.

While previous studies have explored the incorporation of banana pseudo stem fibres into cement-bonded particleboards (CBPBs), there has been limited investigation into the effects of chemical additives, such as calcium chloride, on the physical and mechanical properties of these composites. Specifically, the optimal concentration of calcium chloride to enhance properties like water absorption, thickness swelling, compressive strength, and flexural strength has not been thoroughly examined. This study systematically investigates the impact of varying calcium chloride concentrations (0.5%, 1.0%, and 1.5% by weight of cement) on the performance of banana pseudo stem fibre-reinforced cement composites. By maintaining consistent ratios of sand, cement, water, and fibre, and only altering the calcium chloride content, the study isolates the additive's effect on key properties. The comprehensive testing regime, including water absorption, thickness swelling, compressive strength, flexural strength, and density provides a robust dataset to assess the additive's influence.

This study contributes to sustainable construction material in four distinct ways. First, it pioneers the use of banana pseudo stem, an abundant agricultural residue, in cement-bonded composite boards, whereas previous studies have largely concentrated on residues such as rice husk, bagasse, and coconut coir. Second, the work introduces an evaluation of calcium chloride accelerator at varying levels (0.5%, 1.0%, and 1.5%), enabling improvement of fibre–cement bonding. Third, the study provides a comprehensive performance assessment through mechanical (flexural strength, modulus of rupture, modulus of elasticity, and compressive strength) and physical (density, water absorption, and thickness swelling) tests. Finally, the findings identify the 1% calcium chloride level as the optimum dosage, offering a balanced combination of mechanical strength and dimensional stability. These contributions advance the development of bio-based, environmentally friendly boards for structural applications.

2.0 Materials and Methods/Methodology
The methodology adopted in the production of the composite board are outlined in the subheadings below.

2.1 Material Collection and Preparation
The materials used for the production of the composite board includes
i.   Banana pseudo stem particles: The banana pseudo-stem (Figure 1) was gotten from the Orchard farm, University of Ibadan and was cut into billets measuring approximately 60mm each and then subjected to a sun-drying process for a duration of two weeks (Figure 2 and 3).
ii. Portland Cement: Limestone Portland cement (LPC) was bought along Akala Expressway, Challenge Area, Ibadan. The cement met British Standard (BS 12: 1996) specifications for cement.
iii. Sand: The sharp sand was obtained from a construction material dealer along Akala expressway. The sand was sieved manually to get the desired particle size.
iv. Water: The water used was found to adhere to BS 3148: 1980 Standard.
v.   Manual sieving set
vi. Wood for mould construction
vii. Chemical additives (calcium chloride)
viii. Polyethylene Film.

Figure 1: Banana plant

Figure 2: Sun-drying banana pseudo stem

Figure 3: Dried banana pseudo stem

2.2 Composite Board Preparation

The chemical additive, calcium chloride was used in the production of cement bonded composite made from banana pseudo stem at various percentages. The fibre and chemical additive composition is a percentage function of the of the weight of cement which was 77g (Figure 4 to Figure 6). The water used was half the weight of cement. The chemical additive composition used was 0.5%, 1% and 1.5%. A sand to cement to water ratio 2:1:0.5 was used (Table 3.1). The composites were produced using a rectangular mould measuring (101.6mm x 152.4mm x 11mm) (Figure 7 and 8) then vibrated to ensure proper compaction (Figure 9). To ensure surface finish, polyethylene film was placed beneath the mould before pouring and above the mould after pouring. The cement bonded composite board was then cured before testing (Figure 10). The composite finished product is shown on Figure 11.

Figure 4: Weighing specimens (cement and sand)

Figure 5: Batched specimens (cement and sand)

Figure 6: Calcium chloride

The cement bonded composites made from banana pseudo stem were subjected to water absorption and thickness swelling test, flexural test and compressive strength test.

Figure 7: Mould

Figure 8: Cement bonded composite mixture

Figure 9: Vibrating composite mixture

Figure 10: Curing cement bonded composite board

Table 1: Experimental design

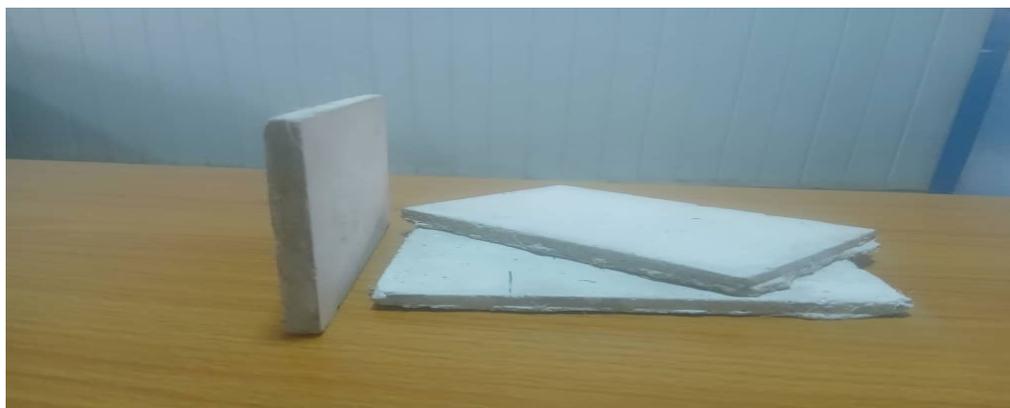| Mixing ratio	Sand (g)	Cement (g)	Water (g)	Chemical additive (%)	Chemical additive (g)	Fibre (%)	Fibre (g)
2:1:0.5	154	77	38.5	0.5	0.4	1	0.8
2:1:0.5	154	77	38.5	1.0	0.8	1	0.8
2:1:0.5	154	77	38.5	1.5	0.12	1	0.8

Figure 11: Banana pseudo-stem composite board

2.3 Composite Board Testing
The composites were subjected to tests which includes water absorption and thickness swelling test, compressive strength test, flexural test and density test.

