FINNISH ThermoWood ASSOCIATION

ThermoWood®
Handbook

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Preface

This handbook has been produced by the members of the Finnish Thermowood Association. When new products and methods of production enter the various markets, it is very important to offer as much information as possible concerning the product and process so as to raise and maintain the level of knowledge as efficiently as possible. Therefore, we hope that this handbook will act as a good information source for specifiers, end users in industry, construction companies, timber merchants, etc.

The aim of the handbook is to present a good mix between theoretical material, laboratory results, information from field testing, and, finally, practical advice for working with the product. The results have been collected from a wide range of sources, most of which are of research institute or university status; experiences of industrial manufacturers have been included too. The results and experiences presented in this handbook should only be used as a guide and are subject to change.

One of the roles of the Finnish Thermowood Association will involve updating this handbook on a regular basis. As new results and experiences become available, new editions will be published outlining the areas that have been updated.

The name ThermoWood is a registered trademark, and may be used only by members of the Finnish ThermoWood Association.

We hope that the readers of this handbook will find it both informative and useful.

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1. Introduction

1.1. Background

It has been known for centuries that burning the surface of wood in open fire will make it more durable in exterior use. Even the Vikings used this method in outdoor structures such as fences.

Heat treatment of wood was scientifically studied by Stamm and Hansen in the 1930s in Germany and by White in the 1940s in the United States. In the 1950s, Germans Bavendam, Runkel, and Buro continued research into the subject. Kollman and Schneider published their findings in the 1960s, and Rusche and Burmester in the 1970's. More recently, research work was carried out in Finland, France, and the Netherlands in the 1990s. The most intensive and comprehensive research work was conducted by VTT in Finland. Significant practical research is also being done by YTI (the Institute of Environmental Technology).

ThermoWood is manufactured using a method developed by VTT. The wood material is heated to a temperature of at least 180 degrees Celsius while it is protected with steam. Besides providing protection, the steam also affects the chemical changes taking place in the wood. As a result of the treatment, environmentally friendly ThermoWood is created. Its colour darkens, it is more stable than normal wood in conditions of changing humidity, and its thermal insulation properties are improved. If carried out at a sufficiently high temperature, treatment also makes the wood resistant to decay. On the other hand, this has a decrease in the bending strength.

1.2. The ThermoWood process in brief

An industrial scale heat-treatment process for wood has been developed at VTT in co-operation with the Finnish wood product industry. The ThermoWood process is licensed to the members of the Finnish Thermowood Association.

The ThermoWood process can divided into three main phases:

– **Phase 1.** Temperature increase and high-temperature drying
  Using heat and steam, the kiln temperature is raised rapidly to a level of around 100 ºC. Thereafter, the temperature is increased steadily to 130 ºC, during which time the high-temperature drying takes place and the moisture content in the wood decreases to nearly zero.
– **Phase 2.** Heat treatment
  Once high-temperature drying has taken place, the temperature inside the kiln is increased to between 185 ºC and 215 ºC. When the target level has been reached, the temperature remains constant for 2–3 hours depending on the end-use application.
– **Phase 3.** Cooling and moisture conditioning
  The final stage is to lower the temperature by using water spray systems; when the temperature has reached 80–90 ºC, re-moisturising takes place to bring the wood moisture content to a useable level, 4–7%.

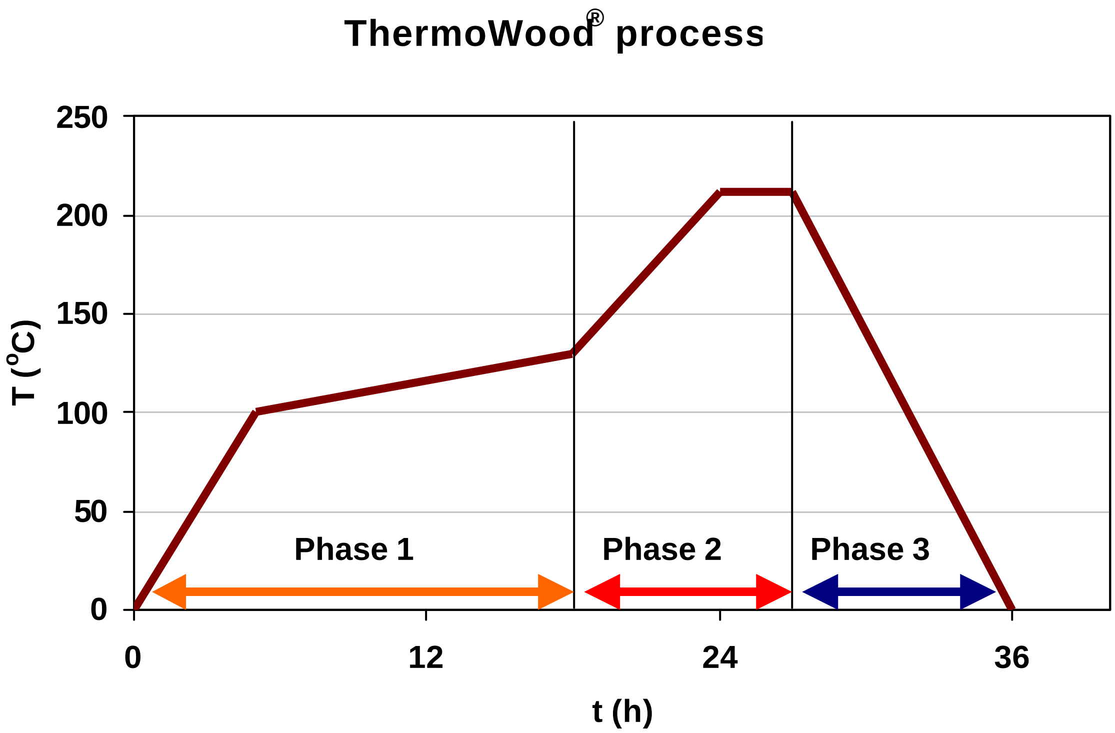


Figure 1-1. Diagram of the production process

When the temperature is raised or lowered, a special adjustment system is used in order to prevent surface and inside splitting and checking. Customised adjustment values are used for different wood species and dimensions.

The raw material can be green or kiln-dried wood. If the process is begun with green wood, the wood can be dried in a very fast high-temperature drying process. The method is suitable for softwood and hardwood species. However, the process must be optimised separately for each wood species.

For more specific details on the ThermoWood process, see chapter 3.

1.3. Changes in wood structure and chemical reactions

As a result of the heat treatment process the wood structure is re-formed, the following pictures show how the structure differs between normal untreated pine and heat treated pine.

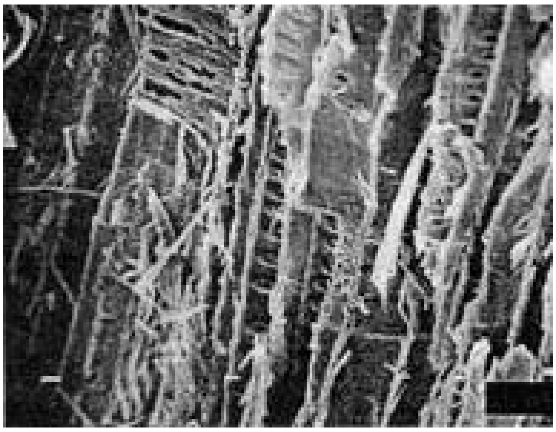


Figure 2-1. Untreated pine

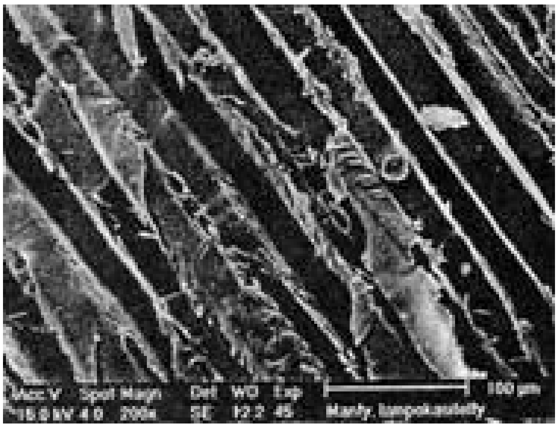


Figure 3-1. Heat-treated pine

Heating wood permanently changes several of its chemical and physical properties. The change in properties is mainly caused by thermic degrading of hemicelluloses. Desired changes start to appear already at about 150 ºC, and the changes continue as the temperature is increased in stages. As a result, swelling and shrinkage due to moisture is decreased, biological durability is improved, colour darkens, several extractives flow from the wood, the wood becomes lighter, equilibrium moisture content decreases, pH decreases, and thermal insulation properties are improved. However, the wood's rigidity and strength properties are also changed.

1.4. Standard ThermoWood treatment classification

Softwood and hardwood species have a separate classification since their properties clearly differ. There are two classes of heat treatment. Having more than two classes is not reasonable since wood properties change slowly at first as the temperature increases. Once the treatment temperature exceeds 200 ^{o}C, the properties change rapidly. Using more than two classes would generate a risk of mixing properties of different classes. 215 ^{o}C is sufficient as a maximum temperature value yet is not so high that the effects of heat treatment on the wood's structural properties would be significant.

In the standard class of ThermoWood treatment, swelling and shrinkage of wood due to moisture, colour change, and biological durability are emphasised as key properties.

Since the ThermoWood material to be supplied to industrial customers is heat-treated in accordance with the agreements between the purchaser and producer, the processing level can be carefully optimised according to the end use application. In this case, the material will be ThermoWood that is not categorised according to the standard treatment classification scheme.

Standard ThermoWood treatment classes
ThermoWood has two standard treatment classes, Thermo-S and Thermo-D.

Thermo-S
The letter 'S' in 'Thermo-S' stands for 'stability'. Along with appearance, stability is a key property in the end use applications of the products in this treatment class. The average tangential swelling and shrinkage due to moisture for Thermo-S class treated wood is 6–8%. Thermo-S class ThermoWood is classified as relatively durable according to the standard EN 113; i.e., its natural resistance to decay meets class 3 requirements.

Recommended end use applications for Thermo-S class heat-treated timber:

Thermo-S Softwood	Thermo-S Hardwood
- building components - furnishing in dry conditions - fixtures in dry conditions - furniture - garden furniture - sauna benches - door and window components	- furnishing - fixtures - furniture - flooring - sauna structures - garden furniture

Thermo-D
The letter 'D' in 'Thermo-D' stands for 'durability'. Along with appearance, biological durability is a key property in the end use applications of products in this treatment class. The average tangential swelling and shrinkage due to moisture for Thermo-D class treated wood is 5–6%. Thermo-D class ThermoWood is classified as durable according to the EN 113 standard; i.e., its natural resistance to decay meets class 2 requirements.

Recommended end use applications for Thermo-D class heat-treated timber:

Thermo-D Softwood	Thermo-D Hardwood
- cladding - outer doors - shutters - environmental constructions - sauna and bathroom furnishing - flooring - garden furniture	End use applications as in Thermo-S. If a darker colour is desired, Thermo-D should be used.

