BAMBOO

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ReBuMat Workshop May 11, 2021

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Auf Wissen bauen

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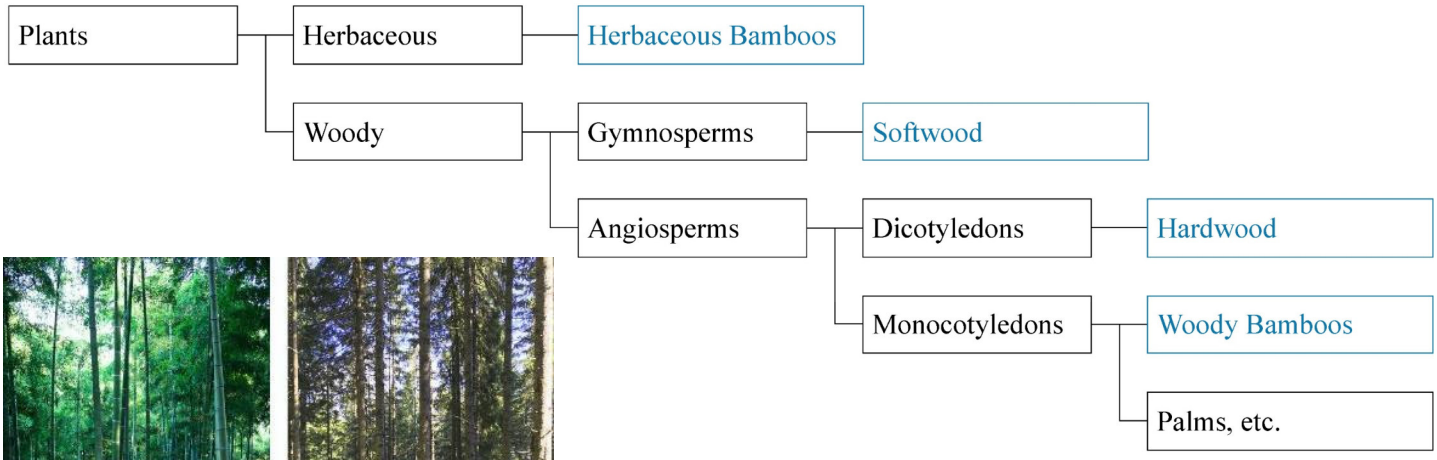
Bamboo

Botanical classification



- Photos of Moso bamboo (left) and Spruce (right)

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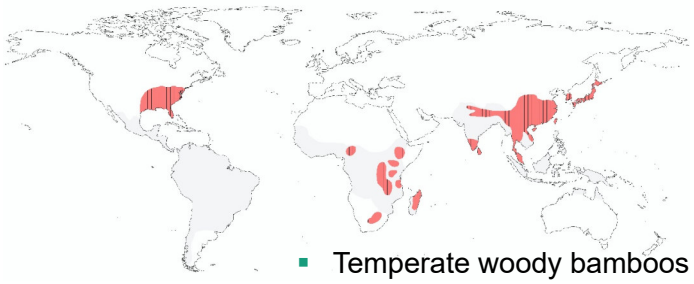
Bamboo

Agricultural specifics

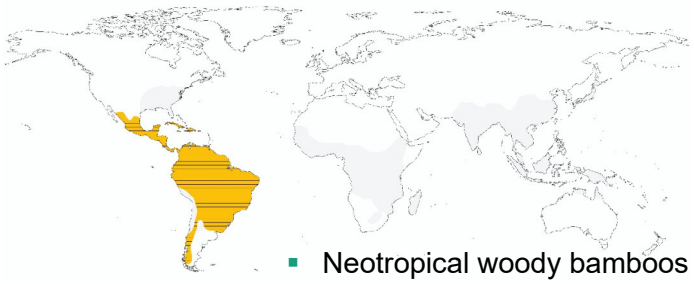
- Fast growing, 4-6 years to become exploitable.
- High yield, annual culm production 7-10 t/ha (Moso bamboo).
- Excellent ecological benefits, annual CO_2 absorption 12 t/ha, water storage 1000 t/ha.
- Grows in non-cultivated land, mountain, steep slope, no competition to food production.

Bamboo growing regions

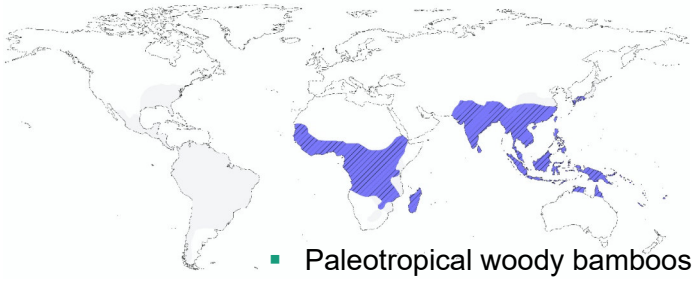
Tropical and subtropical regions in the Asia-Pacific (67%), Americas (30%), and Africa (3%)



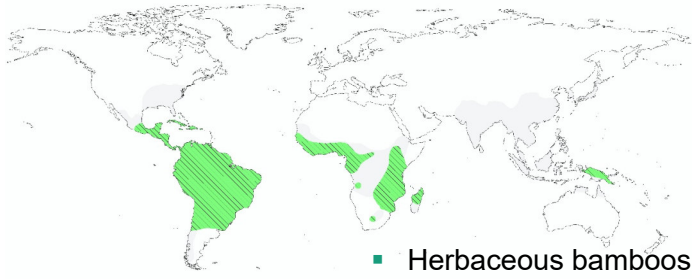
- Temperate woody bamboos



- Neotropical woody bamboos



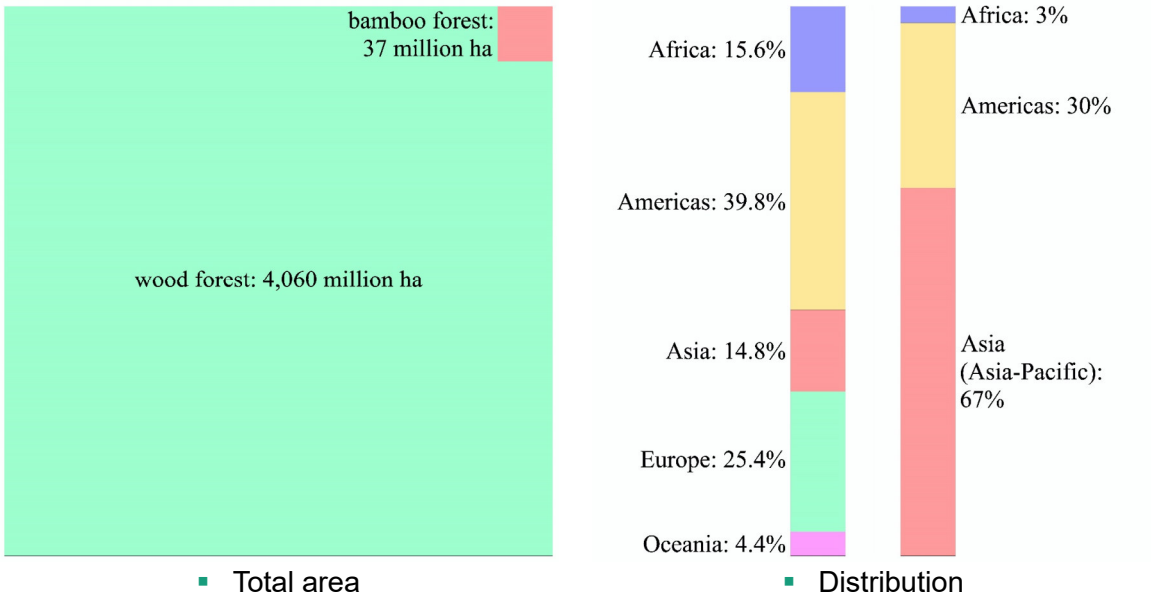
- Paleotropical woody bamboos



- Herbaceous bamboos

Bamboo growing regions

Comparison between wood and bamboo forest resources



Bamboo resources

Bamboo resources of main bamboo producing countries in the Asia-Pacific Bamboo Area