2.3.1 Water Absorption Test and Thickness Swelling
The test was conducted in accordance with ASTM D1037-06. The water absorption test was performed to determine the amount of water a material could absorb when immersed. The thickness swelling test measured the increase in thickness after curing for a specified number of days. Each cement-bonded composite had three replicates for comparison. Each sample was weighed using a specific weighing balance, and its thickness was measured at a marked reference point using a vernier caliper. The samples were then immersed in water for 2 and 24 hours, with the procedures repeated at each interval.

$$\text{WA} = \frac{W_2 - W_1}{W_1} \text{ X } 100 \text{ (Wood Handbook, 2010)}$$

Where: W_1 =   the initial weight of sample before soaking

                    W_2 =   the final weight of the sample

2.3.2 Compressive Strength Test
The compressive strength test on the cement-bonded composite made from banana pseudo stem was conducted to evaluate its ability to withstand axial loads. Rectangular samples were prepared and cured for 14 days to allow the cement matrix to fully hydrate. These specimens were then placed in a universal testing machine UTM, where a gradually increasing compressive load was applied until failure occurred (Figure 12). The maximum load at failure was recorded.

$$Cs = \frac{F}{A}$$

where: F   =   Force

                  A   =   Area

Figure 12: Compressive strength test on Composite Board

2.3.3 Flexural Test
The flexural test on the cement-bonded composite was conducted to evaluate its bending strength and deformation characteristics, following the standard procedures outlined in ASTM C293/C293M-16. A flexural test measures the bending strength and stiffness of materials by applying a load at the midpoint of a specimen supported at both ends until it fractures. This test provides important information about the material's behavior under stress and its mechanical properties, such as the modulus of rupture (MOR) and the modulus of elasticity (MOE) (ISO, 2013). The mechanical properties evaluated in the samples included both the MOR and MOE.

$$\text{MOR} = \frac{3PL^3}{2BD^2} \text{ (Wood Handbook, 2010)} \qquad \text{MOE} = \frac{3PL^3}{4BH^3Y} \text{ (Wood Handbook, 2010)}$$

where: P   =   Ultimate failure load (N

             B   =   width of test sample (m)

             L   =   Span of the sample (m) / Length

             D   =   Thickness of test sample (m)

             Y   =   Deflection

             H   =   Thickness

2.5.4 Density Test
The density test on the cement-bonded composite was conducted to determine its mass per unit volume and assess its compactness. The density test measures the mass and volume of a composite sample by weighing the

specimen and calculating its volume based on precise measurements. This test provides essential information about the material's structural properties, such as its compaction and porosity, which impact strength and durability (ISO, 2013). The density (ϱ) is calculated using the formula:

$$\varrho = \frac{M}{V}$$

where: M =   Mass of the test sample (kg)

        V =   Volume of the test sample (m³) (ASTM, 2015).

3.0 Results and Discussion

3.1 Water Absorption

The water absorption test was performed to evaluate how much water the cement-bonded composites made from banana pseudo-stem particles absorbed over specific time intervals (2 hours and 24 hours). Table 2 and Figure 13 show the Water Absorption Test conducted on three sets of samples. The addition of calcium chloride as a chemical additive was found to have a discernible impact on the boards' water absorption properties across all tested samples. In particular, the composites were divided into three groups, 0.5%, 1.0%, and 1.5%, according to the percentage of calcium chloride added. After two and twenty-four hours of immersion, water absorption was measured for each group, and performance was assessed using the averages. The mean water absorption for Group A, which contained 0.5% calcium chloride, was 0.43% after two hours and 0.097% after twenty-four hours. After two hours, Group B, which had a 1.0% additive, showed comparable water absorption (0.42%), but after twenty-four hours, the absorption was lower (0.047%). Interestingly, Group C showed the lowest absorption values, 0.29% after 2 hours and only 0.003% after 24 hours, despite having the highest additive content (1.5%). This steady decline in water absorption as calcium chloride concentration rises suggests that the additive significantly enhances the composite boards' ability to withstand water. This improvement can be explained by the fact that calcium chloride accelerates cement hydration, which probably leads to a denser, less porous cement matrix that is less vulnerable to water intrusion.

