CALIBRATING TWO WOOD MOISTURE METERS FOR TWO SPECIES OF BAMBOO

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CALIBRATING TWO WOOD MOISTURE METERS FOR TWO SPECIES OF BAMBOO

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ABSTRACT
The moisture content of bamboo is critical to its treatment and use. However, determining the moisture through oven drying is impractical for most applications. Moisture meters however are able to estimate the moisture content almost instantaneously. In this study, two moisture meters, *Benetech GM610* and *Brookhuis FMC*, were calibrated for two bamboo species: *Bambusa Vulgaris* and *Bambusa Blumeana*. The tests were done on dry *Bambusa Blumeana* and *Vulgaris*, and green *Bambusa Blumeana*. It was found that dry bamboo could be accurately measured using these devices, while for green bamboo the results were inconclusive.

KEYWORDS
Bamboo; Moisture Content; Physical Properties; Moisture Meter;

INTRODUCTION

Bamboo is a versatile material that can be used in many applications. It is a fast-growing plant with some species growing 9.7 to 24.5 centimeters per day (Emamverdian, 2020). With some species having compression strengths of around 36.6 MPa, shear strength of 5.69 MPa, and an average modulus of Elasticity of 36.31 GPa (Daud, 2018); it lends itself to being a viable construction material for houses, and potentially a new material that can be developed for use in sustainable construction. With the production of concrete resulting in a significant amount of greenhouse gases, bamboo is a promising alternative that may be explored to help reduce the carbon emissions from construction related processes.

Bamboo has been used as a building material in many areas of the world. They are viable structural components, especially as members that can be used with high material flexibility and through the use of beams (Apsari, 2021). In order to make the integration of bamboo more accessible, further study would be required to provide deeper knowledge on what factors affect its viable usage in the construction industry. Among these factors is the strength of the bamboo, which is dependent on several factors such as the species, diameter, thickness, moisture content, and other properties.

One of the critical factors that indicate whether bamboo may be usable or not is the presence of moisture within the material bamboo. Its processing should be conducted at low moisture contents to avoid dimensional changes due to shrinkage (Suriani, 2018). The moisture content required for material testing is also specified in ISO 22157-1 to be at 12%.

Unlike other types of construction material, wood and bamboo plants contain water differently. The fiber saturation point (FSP) represents the water content at which free water found within the material is completely removed, and only the water within the cells remains (bound water). **Figure 1** shows the relationship of the strength of the fibrous material against the moisture content. The graph shows that the compressive strength of the material is inversely proportional to the moisture content until it reaches the FSP. For moisture contents greater than the FSP, the strength becomes uniform. The FSP of a bamboo specimen depicts the moisture content at which point its strength will start to increase as moisture decreases (Gutiérrez, 2015; Trujillo, 2016; Dinwoodie, 1975)

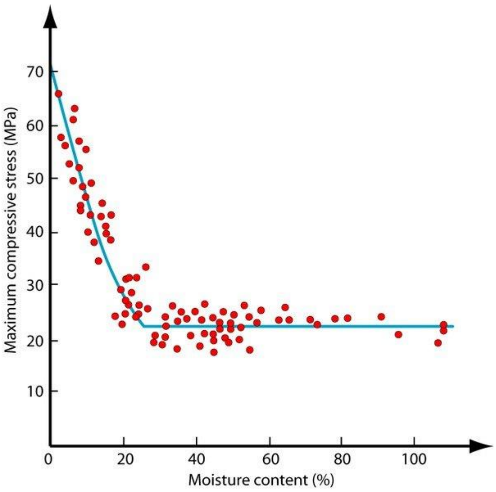


Figure 1: Fiber Saturation Point with Graph of MC vs Compressive Strength (Dinwoodie, 1975)

With many facilities focusing on treating bamboo, one of the difficulties faced is the identification of the appropriate time for harvest and treatment of the bamboo at the critical moisture content. This also applies to identifying when treated dry bamboo would be ready for use in construction. Current methods for obtaining moisture content of bamboo are through the use of conventional oven drying; however, this type of equipment is meant for laboratory purposes, and therefore slow, impractical, and costly to install for use in the field. To address this, moisture meters are used as they are able to infer instantaneously the moisture content. However, a majority of these products have only been calibrated for wood species with very few calibrated for bamboo. Therefore, this study aims to calibrate two wood moisture meters for use on bamboo species. These two devices are an inexpensive *Benetech GM610* and a more costly *Brookhuis FMC*.