Summary of the effects of the ThermoWood process on wood properties, by treatment class

Softwoods (pine and spruce)

	Thermo-S	Thermo- D
Treatment temperature	190 °C	212 °C
Weather resistance	+	++
Dimensional stability	+	++
Bending strength	no change	-
Colour darkness	+	+ +

Hardwoods (birch and aspen)

	Thermo-S	Thermo- D
Treatment temperature	185 °C	200 °C
Weather resistance	no change	+
Dimensional stability	+	+
Bending strength	no change	-
Colour darkness	+	+ +

1.5. List of standards

- EN 20 – 1 Wood preservatives. Determination of the protective effectiveness against Lyctus Brunneus (Stephens). Part 1: Application by surface treatment (laboratory method)
- EN 21 Wood preservatives. Determination of the toxic values against Anobium punctatum (De Geer) by larval transfer (Laboratory method)
- EN 46 Wood preservatives. Determination of the preventive action against recently hatched larvae of Hylotrupes bajulus (Linnaeus) (Laboratory method)
- EN 47 Wood preservatives. Determination of the toxic values against Hylotrupes bajulus (Linnaeus) larvae (Laboratory method)
- EN 84 Wood preservatives. Accelerated ageing of treated wood prior to biological testing. Leaching procedure
- EN 113 Wood preservatives. Test method for determining the protective effectiveness against wood destroying basidiomycetes. Determination of the toxic values
- EN 117 Wood preservatives. Determination of toxic values against Reticulitermes santonensis de Feytaud (Laboratory method)
- EN 252 Field test method for determining the relative protective effectiveness of a wood preservative in ground contact
- EN 302-2 Adhesives for load-bearing timber structures; test methods; part 2: determination of resistance to delamination (laboratory method)
- EN 335 – 1 Durability of wood and wood-based products - Definition of hazard classes of biological attack - Part 1: General
- EN 335 – 2 Durability of wood and wood-based products - Definition of hazard classes of biological attack - Part 2: Application to solid wood
- EN 350 – 1 Durability of wood and wood-based products. Natural durability of solid wood. Part 1: Guide to the principles of testing and classification of the natural durability of wood
- EN 350 – 2 Durability of wood and wood-based products. Natural durability of solid wood. Part 2: Guide to natural durability and treatability of selected wood species of importance in Europe
- EN 392 Glued laminated timber - Shear test glue lines
- EN 408 Timber structures. Structural timber and glued laminated timber. Determination of some physical and mechanical properties
- EN 460 Durability of wood and wood-based products - Natural durability of solid wood - Guide to the durability requirements for wood to be used in hazard classes
- ENV 807 Wood preservatives. Determination of the effectiveness against soft rotting micro-fungi and other soil inhabiting micro-organisms
- EN 927 – 1 Paints and varnishes. Coating materials and coating systems for exterior wood. Part 1: Classification and selection

- EN 927 – 3 Paints and varnishes. Coating materials and coating systems for exterior wood. Part 3: Natural weathering test
- EN 927 – 4 Paints and varnishes. Coating materials and coating systems for exterior wood. Part 4: Assessment of the water-vapour permeability
- EN 927 – 5 Paints and varnishes. Coating materials and coating systems for exterior wood. Part 5: Assessment of the liquid water permeability
- EN 12037 Wood preservatives - Field test method for determining the relative protective effectiveness of a wood preservative exposed out of ground contact - Horizontal lap-joint method
- ISO 5660 – 1 Fire tests; reaction to fire; part 1: rate of heat release from building products (cone calorimeter method)
- ISO 6341 Water quality -- Determination of the inhibition of the mobility of Daphnia magna Straus (Cladocera, Crustacea) -- Acute toxicity test
- ASTM D 3273 Test Method for Resistance to Growth of Mold on the Surface of Interior Coatings In an Environmental Chamber

2. Raw material

2.1. Factors affecting the quality of heat-treated wood

2.1.1. General

The quality of raw material has a significant effect on the quality of the final heat-treated wood product. In principle, all wood species can be heat-treated. However, the parameters used for the process must be optimised separately for each wood species.

2.1.2. Wood species

In Finland, the species used for heat treatment are pine (*Pinus sylvestris*), spruce (*Picea abies*), birch (*Betula pendula*), and aspen (*Populus tremula*). In addition, some experience has been gained in the treatment of Radiata pine (*Pinus radiata*), ash (*Fraxinus excelsior*), larch (*Larix sibirica*), alder (*Alnus glutinosa*), beech (*Fagus silvativa*), and eucalyptus.

There are differences between wood species in terms of annual growth, wood cells, wood pores, the number of chemical components, etc. Moreover, different wood species have, for example, different fibre length properties: the softwoods feature a wide distribution in fibre length compared with hardwoods which on average have much shorter fibre length and less variance.

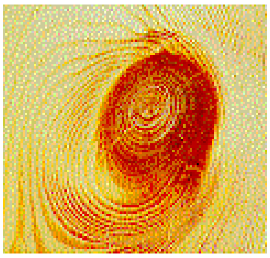
2.2. Sawn timber quality

2.2.1. General Nordic Softwood timber quality grades

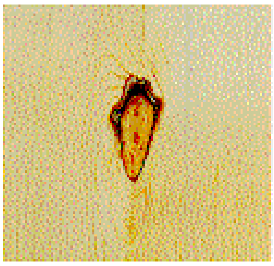
The quality of sawn timber as raw material is controlled with a general quality grading system. The quality grades are divided into three groups according to the number, quality, location, and size of the knots and other features. These are A, B, and C grades, with Grade A divided further into sub-grades A1, A2, A3, and A4. In addition, sawmills use several customer-specific grading applications.

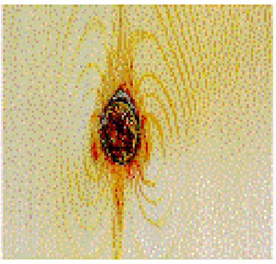
2.2.2. Knots

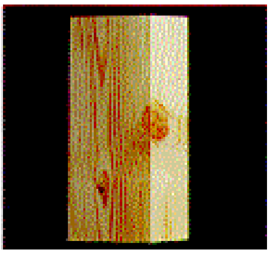
The figures below show different knot types, which are taken into account when selecting the raw material. For the most part, only sawn timber grades with sound knots are selected for heat-treatment.

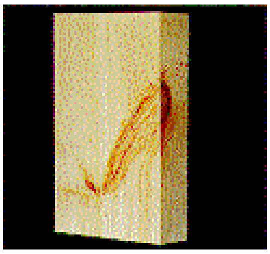

Sound knot

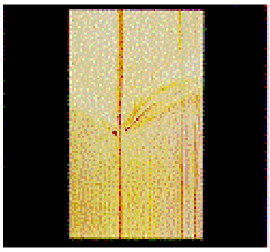

Dry knot


Barkringed knot


Unsound knot


Arris knot


Horn knot


Spike knot

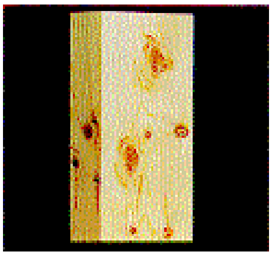

Knot cluster

Figure 1-2. Knot types

2.2.3. Minimum requirements for raw material

The Finnish Thermowood Association has established quality level thresholds for pine, spruce, and hardwood timber used as raw material for ThermoWood. These minimum quality requirements are presented in tables 1 to 3 below.

Table 1-2. Quality requirements for pine timber used for heat-treatment

QUALITY			**A+B furniture**
KNOTS [1] on the worst 2 metres of length			pcs
Sound/dead		On face	8/2
		On edge	4/1
Knots with bark			Not permitted
Knot hole or loose knot			Not permitted
Maximum size of a sound knot on the face			Knot size, mm
Dimension	16, 19, 22, 25 * 75, 100, 115		35
	125, 150		55
	175, 200, 225		55
	32, 38, * 75, 100, 115		55
	125, 150		55
	175, 200, 225		60
	44, 50, *75, 100, 115		60
	125, 150		60
	175, 200, 225		70
	63, 75, * 75, 100, 115		60
	125, 150		60
	175, 200, 225		65
Maximum size of a sound knot on the edge			Knot size, mm
Timber thickness, mm		16,19	= thickness
		22, 25	22
		32, 38	30
		44, 50	40
		63, 75	50
Other knots Tight knots in grades A and B			Maximum size in % of sound knot size
Knot cluster, per knot [2]			70
Dead knot [3]			20
Bark ringed knot [4]			Not permitted
Unsound knot			Not permitted
Other faults			
Top rupture			Max. 20% of width
Exposed pith			Permitted

1	If the knot size is smaller than the value given in the table, the higher number of knots is permitted. However, the sum of knot sizes in mm (= the number of knots * diameter) may not be exceeded for the respective types of knots.
2	A knot cluster consists of a minimum of 4 knots with a diameter exceeding 12 mm, with all located within 150 mm of length on the outside face and the edges. If the knots are not clearly separated by undisturbed grain, they are classified as one knot and evaluated accordingly.
3	If a knot is intergrown to more than ¾ with the surrounding wood, it is considered a sound knot.
4	If less than ¼ of a knot is encircled by bark, it is classified as a dead knot.

Table 2-2. Quality requirements for spruce timber used for heat-treatment

QUALITY		**ST 1-5**
KNOTS [1] on the worst 2 metre of length		pcs
Sound/dead	On face	8/2
	On edge	4/1
Knots with bark		Not permitted
Knot hole or loose knot		Not permitted
Maximum size of a sound knot on the face		Knot size, mm
Dimension	16, 19, 22, 25 * 75, 100, 115	35
	125, 150	40
	175, 200, 225	45
	32, 38, * 75, 100, 115	40
	125, 150	45
	175, 200, 225	50
	44, 50, *75, 100, 115	45
	125, 150	50
	175, 200, 225	55
	63, 75, * 75, 100, 115	50
	125, 150	55
	175, 200, 225	60
Maximum size of a sound knot on the edge		Knot size, mm
Timber thickness, mm	16,19	= thickness
	22, 25	22
	32, 38	30
	44, 50	40
	63, 75	50
Other knots Tight knots in grades A and B		Maximum size in % of sound knot size
Knot cluster, per knot [2]		The sum of knots may not be exceeded
Dead knot [3]		20
Bark ringed knot [4]		Not permitted
Unsound knot		Not permitted
Other faults		
Top rupture		Max. 20% of width
Exposed pith		Permitted

1	If the knot size is smaller than the value given in the table, the higher number of knots is permitted. However, the sum of knot sizes in mm (= the number of knots * diameter) may not be exceeded for the respective types of knots.
2	A knot cluster consists of a minimum of 4 knots with a diameter exceeding 12 mm, with all located within 150 mm of length on the outside face and the edges. If the knots are not clearly separated by undisturbed grain, they are classified as one knot and evaluated accordingly.
3	If a knot is intergrown to more than ¾ with the surrounding wood, it is considered a sound knot.
4	If less than ¼ of a knot is encircled by bark, it is classified as a dead knot.