Table 2: Water absorption of composite board

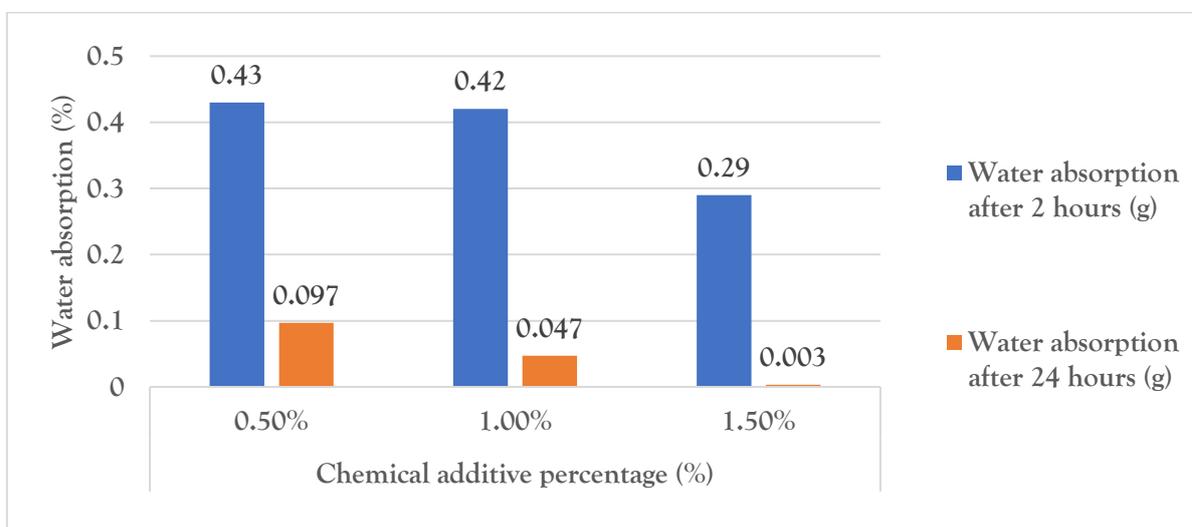| Percentage (%)	Sample	Initial weight (g)	Final Weight after 2 hours (g)	Final weight after 24 hours (g)	Water absorption after 2 hours (%)	Water absorption after 24 hours (%)	Mean water absorption after 2 hours (%)	Mean water absorption after 24 hours (%)
0.15%	A1	289.9	291.1	290.9	0.42	0.34	0.43	0.097
	A2	285.5	286.3	285.6	0.42	0.18		
	A3	261.7	262.9	261.1	0.46	-0.23		
1.0%	B1	332.5	334.1	332.6	0.48	0.03	0.42	0.047
	B2	299.5	300.4	299.6	0.30	0.03		
	B3	256	257.2	256.2	0.47	0.08		
1.50%	C1	354.3	355.8	354.6	0.43	0.08	0.29	0.003
	C2	314.9	316.0	315.6	0.35	0.22		
	C3	321.7	322	320.7	0.09	-0.31		

Figure 13: Relationship between water absorption after 2 and 24 hours

After a day, some samples, especially those in Groups A and C, exhibited negative water absorption. This anomaly, which results in somewhat lower final weights, is not uncommon in experimental settings and may be caused by slight surface drying or evaporation before the final weighing. These negative values are not indicative of the material losing water through absorption.

Calcium chloride appears to improve the dimensional stability of the composite boards, as evidenced by the decreasing trend in water absorption with increasing chemical additive content. A crucial characteristic for building materials subjected to varying moisture levels is reduced water absorption, which results in less swelling and deformation over time. These findings lend credence to the possibility of producing environmentally friendly and water-resistant building boards from banana pseudostem, an agricultural waste. In addition to cutting waste, using such residues provides a practical substitute for traditional wood-based boards, which are more expensive and contribute to deforestation.

Zahari *et al.,* [19] reported reduced water absorption of polypropylene/ijuk fibre composites due to the impact of surface treatment, likewise, Santiagoo *et al.,* [20], reported that treatment enhanced the adhesion between the fibre, thus resulting in less water uptake. This aligned with the current study, where samples with higher percentages of calcium chloride had lower water absorption benefitting from improved matrix-fibre interaction and reduced pore spaces.

3.2 Thickness Swelling Test

Table 3 and Figure 14 show the thickness swelling (TS) percentages for cement-bonded composite boards' dimensional stability after 2 hours and 24 hours moisture exposure. The thickness swelling metric is crucial for evaluating durability and resistance to moisture-induced deformation in construction applications as it quantifies the change in the composite material's thickness following immersion in water. Composites with different calcium chloride contents (0.5 %, 1.0%, and 1.5%) were tested for two and twenty-four hours, respectively.

The thickness swelling in the 0.5% additive group (samples A1–A3) increased by 1.04% on average after two hours, but decreased by -4.81% on average after twenty-four hours, indicating a decrease in thickness, which could be the result of swelling followed by a small amount of shrinkage or densification during the drying process before the final measurement. Interestingly, after 24 hours, the thickness of all three samples in this group decreased, which might indicate a transient absorption followed by moisture release. After two hours, the 1.0% additive group (B1–B3) showed a greater average swelling of 1.47%, but after twenty-four hours, they also showed a mean decrease of -3.64%. The longer-term decrease was less noticeable, suggesting a more consistent performance over time, even though the short-term swelling was marginally greater than that of the 1% group. This implies that adding 1.0% calcium chloride could improve dimensional resilience without causing undue short-term deformation.