This study aims to create a standardized method of using these specific moisture meters for bamboo species in order to make the measurement of the moisture content of bamboo more accessible. This will allow for a quick and accurate method for obtaining the moisture content of bamboo in the field. Whether it may be in already built bamboo structures, during construction, harvesting, or before treatment, obtaining the moisture content would be more easily accessible.

METHODOLOGY

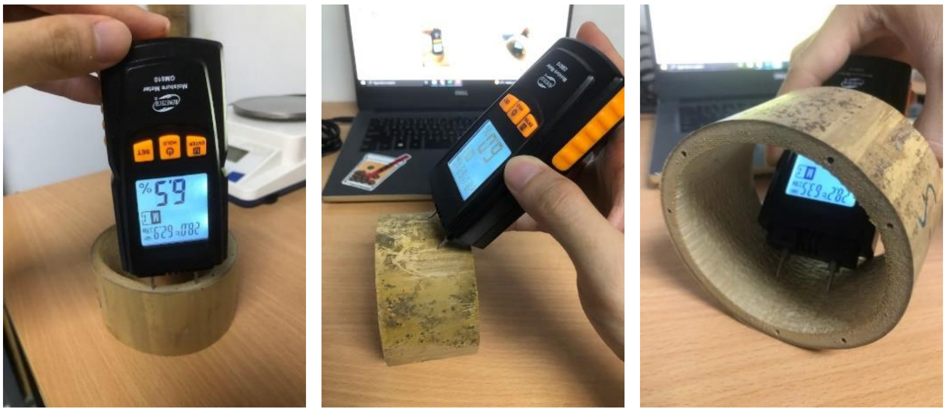
Two moisture meters, namely the *Benetech GM610* and the *Brookhuis FMC* (**Figure 2**), were tested to determine whether they may be calibrated to measure the moisture content of Bamboo. These devices were tested on the following types of bamboo: green *Bambusa Blumeana*, dry *Bambusa Blumeana*, and dry *Bambusa Vulgaris*. For both green and dry bamboo, the sample size was 30 pieces of bamboo with 5 cm off-cuts for testing as shown in **Figure 3**. For the green bamboo specifically, it would be tested for four weeks, with each week testing 30 different specimens from the same bamboo. This is done to observe the decrease of the moisture content and observe whether the moisture can be accurately measured over its gradual decrease.

a) *Brookhuis GM610* b) *Benetech FMC*

Figure 2: Moisture Meters used in the Study

Figure 3: 5-cm Bamboo cut samples

The two moisture meters were inserted into the 5-cm bamboo specimen in three different areas: a) into the end fibres of the piece, b) through the exterior skin, and c) into the interior wall of the culm; this is shown in **Figures 4 & 5**, using the *Benetech GM610* and the *Brookhuis FMC* respectively. Both moisture meters have been designed and calibrated for the measurement of different types of wood. They are given categories (levels) from 1 to 4, with different species of wood assigned to the different levels. These levels are calibrated corresponding to the different amounts of moisture that each tree species can hold. However, since these levels have not been calibrated for bamboo, the measurement at each level must be obtained and compared to the true value (determined through oven-drying) to determine the optimal level for measuring the moisture in bamboo.



a) Punctured into Culm b) Through Exterior c) Interior

Figure 4: *Benetech GM610* Testing Methods

a) Punctured into Culm b) Along Exterior c) Interior

Figure 5: *Brookhuis FMC* Testing Methods

After the measurements have been recorded using the moisture meters, the sample is then weighed and placed in an oven to dry. Using **Eq. 1**, the oven moisture content can be obtained. This method of obtaining moisture content for bamboo follows that of the ISO 22157-1. For each of the moisture meters at each level, the average value was obtained for each point of measurement. From this, the percent error can be obtained as shown in **Eq. 2**, with the oven moisture content is assumed to be the true moisture content of the bamboo sample.

$$\omega_{oven} = \frac{m_w - m_o}{m_o} \qquad \text{Eq. 1}$$

Where m_w is the mass of the sample before it was dried; and
m_o is the mass of the sample after it was oven dried.

$$\%_{error} = \left|\frac{\omega_{oven} - \omega_{average}}{\omega_{oven}}\right| \times 100 \qquad \text{Eq. 2}$$

Where $\omega_{average}$ is the average moisture content obtained by using the moisture meters.