Table 3-2. Quality requirements for hardwood timber used for heat-treatment

QUALITY REQUIREMENTS (applies to all hardwood timber used for heat-treatment)		
	GRADE E Definition: 4-side knot-free, fully faultless side cut	**GRADE A** Definition: 3-side knot-free side cut
Minimum dimensions at delivery moisture content (about 18%)		
Width	Nominal dimension + 6%, with a few millimetres more permitted	
Thickness	Nominal dimension + 3%, with a few millimetres more permitted	
Splits / fissures	Not permitted	
Wane	Not permitted	
Spring	= 8 mm / 3 m	
Bow	= 15 mm / 3 m	
Twist	= 10 mm / 3 m	
Moisture content	< 20%, even in whole batch	
Blue stain	Not permitted	
Delivery length	> 2 100 mm, can be shorter if separately agreed	
Packaging	According to lengths, at 100 mm intervals	
Heartwood Dark or light	Not permitted	Not permitted
Discoloration caused by seasoning	Not permitted	
Discoloration caused by sawing time or storage	Not permitted	
Even discoloration	As agreed	
Species-specific quality instructions	**Birch** Flame and mineral spots permitted.	**Birch** On the worse face, two knots, max. size 10 mm, or one dead knot, max. size 10 mm per timber metre is permitted. Grey heartwood is permitted on single timber pieces max. 20 mm width on 0.5 m of length. **Aspen** On the worse face, some surface knots and discolorations permitted on single timber pieces.
	Aspen No wetwood or cell collapse permitted.	

2.2.4. Wood moisture

With regard to the success of heat-treatment, the wood's starting moisture content has no significance. Treatment can be undertaken with either green or dried wood. In any case, the wood is dried until absolutely dry in the first phase of the treatment. Drying is the longest phase in the heat-treatment process.

Green wood contains water in two forms: free water in cell lumens and bound water in cell walls. During drying, some of the water in the cell lumens travels via capillaries in the direction of the grain due to surface tension and steam pressure differences. If the pores between one cell lumen and another enable its free travel, water can travel several metres. Otherwise, capillary drying reaches only a few cells from the ends of the wood. The great majority of the water is removed by diffusion through the cell walls in the form of steam. This occurs through the cell lumens perpendicular to the grain.

3. The ThermoWood prosess

3.1. Equipment

In the heat treatment process, water, steam, and high temperatures are used. The process conditions are corrosive, as are the constituent compounds evaporating from the wood.

Heat-treatment equipment is made of stainless steel. In addition, high temperature requires non-standard blower and radiator solutions and safety devices.

To generate the required heat in the ThermoWood process hot oil heating systems can be used and fuelled by biofuel, fuel oil, or gas. Other heating solutions, such as direct electric heating, are utilised too. In addition, the equipment used must feature a steam generator for generating the steam required by the process.

Gases evaporating from the wood during the process are processed by such methods as burning. The primary purpose of the processing is to prevent an odour nuisance being imposed on the environment due to compounds evaporating from the wood.

3.2. Phases

Drying

Drying is the most time-consuming phase in the heat-treatment process. This phase is also called high-temperature drying. During this phase, the moisture content in the wood is reduced to nearly zero before the heat-treatment phase begins. The duration of the drying phase depends on the initial moisture content of the wood, wood species, and timber thickness. Raw material can be green or dried wood.

Successful drying is important in order to avoid internal checks. Since the wood becomes elastic at high temperatures, its resistance to deformation is better than in traditional kiln drying.

Heat treatment

The heat treatment is carried out in a closed chamber in which the temperature is increased to 185–215 ºC, depending on the processing level. The heat treatment phase starts immediately after the high-temperature drying phase. Steam is used during the drying and heat treatment as a protective vapour. Protective gas prevents the wood from burning and also affects the chemical changes taking place in the wood. The heat-treatment phase takes 2–3 hours.

Conditioning

Conditioning is carried out after the heat treatment. The wood is cooled down in a controlled way after heat treatment. Care must be taken in this stage as the high temperature difference between the wood and outside air can cause splitting. In addition, the wood must be re-moisturised in order to bring it to an appropriate moisture level for end use. The final moisture level of the wood has a significant effect on its working properties – it is difficult to work with wood that is too dry. After the conditioning, the final moisture of the wood should be 5–7%. Depending on the treatment temperature and timber, the conditioning phase takes 5–15 hours.

3.3. Energy

Energy is needed mainly for drying the wood, which accounts for 80% of the heat energy used. The total energy demand is only 25% higher than that of the ordinary timber drying process. The electricity requirement is the same as for ordinary timber drying.

3.4. Environmental issues

Since no chemicals are required and only water and heat are used, the ThermoWood process is environmentally friendly. As the process releases extractives from the wood, these must be processed - for example, by burning to avoid an odour nuisance.

No significant amount of waste water is generated by the ThermoWood process. The solid components of the generated waste water are separated out in a special settling basin, and the rest is processed at waste water works.

4. ThermoWood properties

All the properties described in this chapter are based on the results of a range of tests, conducted over a period of several years, concerning heat treatment of wood. These properties should be used as a guide only and are subject to variation due to the natural differences between timber pieces. The information is based on current knowledge. Further testing is constantly underway in order to verify previous test results and to accumulate a statistically significant database concerning the most important ThermoWood properties.

Most of the tests that have been carried out are on softwoods (pine, spruce), but some tests have also been carried out on hardwoods (birch, aspen). The differences between spruce and pine are not great, but natural differences such as density and knot type obviously exist.

4.1. Chemical changes

4.1.1. General

VTT, the Helsinki University of Technology, and the University of Helsinki have published several scientific papers about chemical changes in heat-treated wood as part of their joint project entitled ‘Reaction Mechanisms of Modified Wood’ during 1998–2001. In addition, Risto Kotilainen from the University of Jyväskylä has written a dissertation called ‘Chemical Changes in Wood during Heating at 150–260 ºC’.

Understanding the numerous changes that take place in the physical and chemical structure of wood during the heating process requires a good basic knowledge of its chemical composition, structure, and physical properties.

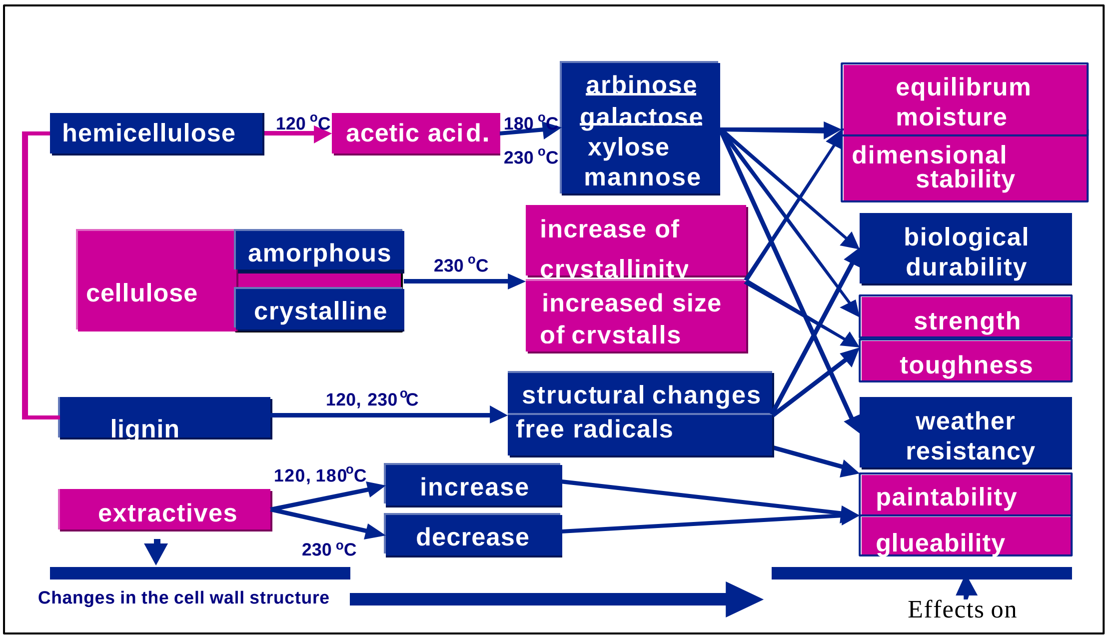


Figure 1-4. Reaction mechanisms of heat-treated wood (source: VTT).

The main components of wood (cellulose, hemicelluloses, and lignin) degrade in different ways under heat. Cellulose and lignin degrade more slowly and at higher temperatures than the hemicelluloses. The extractives in the wood degrade more easily, and these compounds evaporate from the wood during the heat treatment.

4.1.2. Carbohydrates

Cellulose and hemicelluloses are carbohydrates that are structural components in wood. Cellulose constitutes 40–50% and hemicelluloses 25–35% of wood. Cellulose is a long chain (DP 5000–10000) made up of units of glucose, while hemicelluloses are shorter chains (DP 150–200) made up of various monosaccharides. The composition and contents of hemicelluloses vary from one wood species to another. During the heat treatment, both groups undergo changes, but the majority of the changes occur in hemicelluloses with high oxygen content.

Cellulose components, β-D-glycopyranoses, are joined by (1→4)-glycoside bonds. Cellulose chains are joined by bonds between hydroxyl groups. At temperatures under 300 ºC, the degree of polymerisation in cellulose decomposition decreases; water is eliminated; and free radicals, carbonyl, carboxyl, and hydroperoxide groups, as well as carbon monoxide, carbon dioxide, and reactive wood charcoal, are generated.

The components of the hemicelluloses include D-glucose, D-mannose, D-galactose, D-xylose, L-arabinose, and small amounts of L-rhamnose, 4-O-methyl-D-glucuronic acid, and D-galacturonic acid. They are joined by (1→4)- or (1→6)-bonds.

As wood is heated, acetic acid is formed from acetylated hemicelluloses by hydrolysis. The released acid serves as a catalyst in the hydrolysis of hemicelluloses to soluble sugars. In addition, the acetic acid that has formed depolymerises the cellulose microfibrils in the amorphous area. The acid hydrolises the bonds joining the units of glucose, breaking cellulose into shorter chains.

After the heat treatment, the wood contains a substantially lower amount of hemicelluloses. As a result of this, the amount of fungi susceptible material is significantly lower, providing one reason for heat-treated woods improved resistance to fungal decay compared with normal kiln dried softwood. With the degrading of the hemicelluloses, the concentration of water-absorbing hydroxyl groups decreases and the dimensional stability of treated wood is also improved compared to normal kiln dried softwood.

The decomposition temperature of the hemicelluloses is about 200–260 ºC, and the corresponding temperature for cellulose is about 240–350 ºC. Since the amount of hemicelluloses in hardwood species is higher than in softwood species, degrading is also easier in hardwoods than softwoods. However, the breaking of a hemicellulose chain does not reduce as much the strength of the wood as breaking of cellulose chains would do. Instead, breaking of a hemicellulose chain improves the pressability of wood and reduces the generation of stresses and resilience of wood.