Table 3: Thickness swelling test

Percentage (%)	Sample	Initial weight (g)	Final Weight after 2 hours (g)	Final weight after 24 hours (g)	Thickness after 2 hours (%)	Thickness after 24 hours (%)	Mean thickness after 2 hours (%)	Mean thickness after 24 hours (%)
0.15%	A1	8.62	8.31	8.05	-3.60	-6.61	1.04	-4.81
	A2	8.55	8.72	8.2	1.99	-4.09		
	A3	8.04	8.42	7.74	4.73	-3.73		
1.0%	B1	8.09	8.03	7.75	-0.74	-4.20	1.47	-3.64
	B2	10.82	11.08	10.43	2.40	-3.60		
	B3	8.02	8.24	7.77	2.74	-3.12		
1.50%	C1	11.57	11.70	11.29	1.12	-2.42	0.38	-3.94
	C2	9.68	9.79	9.46	1.16	-3.43		
	C3	9.70	9.59	9.12	-1.13	-5.98		

After two hours, the average swelling for the 1.5% additive group (C1–C3) was the lowest at 0.38%, and after twenty-four hours, the long-term thickness change was -3.94%. Out of the three groups, this exhibits the most consistent thickness behaviour. A higher calcium chloride content appears to continue to improve the structural integrity of the composites by decreasing their susceptibility to water-induced expansion, as evidenced by the moderate long-term reduction and minimal short-term swelling.
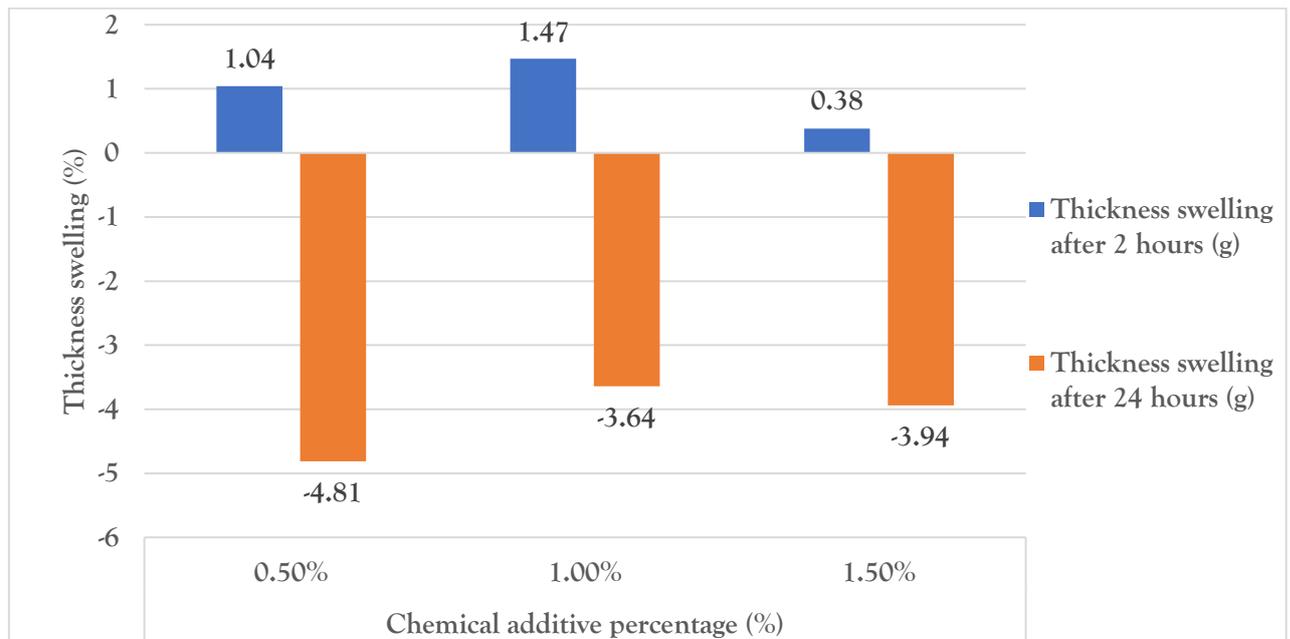
Figure 14: Relationship between thickness swelling after 2 and 24 hours.

The trend of negative swelling after 24 hours in all groups indicates that the composites first absorbed water before losing some to densification or evaporation. The additive's capacity to quicken cement hydration and decrease matrix porosity, which limits water penetration and dimensional changes, is demonstrated by the overall decrease in swelling that occurs as calcium chloride concentration rises.

This result verifies that cement-bonded banana pseudo stem composites are more resistant to dimensional changes brought on by exposure to water when the percentage of calcium chloride is increased. The best-performing composites had 3% calcium chloride, which reduced swelling and provided increased stability.

3.3 Density Test

Table 4 and Figure 15 shows the density values of different samples tested, which range from 1.4179 g/cm^3 to 1.8472 g/cm^3. This gives the compactness and structural integrity of the material at different calcium chloride contents (0.5%, 1.0, and 1.5%), as the density of the cement-bonded banana pseudo stem composite boards affects the composite materials' overall performance, durability, and mechanical strength.

With a mean density of 1.651 g/cm^3, the density values for the 0.5% calcium chloride group (samples A_1–A_3) varied from 1.573 g/cm^3 to 1.705 g/cm^3. In comparison to the other groups, this suggests comparatively higher porosity and lower compactness. The reduced density values at 0.5% additive might indicate that voids were more common or that the cement matrix was not completely compacted, which could have an impact on moisture resistance and mechanical performance.