Additionally, data on the density of the different samples were also recorded and obtained using the following formulas:

$$\rho = \frac{m_w}{V} \qquad \text{Eq. 3}$$

Where v is the volume of the sample

$v = \frac{\pi}{4}\left({d_{ave}}^2 - (d_{ave} - 2 * t_{ave})^2\right) * L_{ave}$ Eq. 4

Where d_{ave} is the average diameter of the sample;
t_{ave} is the average thickness of the sample; and
L_{ave} is the average length of the sample.

RESULTS

Dry Bamboo

From the data collected, the 30 specimens of *Bambusa blumeana* had an average thickness of 7.50 mm with a coefficient of variation of 34.8%. The average density was found to be at $797.94\frac{g}{mm^3}$. While for the *Bambusa vulgaris*, the average thickness was of 7.06 mm with a coefficient of variation of 21.1%. Its average density was found to be at $722.48\frac{g}{mm^3}$.

The dry bamboo moisture content data are shown in **Tables 1 to 4,** the values shown are the average moisture content obtained through the use of the oven drying method and the different moisture meters as well. **Tables 1 & 2** show the data obtained from the *Benetech GM610* for the *Bambusa blumeana* and *Bambusa vulgaris* respectively. **Tables 3 & 4** show the data for the *Brookhuis FMC* measuring the same bamboo specimens. In these tables the average moisture content as well as the coefficient of variation of the 30 specimens are shown for each level at each measurement area. From these values the percent error is obtained using the oven moisture content as the true value.

Table 1: Average *Benetech* Moisture content readings for *Bambusa blumeana*

Oven	Level	Into the end				Exterior wall				Interior wall			
		1	2	3	4	**1**	2	3	4	1	2	3	4
11.02	ω_{ave}	12.90	16.05	19.23	22.47	**12.02**	14.93	17.85	20.77	12.62	15.77	18.95	22.23
0.062	COV	0.117	0.111	0.110	0.113	**0.066**	0.076	0.081	0.083	0.085	0.084	0.083	0.081
-	Error	17.06	45.64	74.53	103.9	**9.04**	35.51	61.98	88.45	14.49	43.07	71.96	101.8

Table 2: Average *Benetech* Moisture content readings for *Bambusa vulgaris*

Oven	Level	Into the end				Exterior wall				Interior wall			
		1	2	3	4	**1**	2	3	4	1	2	3	4
10.96	ω_{ave}	12.43	15.55	18.72	21.88	**11.52**	14.40	17.27	20.12	12.48	15.57	18.75	21.98
0.063	COV	0.086	0.087	0.090	0.088	**0.061**	0.057	0.068	0.078	0.064	0.067	0.063	0.063
-	Error	13.47	41.92	70.82	99.72	**5.11**	31.42	57.59	83.60	13.93	42.07	71.12	100.7

Table 3: Average *Brookhuis* Moisture content readings for *Bambusa blumeana*

Oven	Level	Into the end				Exterior wall				Interior wall			
		1	2	3	4	1	2	3	4	1	2	3	4
11.02	ω_{ave}	**11.17**	13.54	15.93	18.37	10.07	12.33	14.63	16.93	10.72	13.06	15.41	17.79
0.062	COV	**0.111**	0.104	0.099	0.092	0.112	0.112	0.104	0.099	0.101	0.091	0.086	0.078
-	Error	**1.33**	22.90	44.59	66.67	8.62	11.89	32.76	53.66	2.72	18.51	39.87	61.43

Table 4: Average *Brookhuis* Moisture content readings for *Bambusa vulgaris*

Oven	Level	Into the end				Exterior wall				Interior wall			
		1	2	3	4	1	2	3	4	1	2	3	4
10.96	ω_{ave}	**10.74**	13.12	15.45	17.85	9.89	12.08	14.33	16.61	10.58	12.88	15.20	17.54
0.063	COV	**0.124**	0.113	0.105	0.098	0.083	0.065	0.059	0.055	0.119	0.105	0.099	0.094
-	Error	**1.98**	19.71	41.01	62.88	9.71	10.22	30.81	51.62	3.41	17.55	38.69	60.05

From the tests conducted, it was observed that when using the *Benetech GM610* on the dry bamboo, the most accurate reading is found at level 1 while being measured through the exterior skin. This is true for both species of the dry *Bambusa blumeana* and *Bambusa vulgaris,* with a percent error of 9.04% and 5.11% respectively.