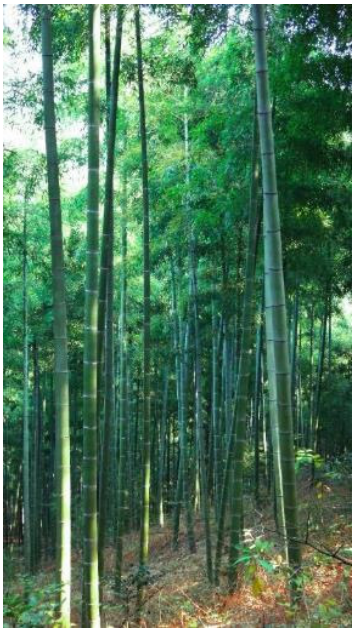
Region	Country	Bamboo forest area [10 thousand hm^2]	Bamboo species	
			genera	species
East Asia	China	641.16	39	870
	Japan	14.13 (2010)	13	230
	South Korea	2.21 (2016)	5	19
South Asia	Bangladesh	49	9	33
	Bhutan	/	15	33
	India	548 (FAO, 2010)/1600	23	136
	Nepal	6	12	53
	Sri Lanka	74.2 (FAO, 2010)	/	19
Southeast Asia	Cambodia	13 (2014)	4	/
	East Timor	/	/	/
	Indonesia	210	25	160
	Laos	224	15	86
	Malaysia	500	10	70
	Myanmar	85.90 (FAO, 2010)	21	102
	Thailand	26	17	72
	The Philippines	18.80 (FAO, 2010)	/	62
	Vietnam	**153.30**	**20**	**216**

Bamboo resources

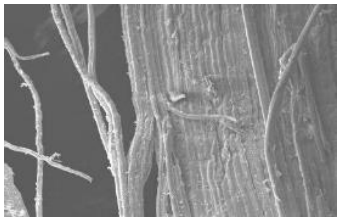
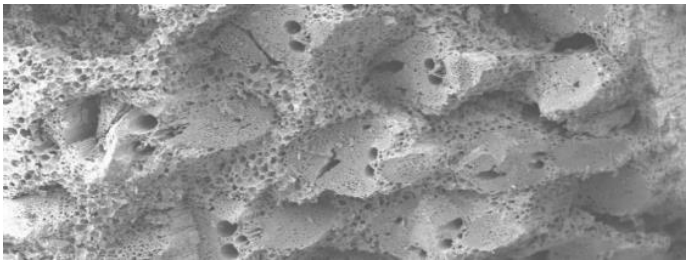
Vietnam

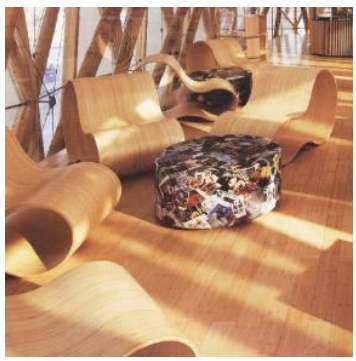
- Bamboo forests account for about 10% of the country's land area. Among them, natural bamboo forests, bamboo-wood mixed forests and planted bamboo forests account for 245,000 ha, 1.10 million ha and 122,000 ha, respectively.
- 10 bamboo species have high potential commercial value, namely *Dendrocalamus barbatus*, *Bambusa longissima*, *Phyllostachys pubescens*, *Dendrocalamus spp.*, *Bambusa spp.*, *Schizostachyum spp.*, *Arundinaria spp.*, *Indosasa spp.*, *Bambusa procera*, *Thyrsostachys siamensis*, and *Maclurochloa sp.*.
- Lung (*Bambusa longissima*) and Luong (*Dendrocalamus barbatus*) are the most common bamboo species in Thanh Hoa and Nghe An provinces, providing main raw materials for Nghe An, Hoa Binh and other traditional bamboo processing areas (such as Hanoi and Thai Binh) to produce handicrafts, furniture and building materials.
- Nationwide, bamboos are mainly used to make handicrafts, furniture, electric poles, houseware and building boards, as well as bamboo charcoal.
- In recent years, Vietnam consumes about 1 billion bamboo culms every year for various purposes. In 2019, Vietnam had about 290 companies engaged in the production of bamboo products, mainly located in the provinces of Ha Tay (now Ha Noi), Thai Binh, Nghe An and Thanh Hoa.

Bamboo potential



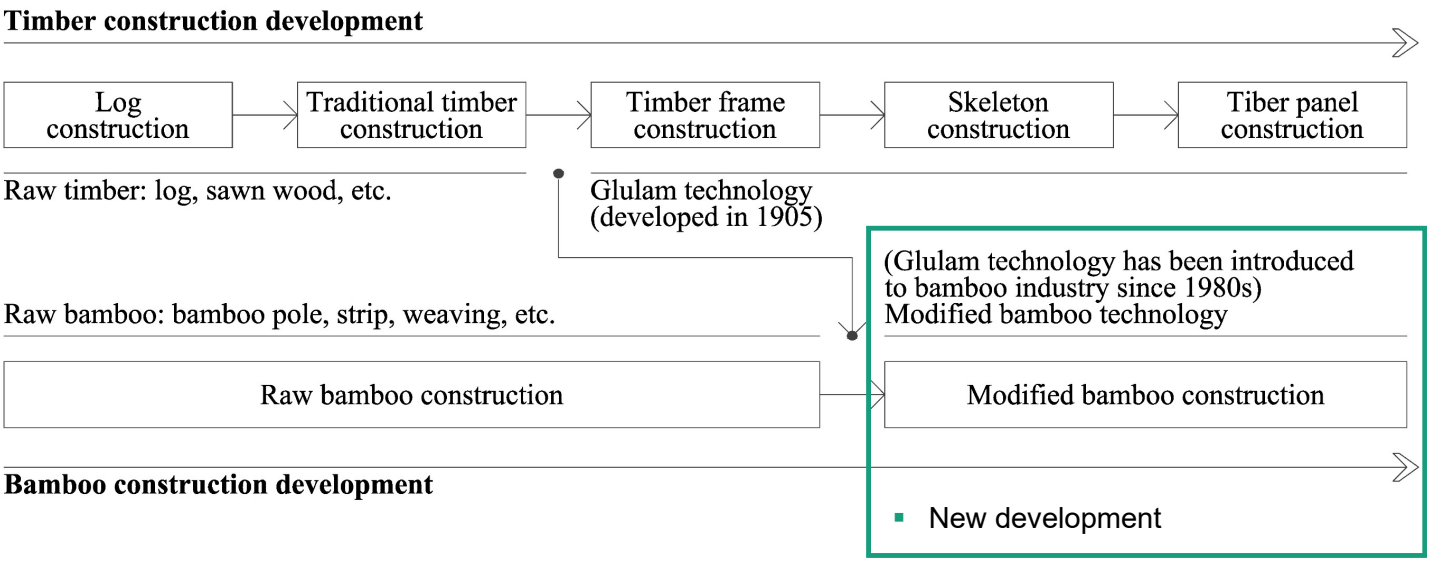
- Unique fibrous tissue, excellent longitudinal mechanical strength.
- Multilevel pore microstructure, hygrothermal characteristics comparable to hardwood.