4.1.3. Lignin

Lignin holds the wood cells together. The dark matter of wood cells' middle lamellae is mainly lignin. It is also found at the primary and secondary cell walls. Lignin constitutes 25–30% and 20–25% of softwoods and hardwoods, respectively. The precise chemical structure of lignin has not yet been determined, but its precursors - i.e., components - have been known for decades. Lignin is primarily composed of these phenylpropane units, which are typically joined by ether- and carbon-carbon bonds (DP 10–50). Softwoods contain mainly guaiacyl units of phenylpropane, and hardwoods contain almost equal amount of guaiacyl and syringyl units of phenylpropane. Both contain minor amounts of p-hydroxyl phenylpropane.

During the heat treatment, bonds between phenylpropane units are partly broken. Aryl ether bonds between syringyl units break more easily than bonds between guaiacyl units. Thermochemical reactions are more common for allylic side chains than aryl-alkyl ether bonds. The longer the autohydrolysis time is, the more condensation reactions occur. Products of condensation reaction include β-ketone groups and conjugated carboxylic acid groups.

Of all wood's constituents, lignin has the best ability to withstand heat. Lignin's mass starts to decrease only when the temperature exceeds 200 ºC, when the β-aryl ether bonds start to break. At high temperatures, lignin's methoxy content decreases and some of lingnin's non-condensed units are transformed into diphenylmethane-type units. Accordingly, diphenylmethane-type condensation is the most typical reaction at the 120–220 ºC temperature range. This reaction has a significant effect on lignin's properties in heat treatment, such as its colour, reactivity, and dissolution.

4.1.4. Extractives

Wood contains minor amounts of small-molecule constituents. Extractives constitute less than 5% of wood. This group includes, for example, terpenes, fats, waxes, and phenoles. Extractives are of heterogenic nature in various wood species, and the number of compounds is very high. Extractives are not structural components in wood, and most of the compounds evaporate easily during the heat treatment.

4.1.5. Toxicity

The ecotoxicity of the leachates of heat-treated spruce has been tested at CTBA (an EU project - Upgrading of non-durable wood species by appropriate pyrolysis thermal treatment, 1998). The tests were carried out on leachates obtained after an EN 84 test. This test is applied to evaluate the fixation of the biosides in wood cells. Small specimens were leached with water, and the water was tested according to NF-EN ISO 506341 against Daphnia magna (small freshwater shellfish) and microtoxicity tests on marine luminescent bacteria. The test results showed that leachates do not contain toxic substances for Daphnia magna and are harmless to bacteria.

ThermoWood has been tested as a bone substitute material (VTT & Surgical Clinic of University Hospital in Turku). Preliminary tests have shown good results: heat-treated birch has similar properties to bone. ThermoWood is sterile, and no toxic substances have been found.

4.2. Physical changes

4.2.1. Density

Density is determined by measuring the weight and the dimensions of the sample. ThermoWood has a lower density than untreated wood. This is mainly due to the changes of the sample mass during the treatment when wood loses its weight. As can be seen from the figure below, the density decreases as higher treatment temperatures are used. However, deviation is high and the coefficient of determination is low, due to natural variation in wood density.

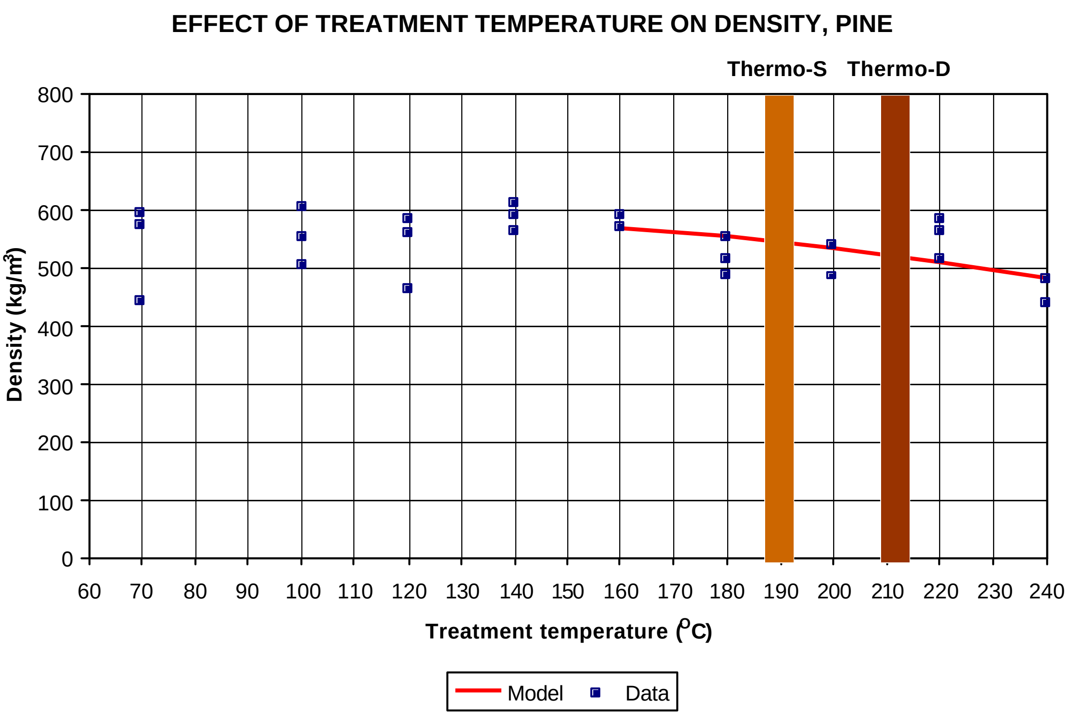


Figure 2-4. The effect of treatment temperature on the density of pine treated for 3 hours at 160–240 °C. The average density in the temperature range T < 160 °C is 560 kg/m3. The test material was conditioned at RH 65% (source: VTT).

4.2.2. Strength

Strength of wood material in general has a strong correlation with density, and ThermoWood has slightly lower density after the treatment. Therefore, it is obvious that ThermoWood in some cases has lower strength values. However, the weight-to-strength ratio can remain practically unchanged. The strength of wood is also highly dependent on the moisture content and its relative level below the grain saturation point. ThermoWood can benefit due to its lower equilibrium moisture content.

<u>Bending strength</u>

Two methods for testing bending strength have been used, one using defect-free material over a short span and the other utilising pieces having natural defects over a longer span. The results (Figure 3-4) show that substantial strength loss in pine starts at temperatures over 220 °C.

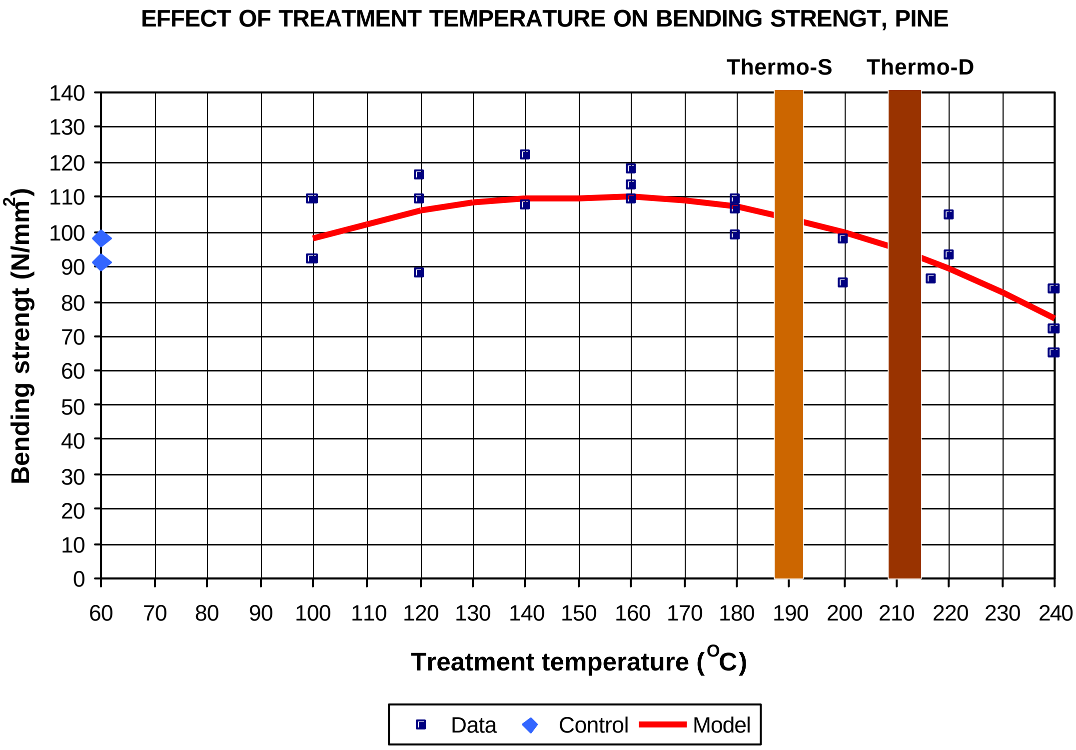


Figure 3-4. The effect of heat treatment temperature on the bending strength of pine, average density 560 kg/m3 (source: VTT)

The results show that heat treatment does not significantly change the modulus of elasticity of wood (Figure 4-4).

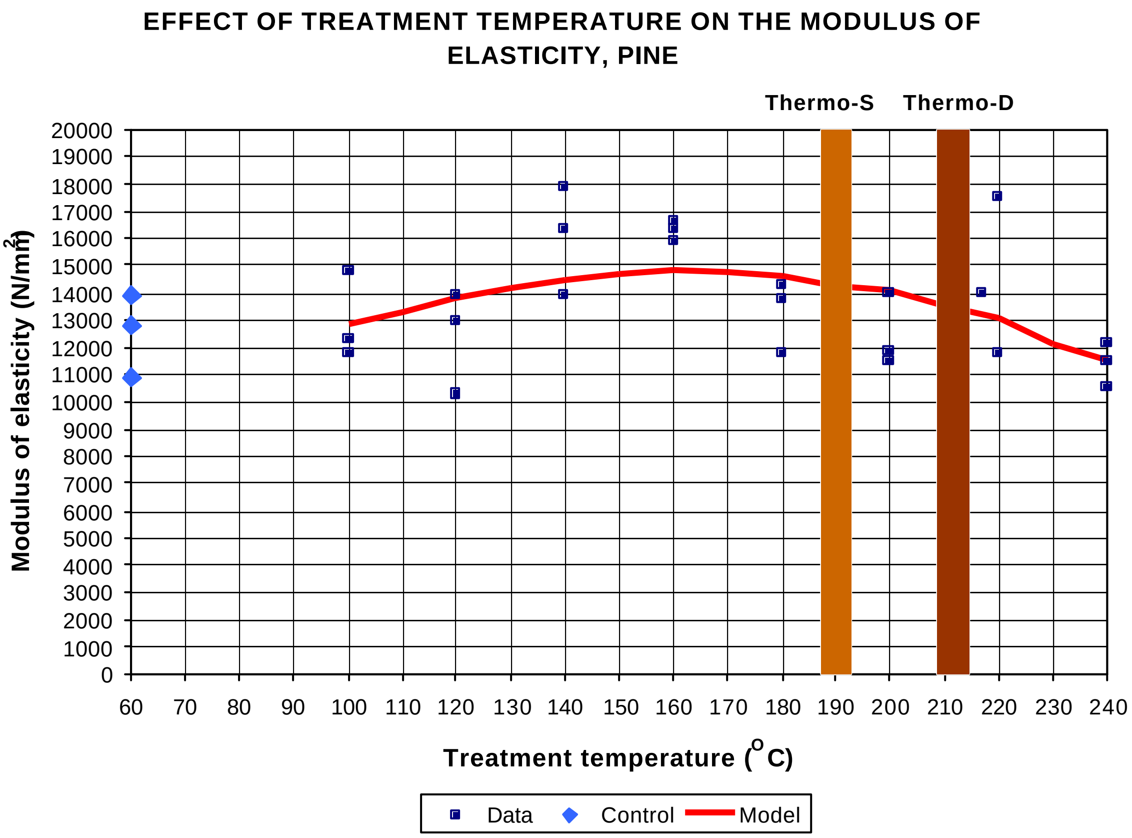


Figure 4-4. Effect of heat treatment temperature on the modulus of elasticity of pine, average density 560 kg/m3 (source: VTT)

The strength of heat-treated (230 °C, 5 hours) spruce was studied with larger test pieces according to EN 408. Prior to testing, the test pieces were conditioned at 45% and 65% relative humidity. The results are presented in table 1-4. With timber containing knots, the strength values for heat-treated wood are lower than those of untreated wood. This is due to, among other factors, the resins being extracted from the wood.