While for the *Brookhuis FMC,* the most accurate reading is found at Level 1 while being measured by puncturing into the end of the culm. The percent error for the *Brookhuis* was found to be much less than the *Benetech* with values of 1.33% and 1.98% for *Bambusa blumeana* and *Bambusa vulgaris* Respectively.

With the values shown, it was found that the range of moisture contents obtained among the 30 specimens are relatively close to each other and shows that the statistical performance of the tests is accurate due to the low coefficients of variation among the different levels and methods. This shows that the accuracy of obtaining the moisture across the different levels was quite high and these were consistent with one another when used for *dry* bamboo.

To summarize, through all the testing on dry bamboo, it was observed that Level 1 was the most accurate in identifying the moisture content for both the *Benetech* and the *Brookhuis* devices. This was consistent for all areas tested but measuring through the exterior and punctured into the end of the culm gave the lowest percent errors for *Benetech* and *Brookhuis* respectively. One other observation made was that the performance of the different levels is also consistent across devices, with Level 1 being the most accurate and level 4 being the least accurate, reaching error percentages greater than 100. It is worth noting that Trujillo et al. (2017) found that Level 1 provided the most accurate reading for dry *Guadua angustifolia* Kunth.

Among the two methods, it can be proposed to use either the puncturing into the culm end or through the exterior when testing on *dry* bamboo. However, for larger specimens there may be a significant difference between the end grain and inner pieces due to the different drying gradients along the culm, therefore perforating the exterior wall is probably the most reliable measurement.

Green Bamboo

For each week 5 cm off-cuts were used from the green bamboo for testing. The thickness and density of the 30 specimens of *Bambusa blumeana* were recorded, and this is shown in **Table 5**. It is observed that the density is decreasing for each consecutive week. This is due to the loss in moisture from the time the bamboo was harvested to when the moisture content was obtained.

Table 5: Average thickness, density, and diameter for green *Bambusa Blumeana*

	Week 1	Week 2	Week 3	Week 4
Average Diameter (mm)	97.05	97.55	97.93	99.52
COV	0.071	0.079	0.069	0.070
$Average\ Thickness\ (mm)$	9.32	9.09	8.70	8.83
COV	0.168	0.185	0.188	0.183
$Average\ Density\left(\frac{g}{mm^3}\right)$	853.33	851.85	823.31	802.33
COV	0.108	0.140	0.195	0.157

The tests were conducted on green *Bambusa blumeana* for 4 weeks in order to observe the gradual decrease in the moisture content over time when subjected to natural air-drying. **Figures 6 & 7** shows the moisture contents measured over these weeks using the *Benetech* and *Brookhuis* moisture meters respectively. Specifically, it shows the average moisture contents at the 4 different levels, measured from the three different points: into the culm, through the exterior, and through the interior. Also shown in the graph is the average of the moisture content obtained from oven drying.