Table 4: Density test

Percentage (%)	Sample	Mass (g)	Dimension (cm³)	Density (g/cm³)	Mean density (g/cm3)
0.5%	A_1	289.9	170.28	1.705	
	A_2	285.1	170.28	1.674	1.651
	A_3	267.9	170.28	1.573	
1.0%	B_1	333.5	170.28	1.959	
	B_2	299.5	170.28	1.759	1.740
	B_3	256.0	170.28	1.503	
1.5%	C_1	294.3	170.28	1.728	
	C_2	314.9	170.28	1.849	1.828
	C_3	324.7	170.28	1.907	

The densities in the 1.0% calcium chloride group (B_1–B_3) ranged more widely, from 1.503 g/cm^3 to 1.959 g/cm^3, with a mean density of 1.740 g/cm^3. This could be due to better hydration and bonding made possible by the calcium chloride, thus, indicating better compaction and a lower void content.
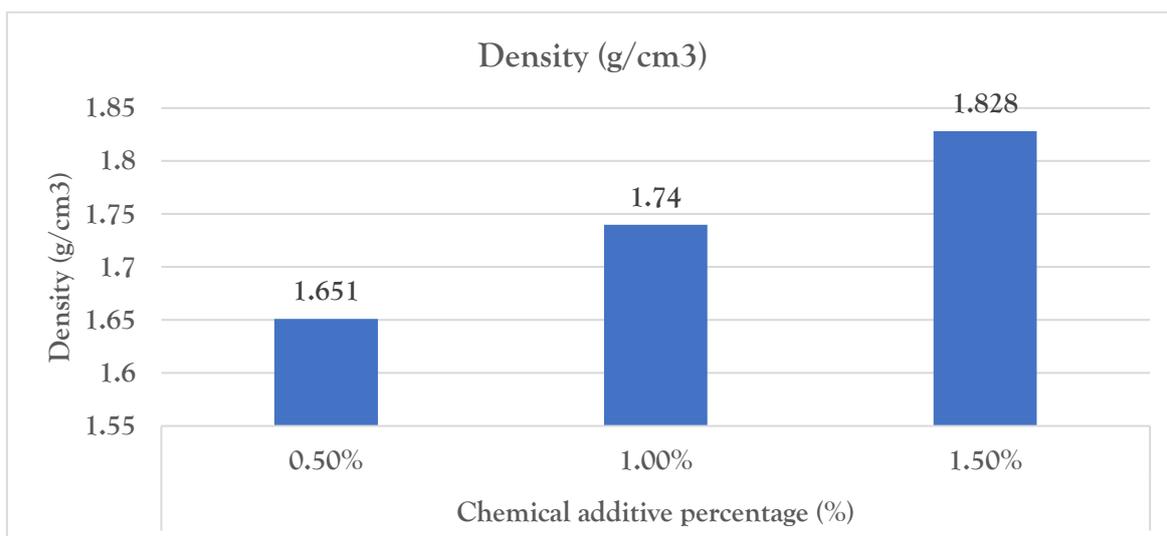
Figure 15: Composite board density relationship

Sample C1 to C3, (1.50%) had a mean density of 1.828 g/cm³ and a range 1.728 g/cm³ to 1.907 g/cm³, showed the highest and most consistent density values. These findings unequivocally demonstrate that the composite board's compactness is improved by raising the chemical addition to 1.5%. Greater strength and durability are correlated with a better-packed matrix with fewer air gaps, which is implied by higher density.

The findings show that the density of the composite board generally improves as the calcium chloride percentage rises. This density increase is consistent with calcium chloride's function as a setting accelerator, which probably encourages faster and more thorough cement hydration. In construction applications where strength and durability are crucial, the denser microstructure attained at higher additive levels helps to improve mechanical performance and resistance to environmental deterioration. The density test indicates a positive relationship between the density of composite boards and their calcium chloride content. At 1.5% additive, the ideal mass-to-compaction ratio was noted, confirming its applicability for improving the structural integrity of cement composites based on banana pseudo stems.

3.4 Flexural Strength Test

Table 5 and Figure 16 shows the flexural strength test results for samples with different additive percentage, specifically at 0.5%, 1.0%, and 1.5% levels. The mould dimension used for this procedure is **(300×50×10) mm**. According to Smith and Jones (2019), the flexural strength of materials is significantly influenced by the percentage of additives, which can modify the microstructure of the material, leading to variations in mechanical properties such as stiffness and resistance to deformation. They argued that an optimal level of additives enhanced the bonding between particles, thus increasing the material's ability to withstand tensile stresses on its surface.

The flexural strength values for the samples at 0.5% additive level (A1, A2, and A3) range 1918.40 N/mm² to 1933.80 N/mm², with a mean of 1925.73 N/mm². These results indicated that the samples exhibited relatively consistent strength values with minimal variation. It shows that the composite can tolerate flexural stresses to a moderate degree. The samples' comparatively narrow range points to a constant composition and curing behaviour at this additive level. In contrast to samples A1 and A3, sample A2 displayed noticeably less deflection (1.00 mm), which could be the result of a brittle failure mode or increased initial stiffness.

Table 5: Flexural strength test result

Percentage (%)	Sample	Force (Kn)	Deflection (mm)	σ(N/mm²)	Mean flexural strength
0.5%	A1	8.79	7.00	1933.80	1925.733
	A2	8.72	1.00	1918.40	
	A3	8.75	7.55	1925.00	
1.0%	B1	8.91	10.00	1960.20	1936.000
	B2	8.71	13.00	1916.20	
	B3	8.78	3.00	1931.60	
1.5%	C1	8.91	8.50	1960.20	1950.000
	C2	8.88	6.00	1953.60	
	C3	8.81	11.50	1938.20	

Higher flexural strength values were observed at the 1.0% additive level. With a mean of 1936.00 N/mm², the 1.0% calcium chloride samples (B1–B3) displayed a somewhat greater range of flexural strength, ranging 1916.20 N/mm² to 1960.20 N/mm². The higher average flexural strength in comparison to the 1% group indicates improved internal cohesion and matrix bonding. This improvement could be explained by the calcium chloride's more effective acceleration of cement hydration, which results in a stronger matrix. It's interesting to note that deflection values in this group varied more (from 3.00 mm to 13.00 mm), which could be a result of variations in microstructural homogeneity or elasticity.