Table 1-4. Bending strength and modulus of elasticity of heat-treated spruce.

Series	width (mm)	height (mm)	length (mm)	RH (%)	density	bending strength 1) N/mm2	modulus of elasticity 1) N/mm2	apparent modulus of elasticity 1) N/mm2
1	38	100	1800	45	425±45	23.0 ± 11.2	11015 ±3142	9495 ±2823
2	38	100	1800	65	392±40	22.5 ± 9.2	12326 ± 1681	11494 ±1280
3	100	38	1800	45	392±25	19.0 ± 5.4	10486 ±1649	9537 ± 1705
4	100	38	1800	65	397±17	27.9 ± 5.9	11913 ±1422	11230 ± 1224

1) mean value and standard deviation

The reference values for untreated spruce at 12% moisture content are: bending strength 40–50 N/mm^2 and modulus of elasticity 9,700–12,000 N/mm^2.

In tests conducted on ungraded timber with defects and a span of 1,800 mm treated at 230 °C for 4 hours (Table 1-4), the bending strength was reduced by up to 40% compared with normal untreated wood. This was due to weakening of areas around the defects. However, with wood treated at lower temperatures of about190 °C for 4 hours, the difference in bending strength was far less.

The majority of testing so far has been performed on small, defect-free pieces. More testing is needed on full-size test pieces and with varying numbers of knots and different knot types. In the absence of sufficient information, we recommend that ThermoWood **NOT** be employed in load-bearing structural usage for the time being.

Screw holding strength

Results from the ‘heat treatment of timber’ study performed by the Institute of Environmental technology in 1999 showed that the major impact on screw holding strength was due more to the general variations in wood density than to the heat treatment itself. The study revealed that in lower-density material the results were better when smaller, pre-drilled holes were used.

Compression strength parallel to grain

According to tests conducted by VTT with timber treated at 195 °C for 3 hours, the compression strength parallel to the grain of the heat-treated timber was about 30% higher than that of normal untreated timber. The test pieces in this study had been submerged in water before testing.

Compression strength is mainly dependent on the actual density of the wood. Tests show that the heat treatment process does not have a negative effect on compression strength values. Actually, the results indicate that the compression strength values were better than with untreated wood even when a higher treatment temperature was used (Figure 5-4).

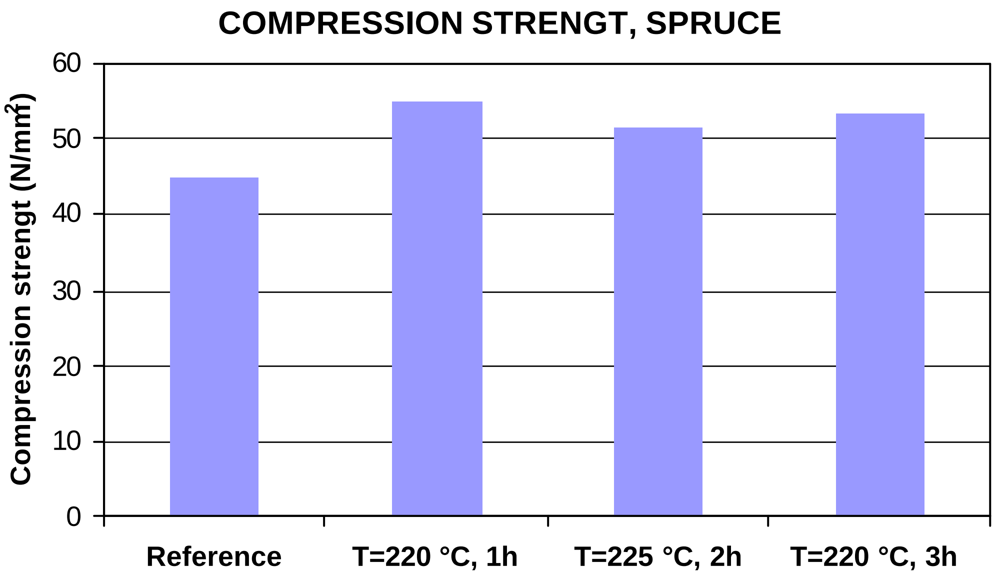


Figure 5-4. The compression strength (N/mm2) of spruce. Average density 420 kg/m^3 (source: VTT).

Tests show that when the maximum compression load was achieved, the pieces broke into smaller sections but didn't buckle like normal kiln-dried timber. This revealed clearly that heat-treated timber is not as elastic as normally kiln-dried timber.

Impact bending strength (dynamic bending)

From test results (CTBA), it can be understood that the impact strength value for ThermoWood is less than that of normal kiln-dried timber. In testing spruce that had been treated for 3 hours at 220 °C, it was found that the impact strength was reduced by about 25 per cent.

Shear strength

The tests were performed (by VTT) by measuring both radial and tangential directions. It was found that with higher-temperature treatments (at 230 °C for 4 hours) the strength properties were reduced in radial tests from 1 to 25% and in tangential tests form 1 to 40%. However, lower-temperature treatments (at 190 °C) had very little effect on pine, although spruce showed a 1–20% decrease in both radial and tangential tests.

Splitting strength

The splitting tests were performed at the Institute of Environmental Technology with spruce, pine, and birch using an extensive range of treatment temperatures. From the test results, it can be concluded that the splitting strength is reduced by 30-40% and the decrease in strength is greater with treatment at higher temperatures.

4.2.3. Hardness

Brinell hardness has been tested according to prEN 1534. The results show that the hardness increases as the treatment temperature increases (Figure 6-4). However, the relative change is very small, therefore having no effect in practice. As with all wood species, the Brinell hardness is highly dependent on the density.

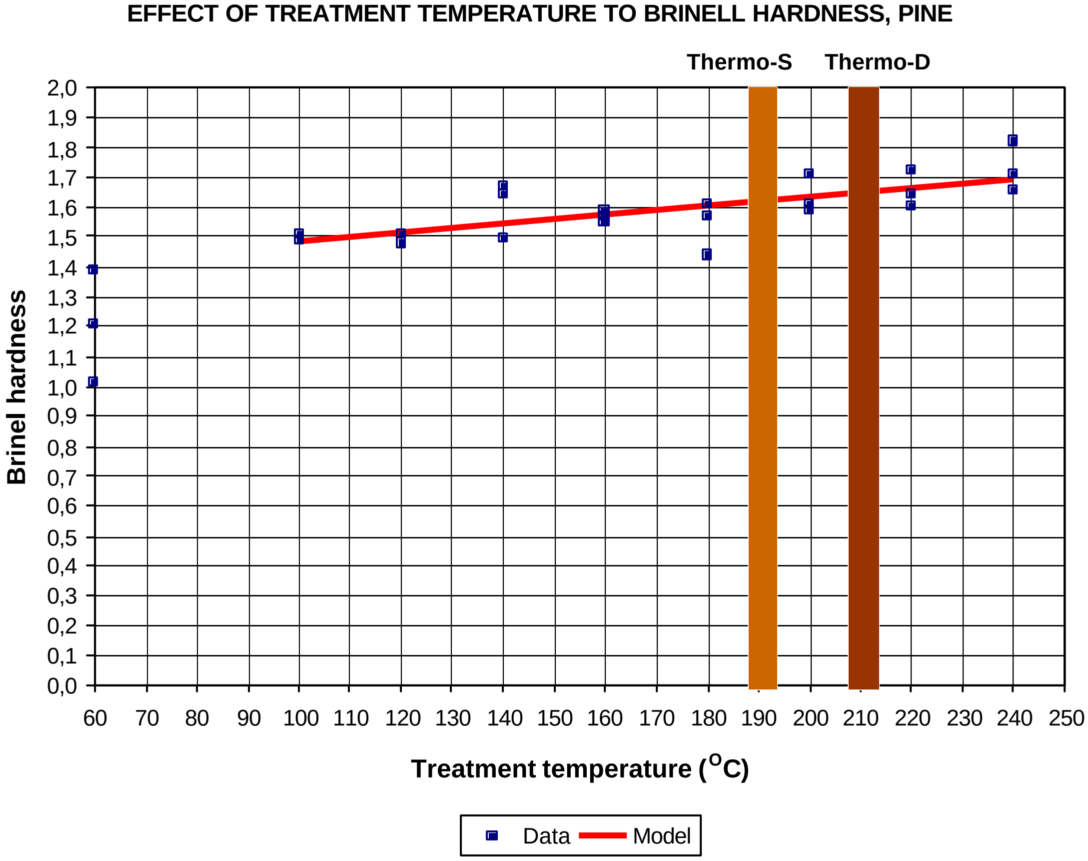


Figure 6-4. The effect of heat treatment on the Brinell hardness of pine. Treatment time of 3 hours (source: VTT).

4.2.4. Equilibrium moisture content

Heat treatment of wood reduces the equilibrium moisture content. Comparisons have been made of heat-treated wood with normal untreated wood at various relative humidities.

Heat treatment clearly reduces the equilibrium moisture content of wood, and at high temperatures (220 °C) the equilibrium moisture content is about half that of untreated wood. The difference in wood moisture values is higher when the relative humidity is higher. The figure below shows the effects on material treated at 220–225 °C for 1–3 hours and at varying humidities.