Bamboo construction development

Evolution of bamboo construction system



Bamboo construction development

Raw bamboo construction cases

- Bali Island, Indonesia, 2016

- Chiang Mai, Thailand, 2018

- Chiang Mai, Thailand, 2018

- Vietnam, 2018

Bamboo construction development

Modified bamboo construction case

- Bamboo Exemplary Building in Hunan University, Changsha, China, 2015

- Building components made of bamboo mat board, Changsha, China, 2015

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Bamboo-based building materials

Industrial bamboo products

- Raw bamboo

flattened bamboo panel

laminated bamboo sheet

bamboo mat board

natural bamboo fiber

bamboo scrimber

bamboo particleboard

bamboo oriented strand board

bamboo charcoal

- Bamboo-based panels
- By-products

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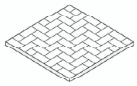
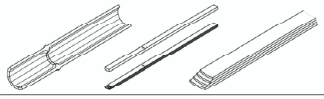
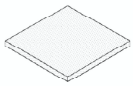
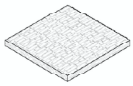
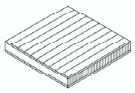
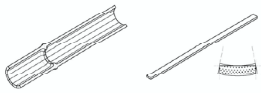
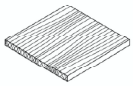
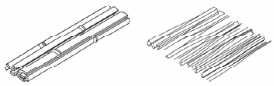
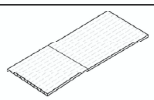
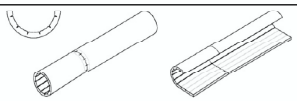
Bamboo-based building materials

Industrial bamboo products

Material	Development	Structure diagram	Constituent unit	Main application
Plybamboo (bamboo mat/curtain board)	1980s			Concrete formwork, truck and bus bottom board, load-bearing component, wallboard
Bamboo particleboard	1990s			Furniture, packaging material
Bamboo oriented strand board	1990s			Concrete formwork, wallboard
Laminated bamboo	1990s			Indoor flooring, finishes, furniture
Bamboo scrimber	2000s			Load-bearing component, indoor/outdoor flooring, finishes
Flattened bamboo panel	2010s			Indoor flooring, finishes

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Bamboo-based building materials

Production of laminated bamboo

strip preparation, rough planning

strip selection, protective treatment

strip assembly, compression with glue

post processing, bamboo sawing and sanding

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Bamboo-based building materials

Production of bamboo scrimber



strip preparation, drying and protective treatment


strip assembly, compression with glue



mold preparation, curing and shaping



post processing, bamboo lumber and sheet

Hygrothermal Properties Test on Bamboo

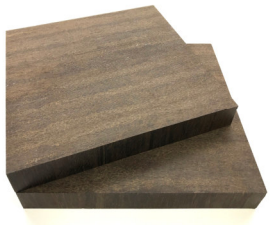
Laminated bamboo and bamboo scrimber, three-dimensional

Basic properties
1) Bulk density test
2) True density test

Hygric properties
3) Sorption test
4) Water immersion test
5) Capillary absorption test
6) Water vapor transmission test
7) Drying test

Thermal properties
8) Thermal analysis
9) Thermal conductivity test

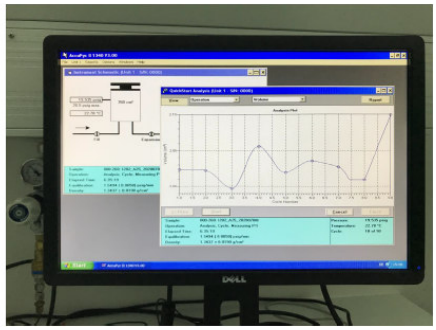


Hygrothermal Properties Test on Bamboo

1) Dry bulk density (ρ_d)
2) True density (ρ_t)
3) Porosity (Φ), calculated from: $\Phi = (\rho_t - \rho_d) / \rho_t \times 100\%$

- Bulk density test



- True density test

Test results - basic properties

1) Dry bulk density (ρ_d)
2) True density (ρ_t)
3) Porosity (Φ), calculated from: $\Phi = (\rho_t - \rho_d) / \rho_t \times 100\%$

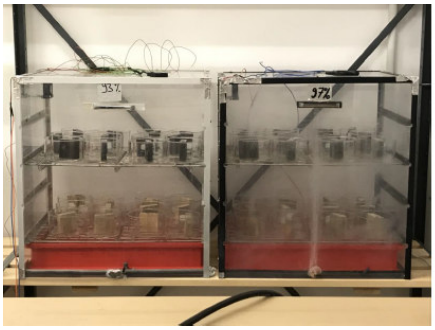
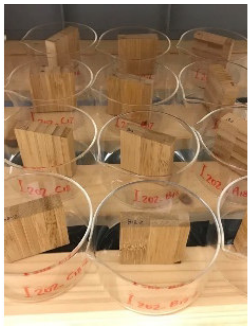
Test results of the basic properties, laminated bamboo and bamboo scrimber

Items	Notation	Value	laminated bamboo	bamboo scrimber
Dry bulk density	ρ_d [kg/m^3]	average	**621**	**1127**
		max.	656	1218
		min.	600	1085
		deviation	+/–28	+/–67
True density	ρ_t [kg/m^3]	average	**1386**	**1277**
		max.	1414	1285
		min.	1344	1269
		deviation	+/–35	+/–8
Porosity	Φ [-]	average	**55.2%**	**11.7%**

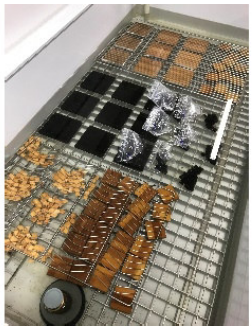
Hygrothermal Properties Test on Bamboo

Moisture storage-related properties

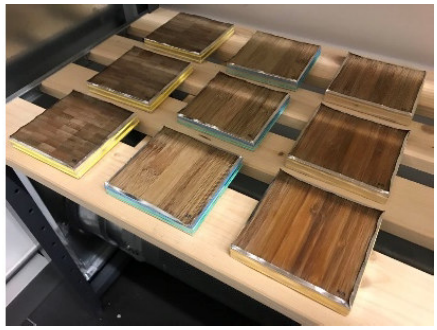
1) Isothermal adsorption and desorption curve (u-RH, T = 23°C)
2) Free water saturation (w_{cap})

- Sorption test



- Water immersion test



- Drying test

(for moisture-transport properties)

Hygrothermal Properties Test on Bamboo

Moisture transport-related properties

1) Capillary water absorption coefficient (A)
2) Water vapor diffusion resistance factor (μ)