The 1.5% calcium chloride group (C1–C3) had the highest mean of 1950.00 N/mm² and the highest flexural strength values, ranging 1938.20 N/mm² to 1960.20 N/mm². This demonstrates how raising the calcium chloride content improves the composite board's strength, suggesting a well-formed matrix with few voids and evenly distributed cement-pseudo stem fibre bonding, by the consistency and high values found in all samples. The boards maintained their high strength despite varying deflection (6.00 mm to 11.50 mm), suggesting a good balance between stiffness and flexibility.
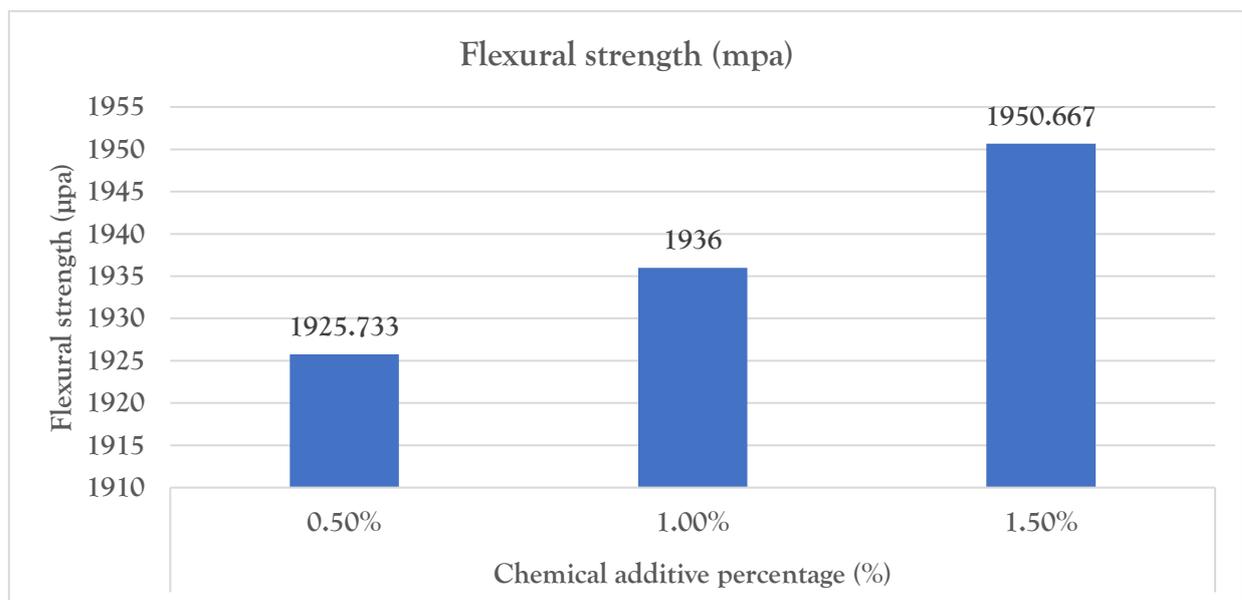

Figure 16: Relationship between flexural strength and percentages of chemical additive.

Li *et al.* [21] found that increasing the additive content generally improved the flexural strength of construction materials, but only up to a certain point. Beyond this point, additional additives had diminishing returns or even negative effects due to issues such as poor dispersion, increased brittleness, or alterations in the internal structure that led to stress concentration points. But from the results gotten in this study, a higher calcium chloride content enhanced the composite boards' flexural strength. The additive containing 1.5% calcium chloride performed the best, confirming its function in improving interfacial bonding and matrix development

3.5 Modulus of Rupture (MOR) and Modulus of Elasticity (MOE)

Table 6 shows the calculated Modulus of Rupture (MOR) and the Modulus of Elasticity (MOE) for each sample, giving information as regards the bending strength and stiffness of the cement-bonded banana pseudostem composite boards with varied calcium chloride content. The MOR values for the 0.5% calcium chloride samples (A1–A3) range 575.80 to 580.10 N/mm2, which indicates uniform material distribution and consistent curing. Likewise, this group's MOE values, which show comparatively high stiffness, range 662.79 to 669.00 N/mm². This consistency indicates that the cement matrix has moderately but reliably reinforced the banana pseudostem fibres at 0.5% calcium chloride, producing boards with a balance of rigidity and strength.

The MOE values in the 1.0% calcium chloride group (B1–B3) range more widely, from 356.87 to 1558.26 N/mm², while the MOR values, which range 574.06 to 587.46 N/mm², are similar to those in the 0.5% group. Significantly higher MOE is shown by B3, which might be the result of a denser and more compact microstructure in that sample, which could be brought on by improved cement-fibre interaction or distribution. The large range in MOE, however, indicates that consistency at this percentage is less dependable, perhaps due to the differences in curing conditions, compaction, or fibre orientation

Table 6: MOR and MOE test results

Percentage (%)	Sample	MOR (N/mm²)	MOE (N/mm²)
0.5%	A1	580.10	669.00
	A2	575.80	666.05
	A3	577.50	662.79
1.0%	B1	587.46	474.38
	B2	574.06	356.87
	B3	578.52	1558.26
1.5%	C1	587.46	558.12
	C2	586.08	788.44
	C3	581.94	407.30

The most balanced performance is shown by the 3% calcium chloride group (C1–C3). MOR values, which range 581.94 to 587.46 N/mm2, are consistent once more, supporting the notion that strength increases marginally with higher calcium chloride levels. In comparison to the 2% group, the MOE values in this group also exhibit a more acceptable range, ranging 407.30 to 788.44 N/mm². This suggests enhanced interfacial bonding and better structural stiffness at 3%, which may be brought about by better matrix development and ideal cement hydration acceleration.