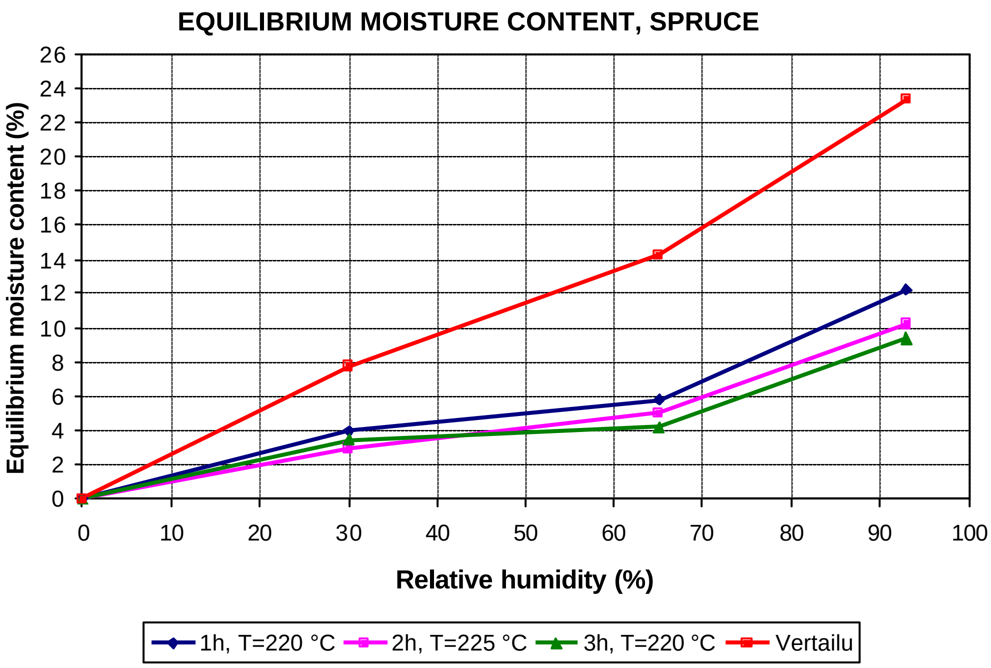


Figure 7-4. The effect of relative humidity on moisture content of heat-treated spruce (source: VTT).

4.2.5. Swelling and shrinkage due to moisture

Heat treatment significantly reduces the tangential and radial swelling (Figures 8-4 and 9-4).

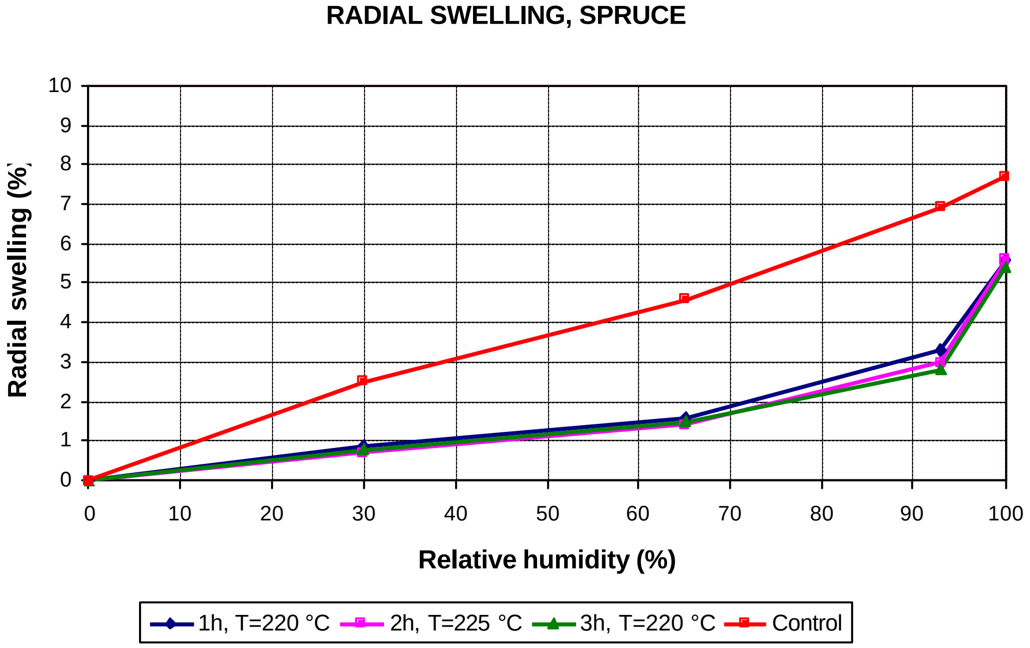


Figure 8-4. The radial swelling of spruce as a function of relative humidity (source: VTT).

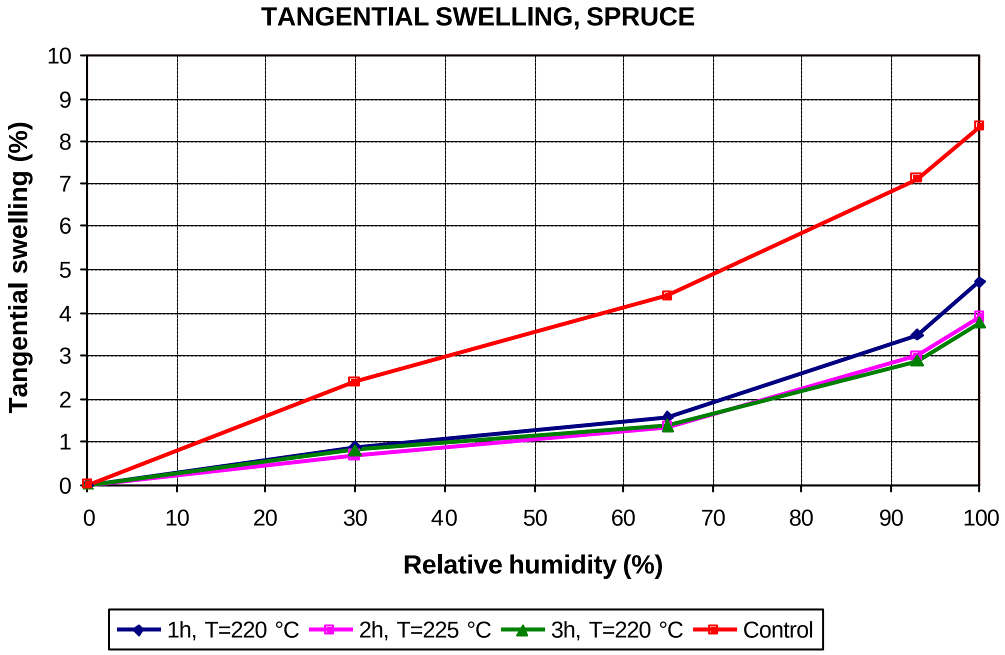


Figure 9-4. The tangential swelling of spruce as a function of relative humidity (source: VTT).

The effect of heat treatment in terms of reduced swelling and shrinkage of wood was clearly shown in relation to cupping of the final product. According to VTT tests, heat-treated wood both with and without a coating maintained its form but CCA-treated and untreated wood were affected by cupping.

Unlike timber in general, heat-treated wood does not feature drying stress. This is a clear advantage, seen when, for example, splitting the material and manufacturing carpentry products. In addition, the wood's swelling and shrinkage is very low.

4.2.6. Permeability

The water permeability of heat-treated wood has been tested by CTBA, examining end grain penetration. This feature is important in, for example, windows. Samples were dipped in demineralised water and then kept in a room with a relative humidity of 65% and a temperature of 20 °C. The samples were periodically weighed over a period of 9 days. The conclusion was that during a short period the water permeability of heat-treated spruce was 20–30 per cent lower than that of normal kiln dried spruce.

VTT has tested the steam permeability of heat-treated wood according to EN 927-4. The results are shown in the figure below (Figure 10-4).

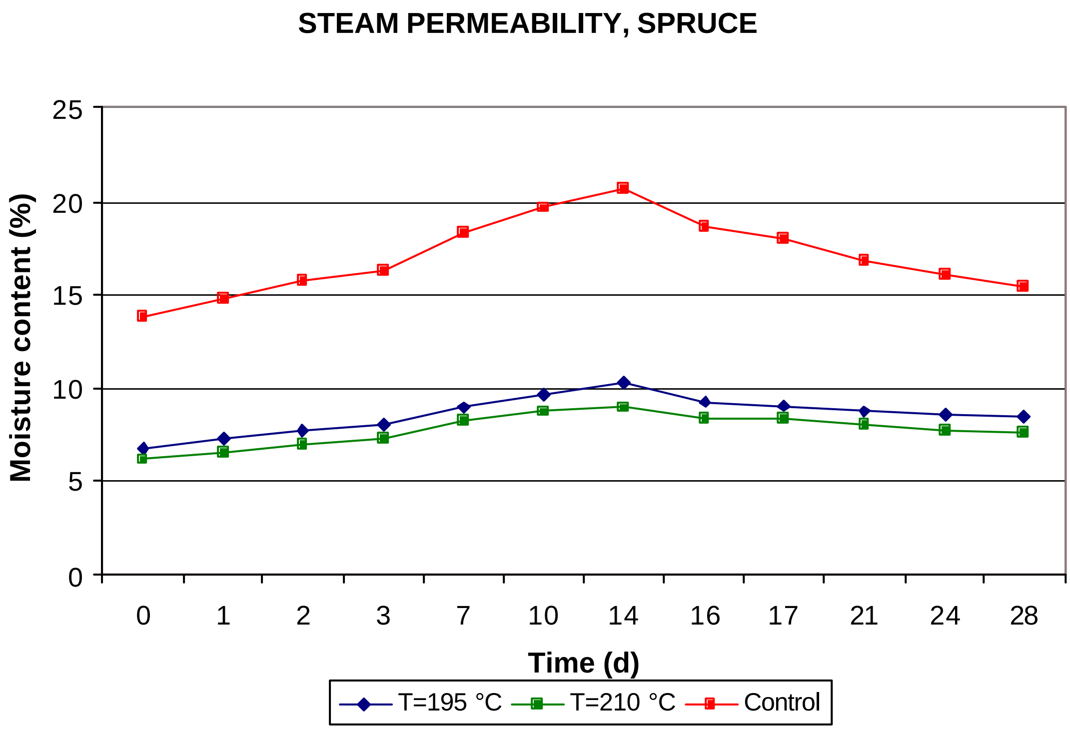


Figure 10-4. The effect of heat treatment on steam permeability (source: VTT).

Water permeability was tested by VTT according to EN 927-5 too. Permeability was determined after the pieces soaked in water for 72 hours with their end surfaces sealed. Untreated spruce gained a moisture content of 22%, while the moisture contents of wood treated at 195 °C and at 210 °C were about 12% and 10%, respectively.

4.2.7. Thermal conductivity

Tests have shown that the thermal conductivity of heat treated wood is reduced by 20–25% when compared with normal untreated softwoods (Taple 2-4). Therefore, ThermoWood is well-suited for applications like outer doors, cladding, windows, and saunas.

According to the VTT tests, the thermal conductivity λ_{10} of Thermo-D class ThermoWood is 0.099 W/(m K). The corresponding value for untreated timber according to Section C4 of the Finnish building code is 0.12 W/(m K).

Table 2-4. Thermal conductivity

Dimension (mm)	Treatment time at 230 °C (h)	Weight loss (%)	Density (kg/m^3)	Moisture content (%)	Thermal conductivity l_{10} W/mK
Pine					
25 x 125	3	8,7	525	4,5	0,107
25 x 125	5	12,1	474	3,6	0,101
	0		505		0,130
Spruce					
22 x 100	3	5,8	445	5,5	0,097
22 x 100	5	9,3	405	4,4	0,082
	0		432		0,110

4.2.8. Fire safety

SBI test (EN 13823)

The fire resistance of construction products according to the new Euroclasses was assessed with a SBI (Single Burning Item) test. In this test, a specimen consisting of two vertical wings forming a right-angled corner is exposed to flames from a gas burner. The height of the specimen wings is 1.5 m, and their widths are 0.5 and 1.0 m. The gas burner placed at the bottom of the corner stands for a single burning item producing a heat attack with a maximum of about 40 kW/m^2 on the product tested.