- Capillary absorption test

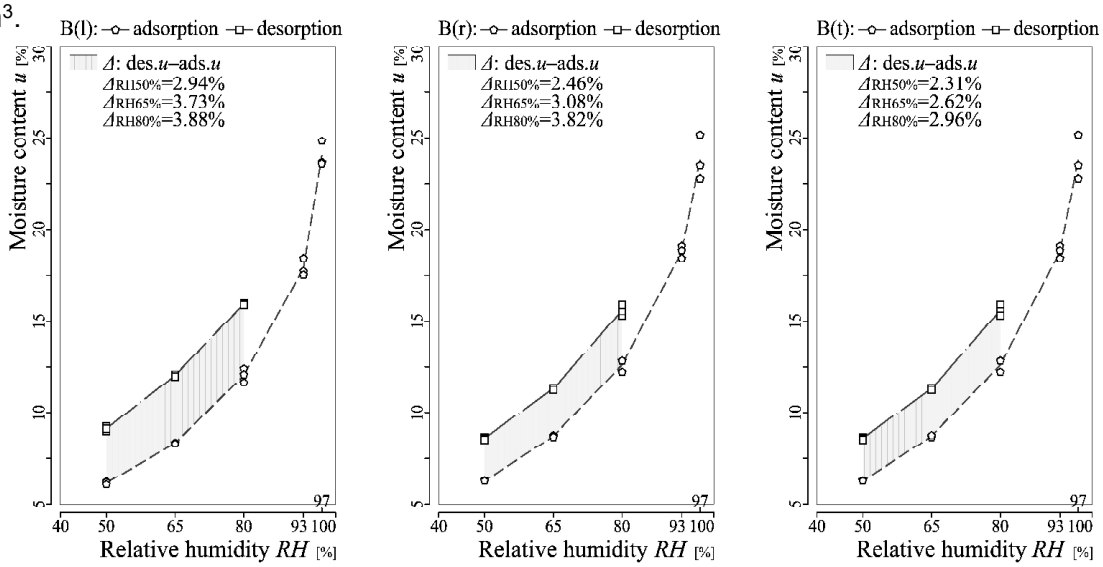

- Water vapor transmission test

Test results - hygric properties

Moisture storage-related properties

1) Isothermal adsorption and desorption curve (T = 23°C), laminated bamboo

- Hysteresis effects：RH = 50%, 65%, 80%, $\Delta_{des.u-ads.u}$ are **2.57%, 3.15%, 3.56%**, or 15.9 kg/m³, 19.5 kg/m³, 22.1 kg/m³.



Test results - hygric properties

Moisture storage-related properties

2) Free water saturation (w_{cap}), laminated bamboo

- Test lasts for about 4.5 months, average u value after immersion is 90.7%, equivalent to 563 kg/m³.
- Radial, tangential, and longitudinal dimension of the specimens expands to 102.8%, 103.9%, and 100.2%, respectively, which means a total volume expansion of 107.0%.
- w_{cap} can be corrected to 563 / 107.0% = 526 kg/m³, equivalent to a volume ratio of 52.6%, which is **slightly lower than the Φ (55.2%)**.

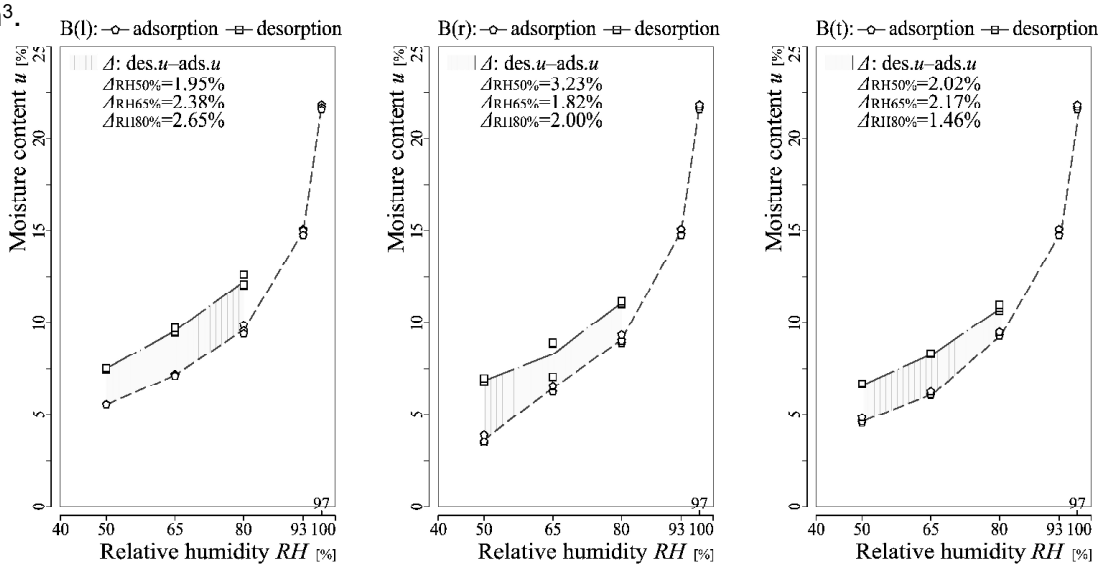
Specimen number	u [mass-%]	w [kg/m³]	Volume expansion [%]	Corrected w [kg/m³]
I202_A1 I202_A2 I202_A3	91	**563**	**7.0**	**526**

Test results - hygric properties

Moisture storage-related properties

1) Isothermal adsorption and desorption curve (T = 23°C), bamboo scrimber

- Hysteresis effects: RH = 50%, 65%, 80%, $\Delta_{des.u-ads.u}$ are **1.95%, 2.38%, 2.65%**, or 21.8 kg/m³, 26.8 kg/m³, 29.9 kg/m³.



Test results - hygric properties

Moisture storage-related properties

2) Free water saturation (w_{cap}), bamboo scrimber

- Test lasts for about 4.5 months, average u value after immersion is 28.3%, equivalent to 323 kg/m³.
- Radial, tangential, and longitudinal dimension expands to 108.3%, 103.2%, and 100.4%, respectively, which means a total volume expansion of 112.2%. (Note: the radial direction corresponds to the compression direction during the material production process)
- w_{cap} can be corrected to 323 / 112.2% = 288 kg/m³, equivalent to a volume ratio of 28.8%, which is **far higher than the Φ (11.7%)**.

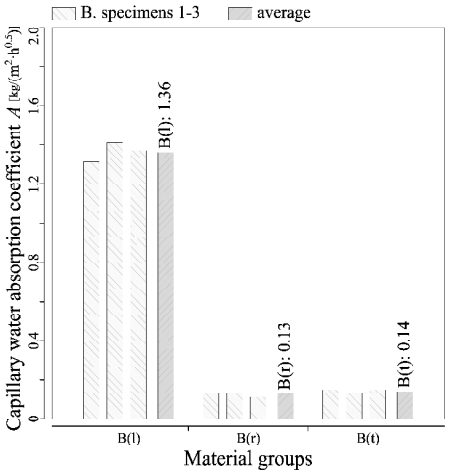
Specimen number	u [mass-%]	w [kg/m³]	Volume expansion [%]	Corrected w [kg/m³]
I202_D1 I202_D2 I202_D3	28	**323**	**12**	**288**

Test results - hygric properties

Moisture transport-related properties

1) Capillary water absorption coefficient (*A*), laminated bamboo

- *A* values in longitudinal, radial, tangential directions, are **1.36 kg/(m²h$^{0.5}$), 0.13 kg/(m²h$^{0.5}$), 0.14 kg/(m²h$^{0.5}$)**.
- *A* value in radial direction is slightly lower than that in tangential direction, and both are about **1/10** of the value in longitudinal direction.