MOE results show that 0.5% and 1.5% calcium chloride additions result in more consistent and dependable boards in terms of stiffness, even though all three groups display comparable MOR values (approximately 575–587 N/mm²). Overall, the 1.5% level seems to be the most efficient, producing composite boards that are strong and somewhat stiff, making them appropriate for structurally demanding but non-load-bearing applications like wall linings, ceilings, or partitions. The 1.0% group's MOE variability points to the need for additional optimisation or improved control at that stage of the manufacturing process

3.6 Compressive Strength Test

Table 7 and Figure 17 shows the compressive strength test results for cement-bonded composites made with 0.5%, 1.0%, and 1.5% chemical additives revealing how well the composites withstand axial compressive forces, which is an important characteristic for load-bearing applications like panels, partitions, or structural infill materials. A **(50 ×50×50) mm** cubic mould was used for this test.

The compressive strengths for the 0.5% calcium chloride samples (A2 and A3) were 427.76 MPa and 516.16 MPa, respectively, yielding a mean value of 471.96 MPa. A moderate compressive capacity is indicated by this. Although the two values differ significantly (by roughly 88 MPa), this could be the result of minor variations in curing conditions, fibre distribution, or compaction. However, these findings demonstrate that adding 0.5% calcium chloride to the composite improves its mechanical strength

Table 7: Compressive strength test

Percentage (%)	Sample	Maximum Force (kN)	Compressive Strength (MPa)	Mean compressive strength (MPa)
0.5%	A2	53.47	427.76	471.96
	A3	64.52	516.16	
1.0%	B1	55.96	447.68	503.17
	B2	61.79	494.32	
	B3	70.94	567.52	
1.5%	C1	57.21	457.68	451.57
	C2	51.48	411.84	
	C3	60.65	485.20	

Compressive strengths rose uniformly in the 1.0% calcium chloride group (B1 to B3), reaching 447.68 MPa, 494.32 MPa, and 567.52 MPa, for a mean of 503.17 MPa. The 1.0% calcium chloride level may provide the best balance between fibre-matrix bonding and accelerated cement hydration, as this is the highest average of the three groups. Better microstructural integrity and effective load transfer between the cementitious matrix and the pseudostem fibres are indicated by the group's steady improvement.

With compressive strengths of 457.68 MPa, 411.84 MPa, and 485.20 MPa, respectively, the 1.5% calcium chloride samples (C1 to C3) performed worse than the 1.0% group, yielding a mean compressive strength of 451.57 MPa. This decrease, though still comparable to the .05% group, might be the result of an over-accelerated setting process that caused inadequate fibre dispersion, insufficient hydration, or increased matrix brittleness. In essence, too much accelerator could cause the structural cohesiveness of the composite to break down.
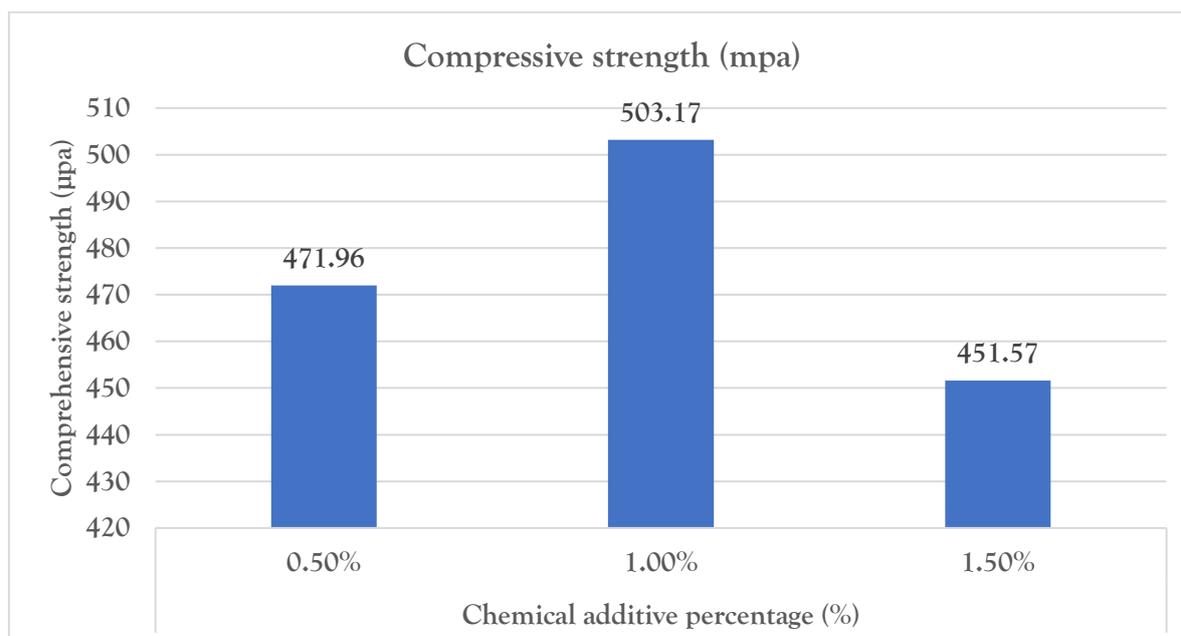
Figure 17: Relationship between compressive strength and percentages of chemical additive

Among the tested percentages, the 1.5% calcium chloride level provides the highest and most reliable compressive strength, suggesting that it is the most appropriate for applications where mechanical strength is crucial. The diminishing returns at the highest level indicate that moderation in additive concentration is essential to achieving the best structural results in cement-bonded banana pseudostem boards.