The effect of heat treatment on RHR (Rate of Heat Release) is shown in Figure 11-4. The RHR level of heat-treated pine was about 10 kW greater than that of untreated pine. The earlier increase of RHR towards the end of the test for the specimen without heat treatment was due to its smaller thickness. In THR, an increase of about 15% due to heat treatment was observed. Smoke production was roughly doubled. In addition, the ignition time (based on a 5 kW increase in

RHR) was shortened by 30%. In conclusion, heat treatment seems to degrade the fire resistance of wood. This is probably related to release of volatile compounds during the heat treatment. Although the temperature during the treatment is not near the ignition temperature of wood, the constituents of wood can still gradually disintegrate. Consequently, the material properties change, leading to slightly degraded fire resistance.

The number of tests made on ThermoWood has been too low to establish exact values. However it can be stated that ThermoWood does not differ significantly from normal wood when it comes to fire safety. ThermoWood is in fire class D.

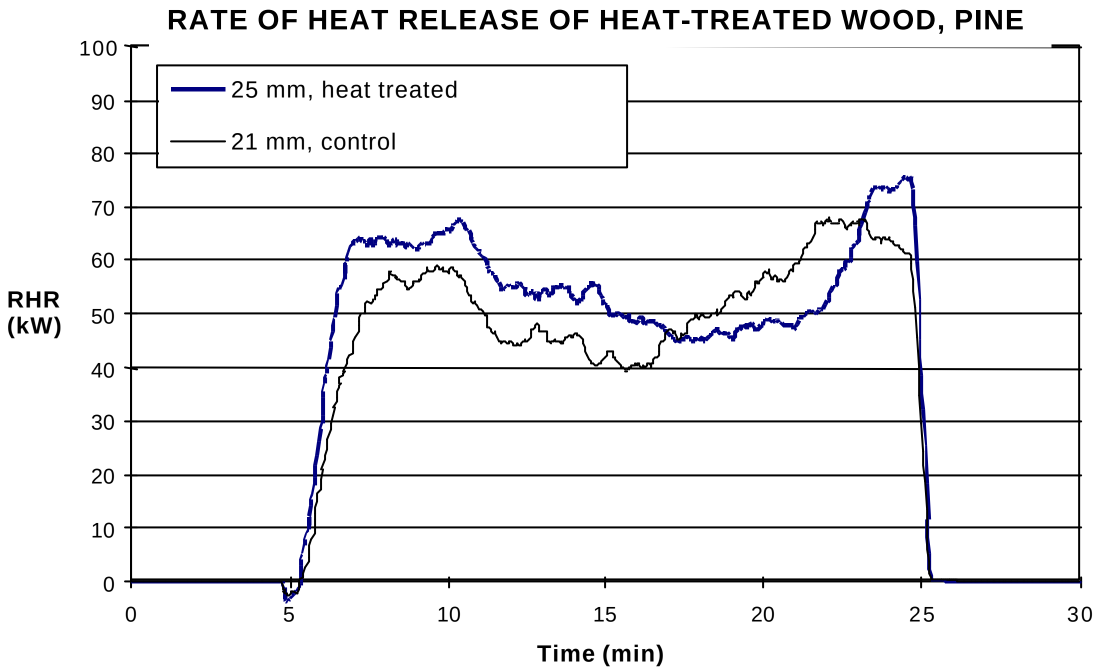


Figure 11-4. Rate of heat release of pine specimens with (2/1) and without (3/1) heat treatment. The specimen thickness was 21 and 25 mm for untreated and heat-treated pine boards, respectively.

Table 3-4. Brandsäkra Trähus – Fas 2: SBI test results for wood-based products

Product	**Thick-ness (mm)**	**FIGRA (W/s)**	**THR_{600s} (MJ)**	**SMOGRA (m^2/s^2)**	**TSP_{600s} (m^2)**
Spruce	18	419	18.0	4	36.3
Pine (heat-treated)	25	581	32.8	6	62.5
Pine	21	321	23.2	3	15.0
Pine (with cavity of 22 mm)	21	329	22.3	4	35.5
Pine	15	361	26.6	4	17.5
Pine	45	587	23.9	12	54.4
Spruce (tongue and groove), vertical	15	452	17.0	3	34.0
Spruce (tongue and groove), horizontal	15	494	18.4	4	50.0
Plywood (spruce)	12	596	15.8	3	45.0
Plywood (pine surface)	12	437	16.6	1	21.0

ISO 5660 test

VTT tested the fire resistance properties of ThermoWood were tested according to ISO 5660. Heat treatment decreased the ignition time for both pine and spruce samples (Tables 4-4 and 5-4) to half that of untreated wood. With pine samples, the rate of heat release (RHR) decreased 32%. The heat-treated spruce samples showed no difference. The production of smoke was small with heat-treated pine and spruce samples in comparison to untreated samples.

Table 4-4. Cone calorimetric test ISO 5660, radiation level 50 kW/ m2, pine.

Dimension (mm)	**Treatment time at 230 °C (h)**	**Weight loss (%)**	**Ignition time (s)**	**RHR (60 s,ave) (kW/m^2)**	**Smoke (m^2/kg)**
50 x 150	5	7.2	12	137	180
50 x 150	8	11.8	13	136	47
50 x 150	10	14.4	16	160	120
50 x 150	0		19–25	150–200	25–100 (200)

Table 5-4. Cone calorimetric test ISO 5660, radiation level 25 kW/m2, spruce.

Dimension (mm)	**Treatment time at 230 °C (h)**	**Ignition time (s)**	**RHR (60 s,ave) (kW/m^2)**	**Smoke (m^2/kg)**
50 x 150	8	97	112	21
50 x 150	0	193	113	72

Test according to NF B 52501 standard

Tests were carried out by CTBA according to the NF B 52501 standard. All samples studied can be classified in Class M_3. The tests indicate that the fire resistance of heat-treated wood has to be considered to be the same as that of untreated wood of corresponding species.

Test to British Standard, surface spread of flame, BS 476 Part 7

A very limited number of pine and spruce pieces treated at 210 °C were tested in the United Kingdom in accordance with Class 1 surface spread of flame standard BS 476, Part 7. The results showed that both heat-treated wood species attained a class 4 rating. The standard rating for normally treated wood is class 3. The heat-treated wood exceeded the limit for class 3 within the first minute.

Due to the very small number of test pieces used, it is concluded that the results cannot be relied upon and more extensive testing is needed using material treated at varying temperatures and moisture contents. The BS tests and results only focused on flame spread speed, and this element is only one part of the testing procedure set forth in new EN standards. The heat-treated wood had a clearly shorter ignition time but was better than the normally dried softwoods in terms of heat and smoke release.

Performance of ThermoWood in relation to the Finnish building codes

The fire safety requirements for structures and the products used in them are defined in section E1, ‘Structural fire safety in buildings’, 1997, of the National Building Code of Finland. Structural fire design is performed according to section B1, ‘Structural safety and loads’, 1998, and section B10, ‘Timber structures’, 1983, amended 1990, of the National Building Code of Finland.

The test methods and acceptance criteria used for defining the fire reaction characteristics of construction materials, construction elements, and devices are presented in ‘Ympäristöopas 35 1998, Rakennustuotteiden palotekninen hyväksyntä’ (Environment guide 35, 1998; Fire-engineering acceptance of construction products) published by the Ministry of the Environment.

ThermoWood can be regarded as meeting the inflammability Class 2 requirements laid out in the publication mentioned above.

4.2.9. Biological durability

VTT carried out three tests to determine the biological durability of heat-treated timber. The tests were carried out in accordance with the EN 113 standard, with a 16-week decay time. In addition, a modification of the EN 113 test was used; the test time was accelerated by using smaller test pieces and a shorter decay time (6 weeks). The third test was made in soil contact according to ENV 807, the test times being 8, 16, 24, and 32 weeks. The test fungi were *Coniophora puteana* and *Poria placenta* since these are regarded as the most common and problematic fungi.

The results revealed a remarkable ability of the heat-treated wood to resist decay by brown rot. Against the two fungi, the heat-treated wood showed varying results. The heat-treated wood required a higher treatment temperature in order to gain maximum resistance against *Poria placentia* compared to resistance against *Coniophora puteana* (Figure 12-4).

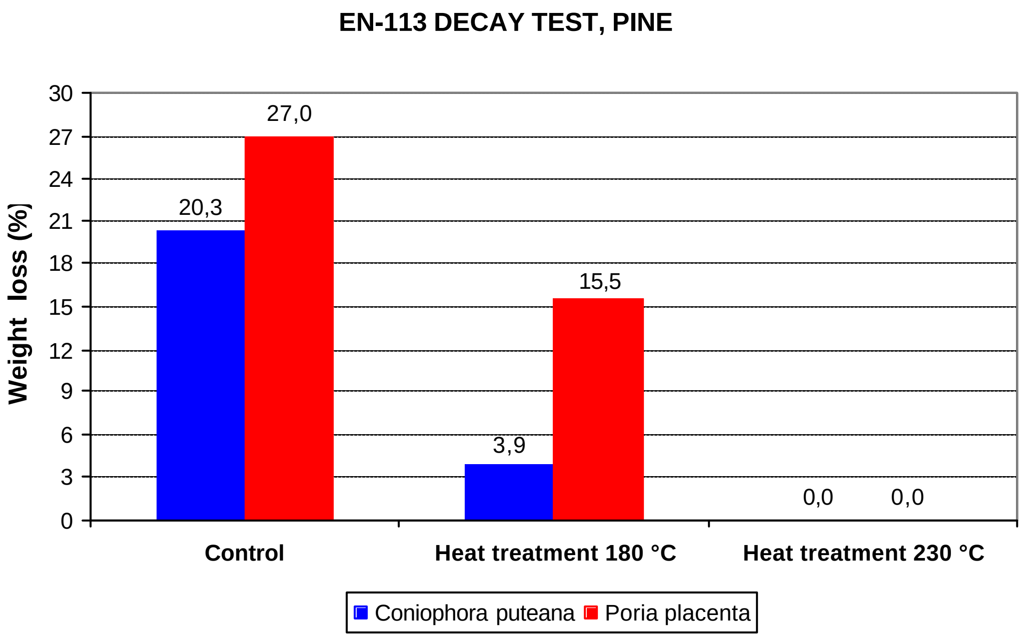


Figure 12-4. The effect of heat treatment on decay by brown rot in a modified EN 113 test. Heat-treated pine, treatment time of 4 hours (source: VTT).

The biological resistance test in accordance with EN 113 revealed very good durability depending on the treatment temperature and time. In order to treat the wood to meet the class 1 (very durable) requirements, temperatures of over 220 °C for 3 hours are required, and to gain class 2 (durable) status, the desired result is achieved at about 210 °C (Figure 13-4).