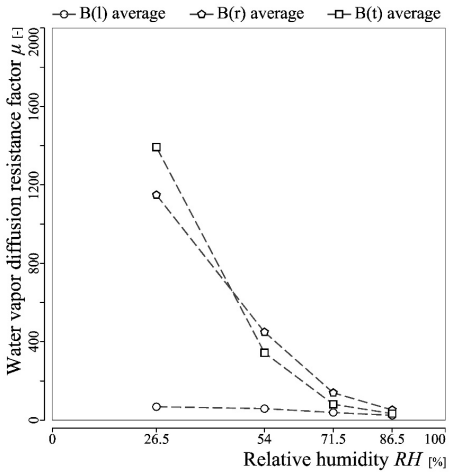


Test results - hygric properties

Moisture transport-related properties

2) Water vapor diffusion resistance factor (μ), laminated bamboo

- $\mu_{RH33\%-75\%}$ values in radial and tangential directions are, respectively, **19.1 and 14.6 times** that in longitudinal direction.

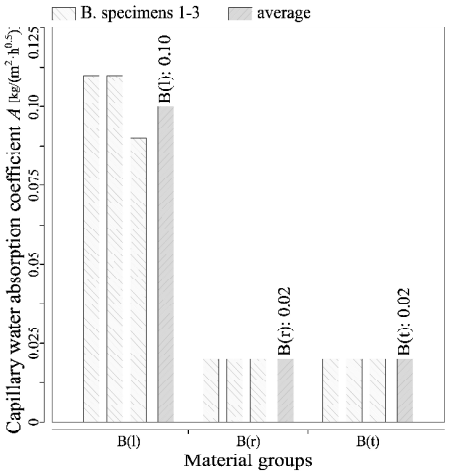


Test results - hygric properties

Moisture transport-related properties

1) Capillary water absorption coefficient (A), bamboo scrimber

- A values in longitudinal, radial, tangential directions, are **0.10 kg/(m²h$^{0.5}$), 0.02 kg/(m²h$^{0.5}$), 0.02 kg/(m²h$^{0.5}$)**.
- A values in radial direction and tangential direction are both **1/5** of the value in longitudinal direction.

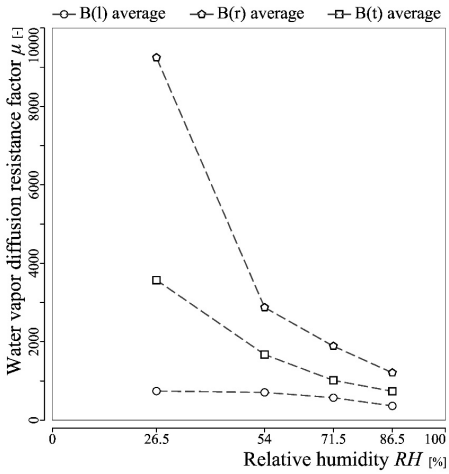


Test results - hygric properties

Moisture transport-related properties

2) Water vapor diffusion resistance factor (μ), bamboo scrimber

- $\mu_{RH33\%-75\%}$ values in radial and tangential directions are, respectively, **33.8 and 23.6 times** that in longitudinal direction.



Hygrothermal Properties Test on Bamboo

Heat storage-related properties

Specific heat capacity (*c*)

Heat transport-related properties

Thermal conductivity (*λ*)

- Thermal analysis

- Thermal conductivity test

Test results - thermal properties

Heat storage-related properties

Specific heat capacity (*c*)

- Laminated bamboo: *T* = –15-40°C, *c* value is 1430.6 J/(kg·K). It increases to 1776.3 J/(kg·K) in *T* = 10-30°C.
- Bamboo scrimber: *T* = –15-40°C, *c* value is 1630.8 J/(kg·K). It increases to 1882.1 J/(kg·K) in *T* = 10-30°C.

Test results of the thermal properties (heat storage-related), laminated bamboo

Items	Notation	Value	within –15-40°C	within 10-30°C
Specific heat capacity	*c* [J/(kg·K)]	average	**1430**	**1776**
		max.	1436	1797
		min.	1425	1754
		deviation	+/–5.4	+/–21.5

Test results of the thermal properties (heat storage-related), bamboo scrimber

Items	Notation	Value	within –15-40°C	within 10-30°C
Specific heat capacity	*c* [J/(kg·K)]	average	**1631**	**1882**
		max.	1874	2128
		min.	1387	1636
		deviation	+/–244	+/–246

Test results - thermal properties

Heat transport-related properties

Thermal conductivity (λ)

Test results of the thermal properties (heat transport-related), laminated bamboo

Items	Notation	Value	B(l)	B(r)	B(t)
Dry thermal conductivity	λ_d [W/(m·K)]	average	**0.308**	**0.209**	**0.211**
		max.	0.323	0.214	0.214
		min.	0.297	0.206	0.207
		deviation	+/–0.013	+/–0.004	+/–0.003
Moisture-dependent λ supplement	a_w [%/M.-%]	average	1.01	0.94	1.23

Test results of the thermal properties (heat transport-related), bamboo scrimber

Items	Notation	Value	B(l)	B(r)	B(t)
Dry thermal conductivity	λ_d [W/(m·K)]	average	**0.427**	**0.270**	**0.299**
		max.	0.444	0.293	0.303
		min.	0.409	0.250	0.297
		deviation	+/–0.017	+/–0.021	+/–0.003
Moisture-dependent λ supplement	a_w [%/M.-%]	average	1.02	1.70	1.72

Note: B(l): Bamboo longitudinal; B(r): Bamboo, radial; B(t): Bamboo, tangential

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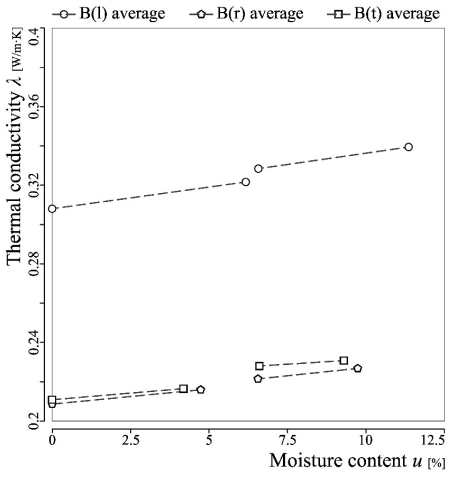
Test results - thermal properties

Heat transport-related properties

Thermal conductivity (λ), laminated bamboo

- λ_d values in longitudinal, radial, tangential directions are, **0.308 W/(m·K), 0.209 W/(m·K), 0.211 W/(m·K)**.



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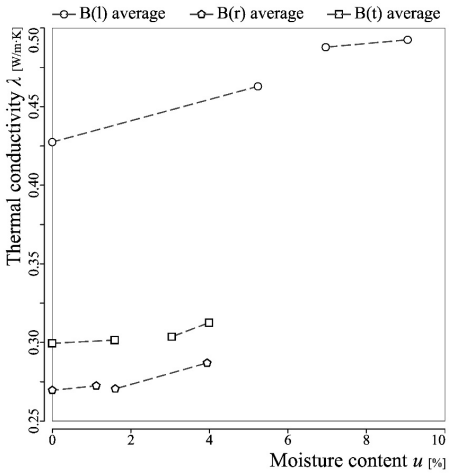
Test results - thermal properties

Heat transport-related properties

Thermal conductivity (λ), bamboo scrimber

- λ_d values in longitudinal, radial, tangential directions are, **0.427 W/(m·K), 0.270 W/(m·K), 0.299 W/(m·K)**.