These results aligned with the findings of Mugume *et al.* [22], who observed that the compressive strength of banana/sisal fibre composites increased with fibre content up to an optimal point of 1.0%, after which further increases led to a decline in strength due to poor bonding and the development of microstructural defects.

4.0 Conclusion, Limitations and Recommendations
4.1 Conclusion
This study examined the use of banana pseudo-stem fibres in cement-bonded composites boards with varying levels of additives (0.5%, 1.0%, and 1.5%). The main objective was to evaluate the material's mechanical and physical properties, including density, flexural strength, modulus of rupture (MOR), modulus of elasticity (MOE), and compressive strength and to identify the optimal mix for construction applications. The density tests revealed a wide range of values, from 1.418 g/cm³ to 1.847 g/cm³, indicating that the composites could be tailored for different applications. Higher-density samples demonstrated stronger mechanical properties, making them suitable for more demanding construction roles, such as partition walls or structural support. Lower-density samples, on the other hand, could be applied in areas where lightweight materials are desirable, such as ceiling boards or insulation.

The flexural strength tests showed that increasing the additive content up to 1.0% enhanced the material's ability to resist deformation under load. At 0.5%, flexural strength was moderate, ranging 1918.40 N/mm² to 1933.80 N/mm². When the additive level was increased to 1.0%, flexural strength improved to a range 1916.20 N/mm² to 1960.20 N/mm². However, further increasing the additive content to 1.5% did not result in significant improvements and even led to slight performance declines. This suggests that 1.0% is the optimal additive level for maximizing flexural strength while maintaining material integrity. The modulus of rupture (MOR) and modulus of elasticity (MOE) tests yielded similar trends. MOR values at the 1.0% additive level were highest, ranging 587.46 N/mm² to 578.52 N/mm², with MOE values also peaking at this additive level. These findings suggest that the composite at 1.0% additive offers a good balance between stiffness and flexibility, making it well-suited for applications requiring strength without excessive brittleness. This balance is crucial for applications such as load-bearing panels or structural components where flexibility under stress is important.

The compressive strength test results further corroborated the conclusion that 1.0% is the optimal additive level. At 0.5% additive, compressive strength ranged 427.76 MPa to 516.16 MPa. At 1.0%, compressive strength peaked, with values ranging 447.68 MPa to 567.52 MPa. However, at 3%, compressive strength dropped slightly, ranging 411.84 MPa to 485.20 MPa. The decrease at 1.5% may be due to the saturation effect of the additives, which could result in poor dispersion and a less homogenous material structure. The study demonstrates that banana pseudo-stem fibre can be a valuable material for cement-bonded composites, particularly at a 1.0% additive

level. This level offers the best overall mechanical performance across all tested parameters, including flexural strength, MOR, MOE, and compressive strength. The findings align with previous research on the use of natural fibres in construction composites, which has shown that optimal additive levels can enhance performance but must be carefully calibrated to avoid diminishing returns.

Across the performance parameters tested, the 1% calcium chloride dosage consistently provided the most balanced results. For example, while the highest mean compressive strength was observed at 2% (503.17 MPa), the 1% composites achieved a comparably high value (471.96 MPa) while also demonstrating lower thickness swelling and more stable flexural performance. Similarly, MOR and MOE results at 1% (577.8 N/mm² and 666 N/mm², respectively) were steady and less variable than at 2% and 3%, where fluctuations were evident. Water absorption and dimensional stability also improved at 1% compared with higher dosages, indicating better long-term durability. This cross-parameter consistency validates the conclusion that 1% calcium chloride offers the optimum balance of mechanical strength, dimensional stability, and durability, making it more suitable for structural applications than higher additive levels, which may increase brittleness or variability.

4.2 Limitations

A limitation of this study is the absence of microstructural analysis techniques such as Scanning Electron Microscopy (SEM) and Energy Dispersive X-ray Spectroscopy (EDS). While these tests would provide valuable insights into fibre–matrix interaction, hydration products, and interfacial bonding, the present research prioritized macro-level engineering properties due to limitations in laboratory access and equipment availability. Future studies are therefore recommended to incorporate SEM/EDS analysis to complement the mechanical and physical evaluations presented here. Such microstructural characterization would deepen understanding of the bonding mechanism between banana pseudo stem fibres and cement matrices, further strengthening the scientific basis for their use in sustainable construction materials.

4.3 Recommendations

The study gives the following recommendations for future studies

i. Additional pretreatment methods, such as CO_2 injection and hot water treatment, to further enhance material performance should be explored.
ii. The effects of increased fibre content in cement composites be thoroughly investigated.
iii. Both Scanning Electron Microscopy (SEM) and Energy Dispersive X-ray Spectroscopy (EDS) analyses be conducted to better understand the material's microstructural properties and elemental composition.

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