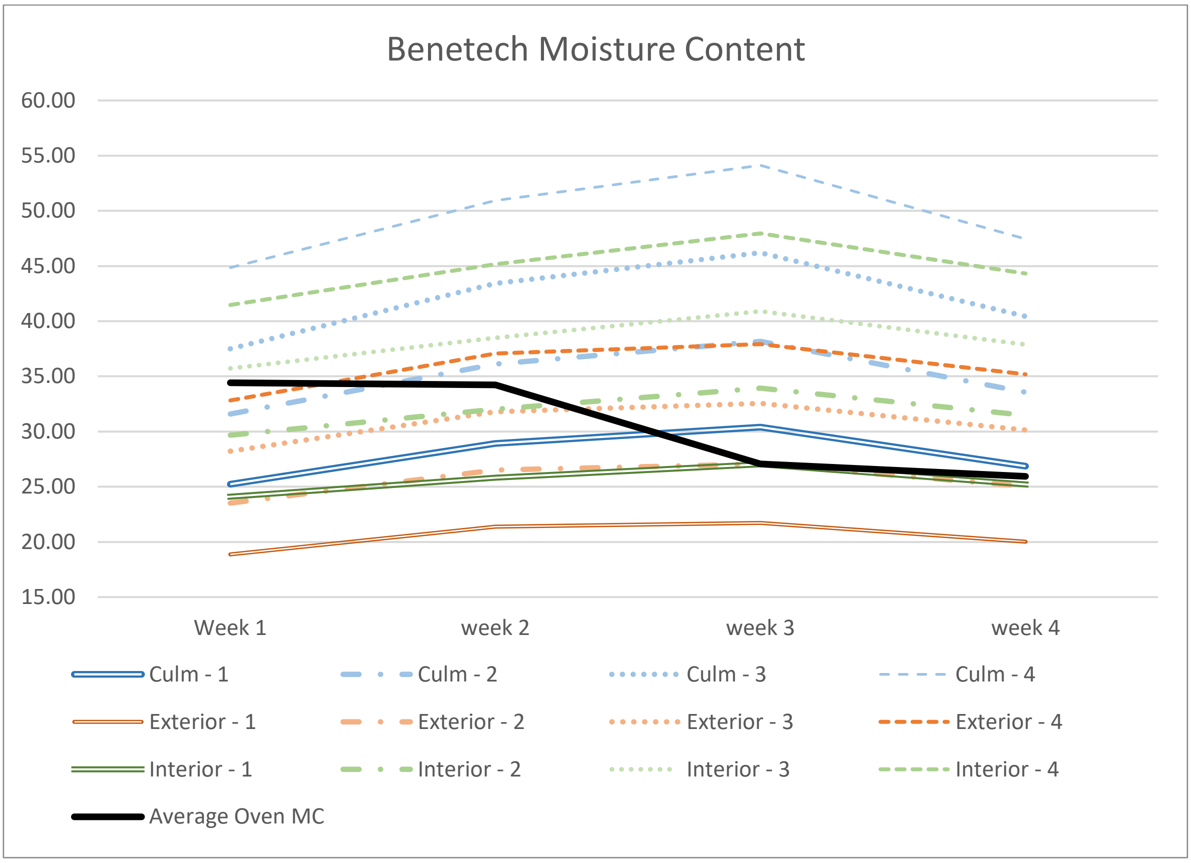


Figure 6: Average Moisture Content Reading for *Benetech GM610*

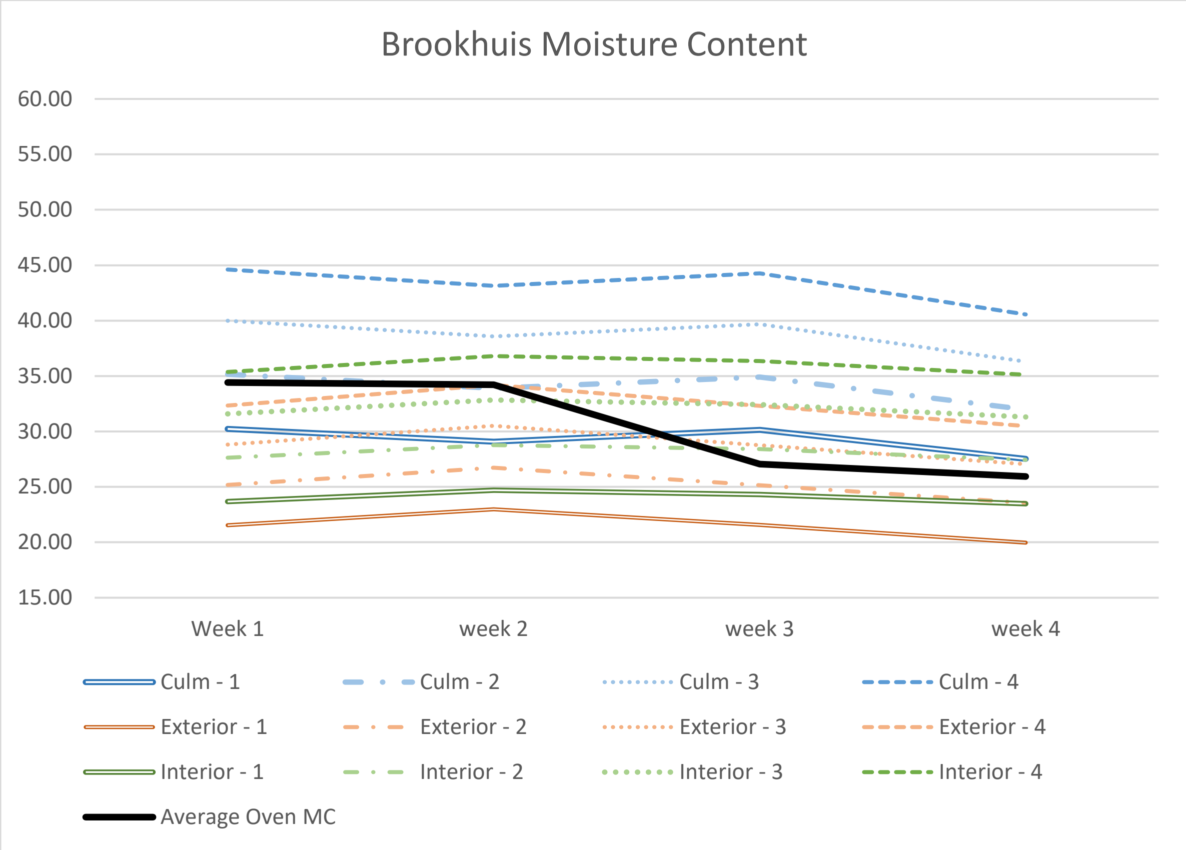


Figure 7: Average Moisture Content Reading for *Brookhuis FMC*

From these graphs, it can be seen that there is a consistent trend with the readings for each device even at different locations and levels. It can be observed that for the *Benetech*, the moisture content increased from weeks 1 to 3. While for the *Brookhuis*, it also increased its moisture content at week 3 however it was not as high as the *Benetech*. Additionally, the readings from the *Brookhuis* are more consistent with each other when compared to that of the *Benetech*.

However, both the trends of the *Benetech* and *Brookhuis* are not consistent with the trend of the average moisture content obtained using the oven. To better show the accuracy of the measurements compared to the average oven moisture content, **Tables 6 & 7** show the average values, coefficient of variance, and the error percentage of the *Benetech* and the *Brookhuis* devices respectively.

Table 6: Average *Benetech* Moisture content readings for green *Bambusa blumeana*

		Oven	Into the end				Exterior wall				Interior wall			
			1	2	3	4	1	2	3	4	1	2	3	4