Comparison with reference timber products

Reference timber (RT) selected for comparison

RT for comparison with laminated bamboo:

12 timber products provided by Fraunhofer IBP, and 1 additional 'Spruce, tangential' from the LTH Lund University.

Group	Product name	*Source*
Raw material - softwood	Softwood	IBP
	Spruce, longitudinal	IBP
	Spruce, radial	IBP
	Spruce, tangential	LTH
Raw material - hardwood	Hardwood	IBP
	Oak, longitudinal	IBP
	Oak, radial	IBP
Laminated timber	Stora Enso CLT (cross laminated timber)	IBP
	3-ply cross-laminated panel	IBP
	Laminated veneer lumber	IBP
Plywood	Veneer plywood BFU 100	IBP
	Plywood board	IBP
	veneer plywood beech BFU-BU	IBP

RT for comparison with bamboo scrimber:

13 timber products provided by Fraunhofer IBP, LTH Lund University, and NTNU Norwegian University of Science and Technology.

Group	Product name	*Source*
Raw material - softwood	Softwood	IBP
	Spruce, longitudinal	IBP
	Spruce, radial	IBP
	Spruce, tangential	LTH
Raw material - hardwood	Hardwood	IBP
	Oak, longitudinal	IBP
	Oak, radial	IBP
Plywood	Veneer plywood BFU 100	IBP
	Plywood board	IBP
	veneer plywood beech BFU-BU	IBP
Wood fibreboard (hard)	Woodfibreboard, hard	LTH
	Wood fibreboard, hard - wind barrier	NU
	Woodfibre board, hard	NU

Comparison with reference timber products

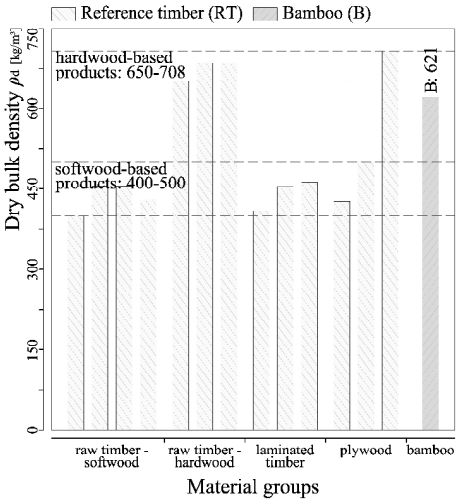
Basic properties, moisture and heat storage-related properties

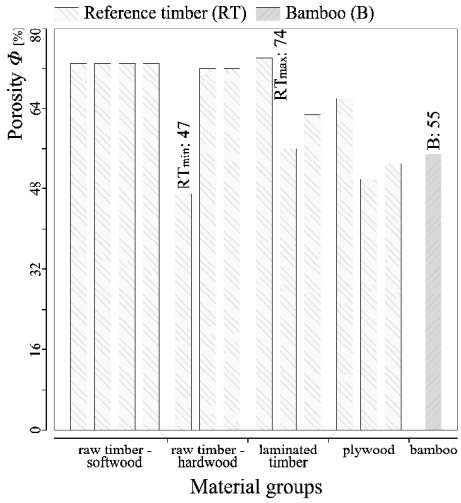
1) Dry bulk density (ρ_d), laminated bamboo

- The softwood-based products have ρ_d values in a range 400-500 kg/m^3, and the hardwood-based products have ρ_d values in a range 650-708 kg/m^3. The ρ_d of laminated bamboo is **621 kg/m^3**, which is **closer to hardwood**.

2) Porosity (Φ), laminated bamboo

- The given range of Φ among the RT is 0.47-0.74, showing no clear difference between softwood and hardwood-based products. The **Φ of laminated bamboo is 0.552, lower than the mid. value of RT (0.61)**.



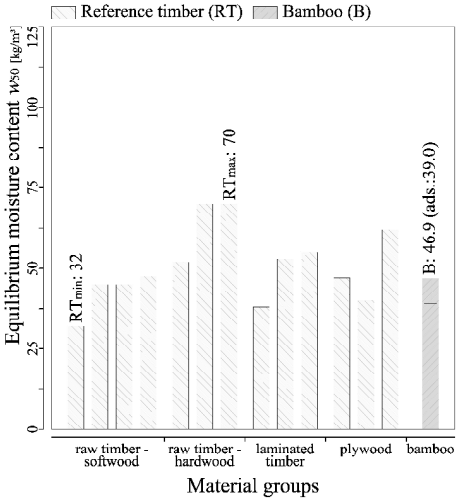


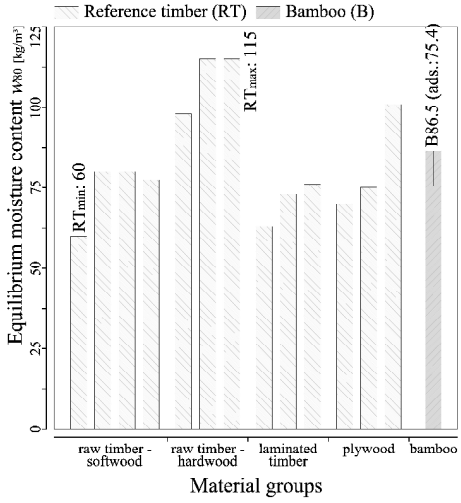
Comparison with reference timber products

Basic properties, moisture and heat storage-related properties

3) Equilibrium moisture content (w_{50} and w_{80}), laminated bamboo

- The w values of laminated bamboo are taken by the average of adsorption and desorption processes.
- **w_{50}** and **w_{80}** values of laminated bamboo fall in the **middle area within the RT range**.
- **If the adsorption w is used for comparison**, the w_{50} and w_{80} of laminated bamboo will be in a lower position in the RT range.



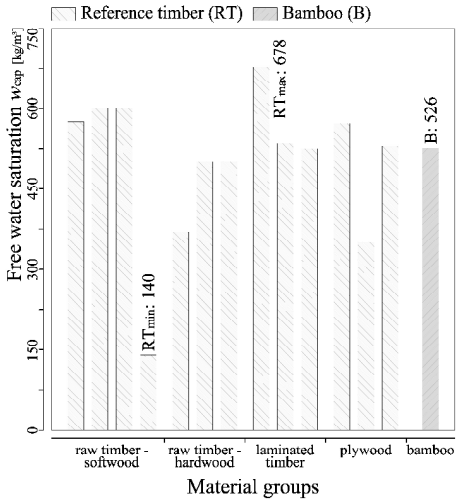


Comparison with reference timber products

Basic properties, moisture and heat storage-related properties

4) Free water saturation (w_{cap}), laminated bamboo

- There are large differences among different timber products, ranging from **140 to 678 kg/m³**. If converted to the volume ratio, **some of them are quite closed to the corresponding *Φ*, while the others are far lower than *Φ***.
- Bamboo specimens are immersed in water for about 4.5 months. The resulted w_{cap} of laminated bamboo is quite close to its *Φ* value, and **higher than the mid. value of RT**.

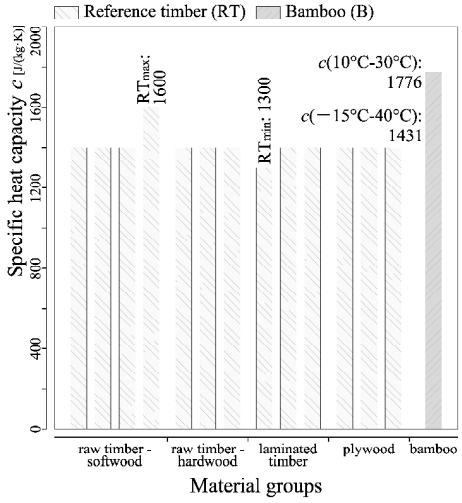


Comparison with reference timber products

Basic properties, moisture and heat storage-related properties

5) Specific heat capacity (*c*), laminated bamboo

- If *c* value corresponding to **temperature range 10-30°C** is taken, it is **higher than the max. value of RT**.
- If **temperature range –15-40°C** is considered, the *c* value is **close to the mid. value of RT**.



Comparison with reference timber products

Moisture and heat transport-related properties

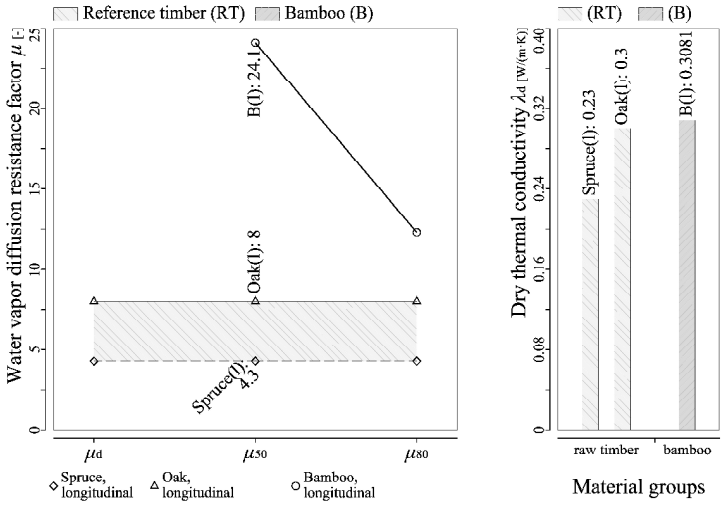
Laminated bamboo, longitudinal direction

1) Moisture transport

- Moisture transport rate of laminated bamboo is **lower than the RT**. The μ_{50} is **3.0 and 5.6 times** that of Oak and Spruce, respectively.

2) Heat transport

- In contrast, the heat transport rate of laminated bamboo is **higher than the RT**. The λ_d of laminated bamboo is **0.308 W/(m·K)**, higher than both the Oak and the Spruce.



Comparison with reference timber products

Moisture and heat transport-related properties

Laminated bamboo, radial and tangential directions

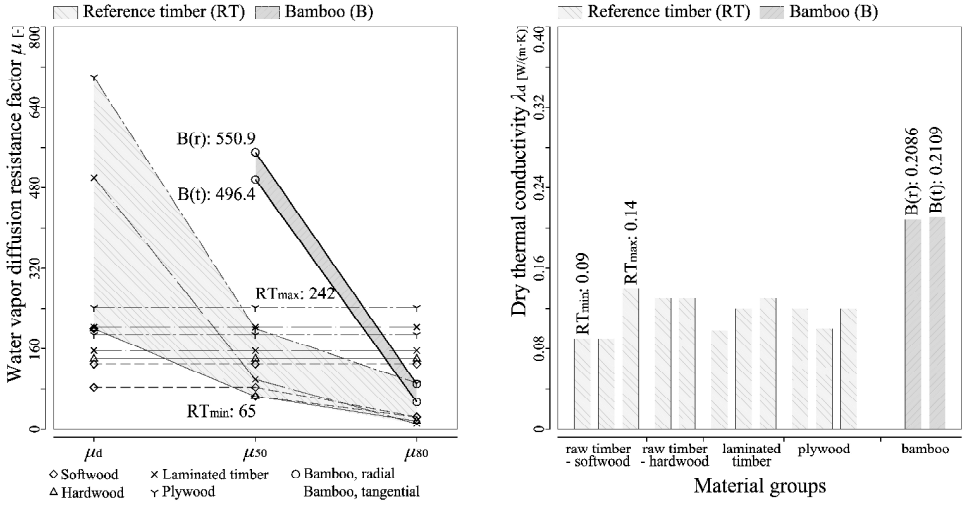
1) Moisture transport

- Shows **similar law to the longitudinal direction**.

- Both directions have μ_{50} values that are higher than the corresponding max. values of RT, as well as DWS_{80} values that are lower than the min. values of RT.

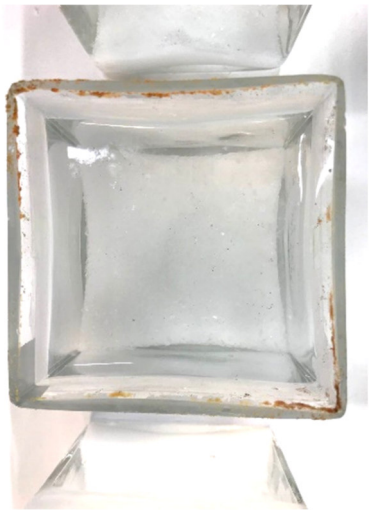
2) Heat transport

- λ_d values of laminated bamboo are about **50% higher** than the max. value of RT.



Mould growth on specimens

Mold growth occurs on the surfaces of specimens in three groups of the sorption test (adsorption process in ***RH* = 80%/93%/97%),** and two groups of the water vapor transmission test (wet cups with salt solution corresponding to ***RH* = 93%).**



Mould growth on specimens

Record of the Mould Index (MI)

- Observation for MI 1 and MI 2 is only possible by microscope. So only the **MI 3-6 is preliminary recorded**.

Mould Index for Experiments and Modeling (VTT model)

Index	Description of the growth rate
0	No growth
1	Small amounts of mould on surface (microscope), initial stages of local growth
2	Several local mould growth colonies on surface (microscope)
3	Visual findings of mould on surface, < 10% coverage, or < 50% coverage of mould (microscope)
4	Visual findings of mould on surface, 10% - 50% coverage, or > 50% coverage of mould (microscope)
5	Plenty of growth on surface, > 50% coverage (visual)
6	Heavy and tight growth, coverage about 100%

Mould growth on specimens

Record of the Mould Index (MI)

- In ***T* = 23°C, *RH* = 80%,** mould growth occurs in the laminated bamboo specimen groups in all three directions, as well as the bamboo scrimber groups in longitudinal direction.
- It indicates that the internationally used **critical *RH* value (80%) is not applicable**.