Week 1	ω_{ave}	34.42	25.23	**31.59**	37.50	44.85	18.87	23.52	28.22	**32.82**	24.10	29.67	**35.72**	41.47
	COV	0.433	0.289	**0.293**	0.332	0.299	0.237	0.238	0.240	**0.238**	0.279	0.289	**0.296**	0.305
	Error %	-	26.69	**8.22**	8.95	30.31	45.19	31.68	18.02	**4.66**	29.98	13.81	**3.77**	20.48
Week 2	ω_{ave}	34.23	28.92	**36.10**	43.43	50.93	21.37	26.52	**31.78**	37.08	25.82	**32.02**	38.50	45.15
	COV	0.538	0.284	**0.291**	0.293	0.297	0.310	0.315	**0.320**	0.320	0.313	**0.322**	0.320	0.320
	Error %	-	15.52	**5.47**	26.89	48.81	37.58	22.53	**7.14**	8.34	24.57	**6.46**	12.48	31.91
Week 3	ω_{ave}	27.05	**30.40**	38.17	46.20	54.12	21.72	**27.05**	32.55	37.92	**27.03**	33.93	40.90	47.95
	COV	0.497	**0.277**	0.277	0.277	0.278	0.309	**0.313**	0.311	0.317	**0.296**	0.300	0.299	0.301

	Error %	-	**12.38**	41.09	70.79	100.06	19.72	**0.00**	20.33	40.17	**0.06**	25.45	51.20	77.26
Week 4	ω_{ave}	25.94	**26.87**	33.57	40.43	47.45	20.03	**25.03**	30.15	35.18	**25.22**	31.48	37.88	44.33
	COV	0.627	**0.350**	0.352	0.352	0.353	0.348	**0.350**	0.351	0.352	**0.346**	0.348	0.347	0.350
	Error %	-	**3.58**	29.41	55.88	82.93	22.77	**3.49**	16.23	35.64	**2.78**	21.37	46.05	70.91

Table 7: Average *Brookhuis* Moisture content readings for green *Bambusa blumeana*