Mould Index		0	1	2	3	4	5	6
T=23°C, *RH*=80%	B(l),1	 2020-11-13	no record		 2020-12-18	 2020-12-25	 2021-01-08	 2021-01-26
	B(l),2	 2020-11-13			 2020-12-22	 2020-12-29	 2021-01-15	 2021-02-05
	B(l),3	 2020-11-13			 2020-12-18	 2020-12-25	 2021-01-05	 2021-01-19

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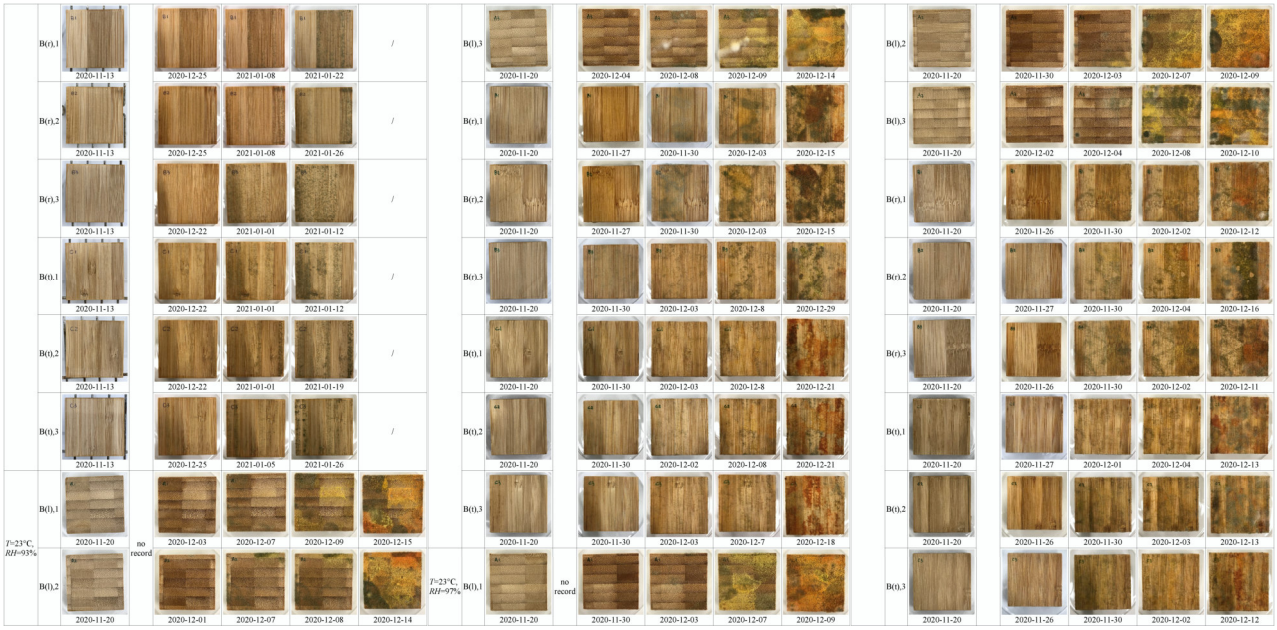
Mould growth on specimens

Record of the Mould Index (MI)

Laminated bamboo, *T* = 23°C, *RH* = 80%, 93%, 97%.



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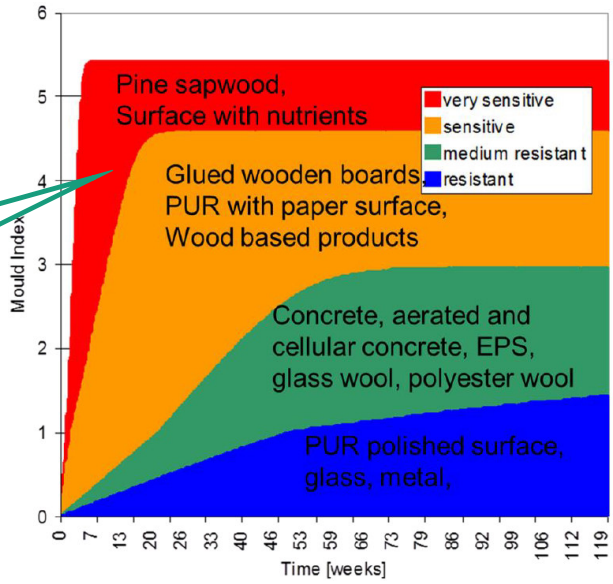
Mould growth on specimens

Record of the Mould Index (MI)

- Both laminated bamboo and bamboo scrimber can be classed to "**very sensitive**" in the VTT model.

This record cannot yet provide complete and sufficiently accurate MI parameters, but it shows that both laminated bamboo and bamboo scrimber fall in this zone of "very sensitive"



Ojanen, T., Viitanen, H., & Peuhkuri, R. (2007). Modelling of mould growth in building envelopes: Existing models, discussion on improvement aspects, sensibility analysis. Paper presented at Annex 41 working meeting, Porto, Portugal.

Summary

Material parameters. Nine laboratory test items have been carried out on laminated bamboo and bamboo scrimber, which provides necessary material parameters for describing the heat and moisture transfer characteristics of these bamboo products.

Comparison between bamboo in different directions. The heat and moisture transport-related properties of the bamboo specimens in different directions are compared, showing that both heat and moisture transport rate in radial and tangential directions are far lower than that in longitudinal direction. In general, the heat and moisture transport rate in radial direction is lower than that in tangential direction.

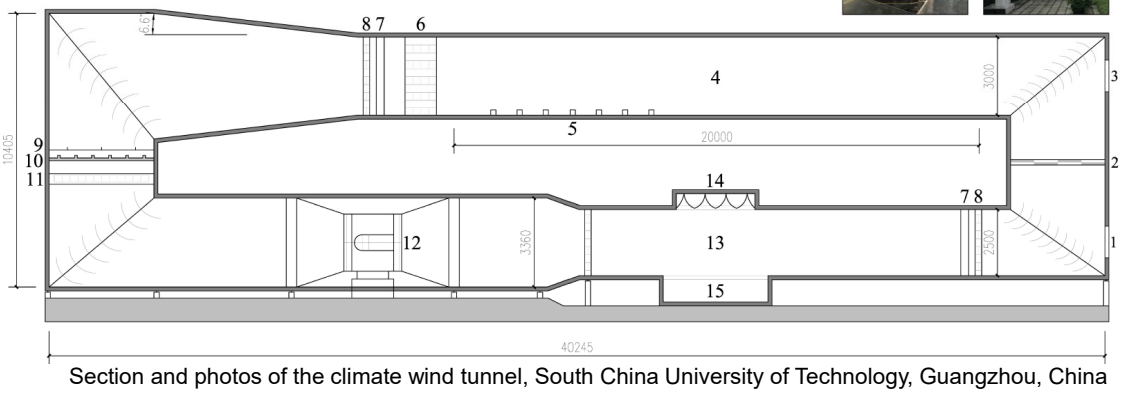
Comparison between bamboo and reference timber. The comparison between bamboo and corresponding reference timber (RT) shows that, in terms of basic properties, laminated bamboo is closer to hardwood and far different from softwood. In terms of hygric and thermal properties, both laminated bamboo and bamboo scrimber have generally lower moisture storage and transport properties, and higher heat storage and transport properties than RT. In many cases, the properties parameters of bamboo scrimber exceed the value range of RT.

Preliminary record for Mould Index. The MI of the laminated bamboo and bamboo scrimber in longitudinal, radial and tangential directions in climate conditions of T = 23°C, and RH = 80%, 93%, 97% is preliminarily obtained, but the test cannot yet provide complete and sufficiently accurate MI parameters. It shows that both laminated bamboo and bamboo scrimber can be classed to "very sensitive" in the VTT model, and the internationally used critical RH value (80%) is not applicable to laminated bamboo and bamboo scrimber.

Future perspective

Hygrothermal performance-oriented study

- Mould growth test
- Field test
- Computer simulation with local climate conditions
- Climate wind tunnel test (in Guangzhou, China)



Section and photos of the climate wind tunnel, South China University of Technology, Guangzhou, China

BAMBOO

ReBuMat
German-Vietnamese Collaborative Project on Resource-efficient Construction using Sustainable Building Materials

ReBuMat 2021

Hartwig M. Künzel
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Thank you for your attention

Auf Wissen bauen