		Oven	Into the end				Exterior wall				Interior wall			
			1	2	3	4	1	2	3	4	1	2	3	4
Week 1	ω_{ave}	34.42	30.23	**35.16**	39.99	44.61	21.54	25.18	28.82	**32.34**	23.69	27.63	31.58	**35.36**
	COV	0.433	0.350	**0.342**	0.330	0.319	0.273	0.256	0.246	**0.237**	0.288	0.276	0.268	**0.259**
	Error %	-	12.17	**2.14**	16.18	29.61	37.41	26.84	16.26	**6.03**	31.18	19.71	8.26	**2.72**
Week 2	ω_{ave}	34.23	29.08	**33.90**	38.57	43.13	22.98	26.73	30.51	**34.19**	24.70	28.77	**32.84**	36.80
	COV	0.538	0.335	**0.329**	0.323	0.315	0.332	0.315	0.304	**0.293**	0.345	0.334	**0.326**	0.317
	Error %	-	15.04	**0.96**	12.69	26.02	32.85	21.92	10.86	**0.11**	27.85	15.94	**4.06**	7.51
Week 3	ω_{ave}	27.05	**30.14**	34.92	39.67	44.27	21.58	25.15	**28.77**	32.31	24.32	**28.42**	32.44	36.34
	COV	0.497	**0.349**	0.338	0.330	0.322	0.366	0.345	**0.332**	0.321	0.354	**0.340**	0.330	0.321
	Error %	-	**11.41**	29.11	46.65	63.66	20.21	7.01	**6.37**	19.44	10.11	**5.06**	19.92	34.34
Week 4	ω_{ave}	25.94	**27.53**	31.98	36.30	40.56	19.97	23.56	**27.05**	30.49	23.48	**27.44**	31.31	35.12
	COV	0.627	**0.439**	0.425	0.411	0.400	0.401	0.383	**0.370**	0.359	0.456	**0.435**	0.421	0.409
	Error %	-	**6.15**	23.30	39.96	56.38	23.01	9.17	**4.30**	17.56	9.47	**5.79**	20.72	35.39

When comparing the most accurate method of measurement for the moisture meters to that of the oven moisture content, it was observed that the best method and level would change each week. The most accurate level for the *Benetech* was Level 3 through the exterior at Week 1. This would change the following week to using Level 2 through puncturing into the culm end. The 3rd week, the most accurate was level 2 through the exterior method. Finally, by week 4, it changed to level 1 through the interior method. For the *Brookhuis*, the best method during the first week was level 2 through puncturing into the culm, however by the 2nd week it changed to level 4 through the exterior. Come 3rd week, it was Level 2 through interior. And finally, the 4th week was level 3 through the exterior. It can be observed that with both the *Benetech* and the *Brookhuis*, there was no consistent level that would accurately record the green bamboo's moisture content through the 4-week period. Because of this, it is difficult to identify the ideal level or method of measuring that would yield consistent and accurate results for measuring the moisture content of green bamboo.

However, when analyzing the different methods of measurement alone, it was found that as the moisture of the bamboo decreased each week, the most accurate level would also decrease. It was assumed that if the trend continues, all of the different methods will reach level 1 once dry. This is based upon the results of the dry bamboo tests since the same devices and bamboo species were used.

Based on the results, it is inconclusive whether the moisture meters can be calibrated for green bamboo. Due to the difference in the accuracy of the measurements from week to week, it is difficult to create a methodology for use in the field.

CONCLUSION

Through this study, a methodology for measuring the moisture content of dry bamboo was found, with accurate readings obtained at level 1 for both devices. Among the two devices, the more accurate is the *Brookhuis* with error percentages less than 2%; however, the *Benetech* still obtained error percentages of less than 10%. Therefore, either device would be recommended for use in the field, and it is advised to use either of these devices on dry bamboo at level 1 and punctured into the culm end or, preferably, through the exterior.

On the other hand, for the experiments with green bamboo, no optimal level can be recommended for testing its moisture content and its different levels. This is due to the variation in optimal settings as it dries. However, if the end user understands the limitations of each device and uses it with the sole aim of knowing how close a batch is to the dry condition, then its limited accuracy in the green condition should not be a hinderance.

Based on the results, it can be recommended to test the moisture content on more species of dry bamboo in order to verify if the methods recommended in this paper is applicable broadly on various bamboo species. Other studies may also be done on practical applications such as actual moisture contents of bamboo-built structures. For green bamboo, further testing may be done with a similar methodology to what was conducted in this study. It would be recommended to record precisely when the bamboo was cut from its stem in order to properly monitor the time from when it was cut to testing and to continuously monitor the change in moisture content to establish at what moisture content the moisture meters readings become tolerably reliable. It is also recommended to test on more green bamboo species in order to find more generalized conclusions on how green bamboo moisture content can be measured.

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CONFLICT OF INTEREST

The authors declare that they have no conflicts of interest associated with the work presented in this paper.

DATA AVAILABILITY

Data on which this paper is based is available from the authors upon reasonable request.