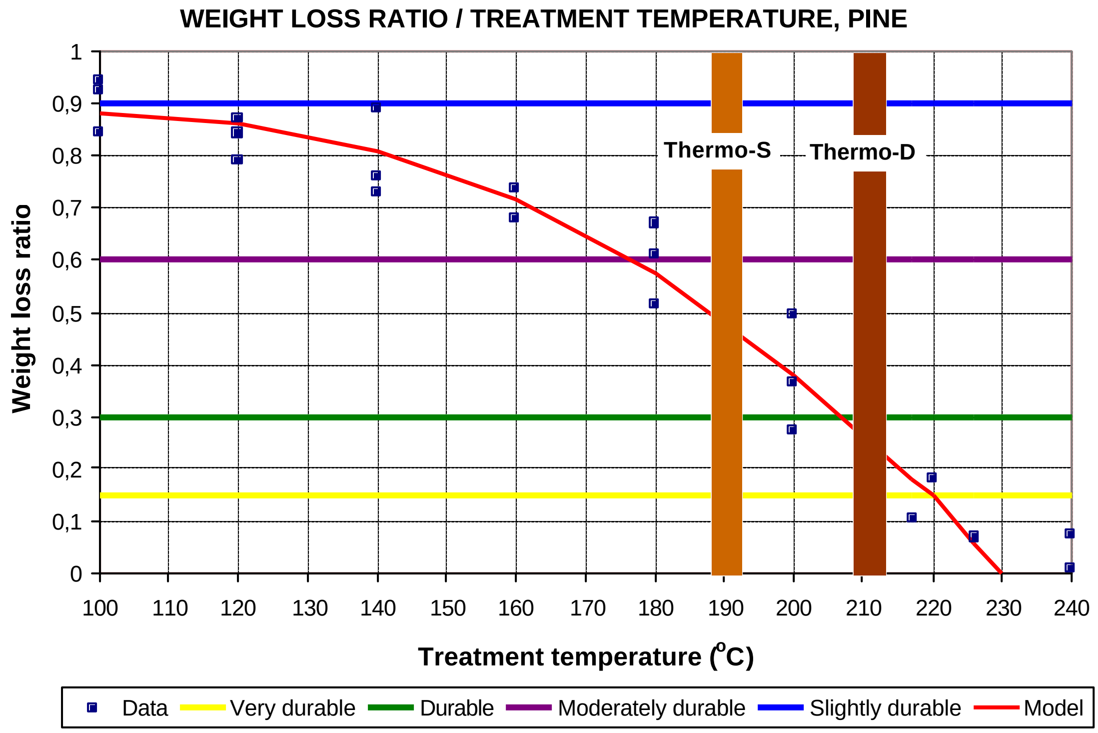


Figure 13-4. The effect of temperature on the weight loss ratio. Pine, treatment time of 3 hours. Standard EN 350-1. Natural durability (source: VTT).

Based on the results of the field test (EN 252), it is **recommended that ThermoWood not be used in deep ground applications where structural performance is required.** It is assumed that the indicated loss of strength is due to a moisture and not caused by any micro-organism. Establishing the reason behind this phenomenon will require further study. However practical experience has found that usage of Thermo-D material in ground contact where structural performance is not critical and periodic drying of the surfaces is allowed does not cause any significant deterioration to the material. This is especially apparent when the ground has good drainage and is made up of sand or shingle.

4.2.10. Resistance to insects

Tests were carried out by the CTBA in France. Longhorn beetles are found in sapwood of softwoods. The common furniture beetle (*Anobium punctatum*) attacks hardwoods in particular. *Lyctus Bruneus* is found in some hardwood species. The tests showed that ThermoWood was resistant to all three of the above insects.

Tests made at the University of Kuopio also prove that ThermoWood has good resistance against longhorn beetles. The test report concludes that beetles recognise pine from its terpene emissions to be a suitable place for egg laying. Because terpene emissions from ThermoWood are drastically reduced in comparison to normal wood (see Section 4.2.13), it is expected that beetles will choose normal wood over ThermoWood, whenever possible. According to the report, the same phenomena can apply also to termites. However, more testing is needed in this area.

Figure 14-4. Longhorn beetle and a larva in tested ThermoWood (photos: Jarmo Holopainen, University of Kuopio).

Concerning termites, the problem is currently more apparent in Southern hemisphere locations, but termites have already spread through France and cases have also been reported in countries further north in Europe. Termites attack buildings from the earth below, avoiding direct sunlight whenever possible. Termites will attack both wood and concrete-based materials in their quest for nutrition. Various measures have been developed to control the problem; these include polythene membranes being installed in the foundations of the building. Also, various bituminous paint products are available to seal possible routes up the building. So far, the test results indicate that ThermoWood is unable to resist attack from termites. However, local tests are recommended since termite types vary from one region to another. In addition, more research into termite attack is needed.

4.2.11. Weather resistance

Weather resistance without surface treatment

Rain
Various field tests have been carried out to study the performance of ThermoWood against natural weathering. Material that had been treated at 225 °C for 6 hours had about half the moisture content of untreated wood; this difference remained after five years' exposure. The following diagram describes the moisture content development in natural weather conditions of untreated wood, ThermoWood, and CCA-treated wood.

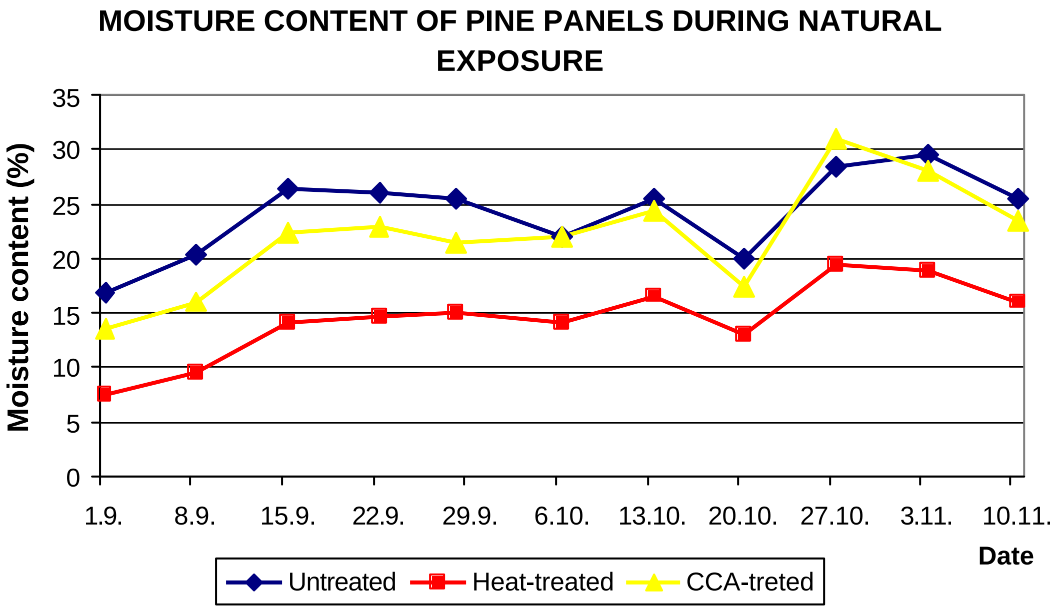


Figure 15-4. The moisture content of planed pine panels during natural exposure, 1994 (source: VTT).

As with all materials exposed to the natural environment, surface mould growth can appear on ThermoWood. Due to bacteria in the air or dirt carried in the rain, fungi can grow on the untreated surface. However, this is on the surface only and can be removed by wiping or scraping.

Sunlight

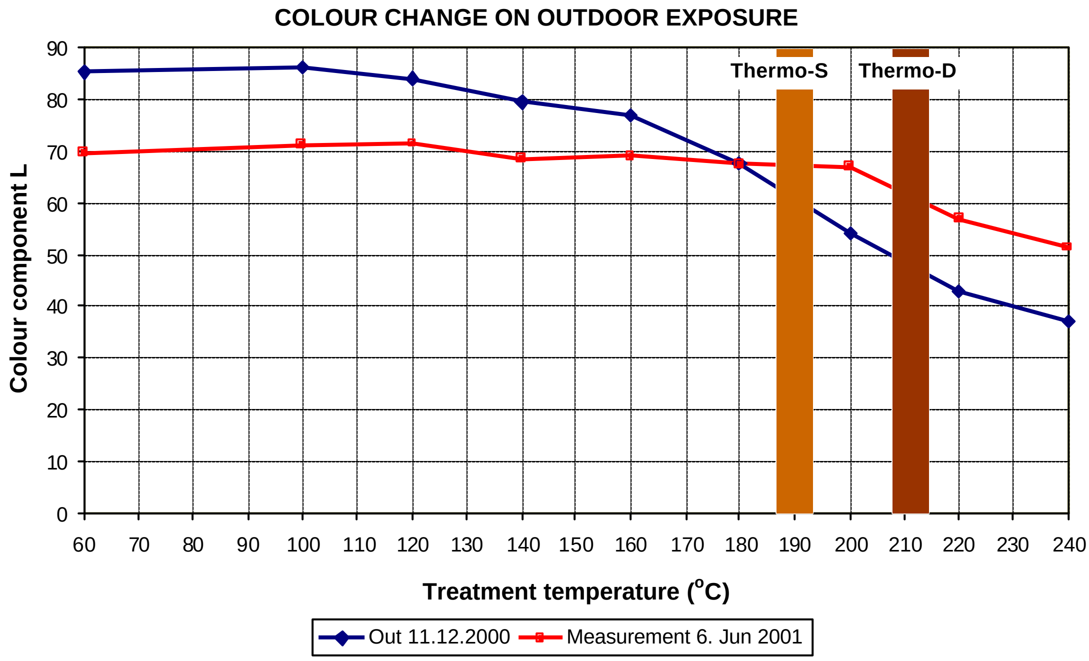


Figure 16-4. The effect of heat treatment temperature on colour changes due to outdoor exposure. Pine, treatment time 3 hours (source: VTT).

Field tests have been conducted to measure ThermoWood's resistance to the effect of sunlight (ultraviolet radiation). As with most natural materials, ThermoWood is unable to resist UV radiation. As a result, the colour changes over a period of time from the original brown appearance to a grey weathered colour when exposed to direct sunlight. The above diagram shows the change in colour component L over a six-month period. The original ThermoWood colour can be preserved with pigmented or UV-protective preservatives.

Although moisture content and swelling and shrinkage due to moisture are greatly reduced with ThermoWood, the ultraviolet radiation causes small surface shakes to occur on uncoated panels when exposed. Levels of surface shakes in ThermoWood did show signs of improvement over the untreated control material when higher temperatures were used (Figure 17-4).

The effect of the heat treatment process on surface shakes and surface fungal growth is shown in the following diagram. The shakes were graded as follows:

– size (0–5):

0	no shakes
1	the shake is seen with the loop, 10 times enlargement
2	the shake is just seen by the eye
3	the shake is clearly detectable
4	shakes where the width is under 1 mm
5	large shakes, with width over 1 mm

– density (0–5):
  1 one shake
  5 the surface is full of shakes

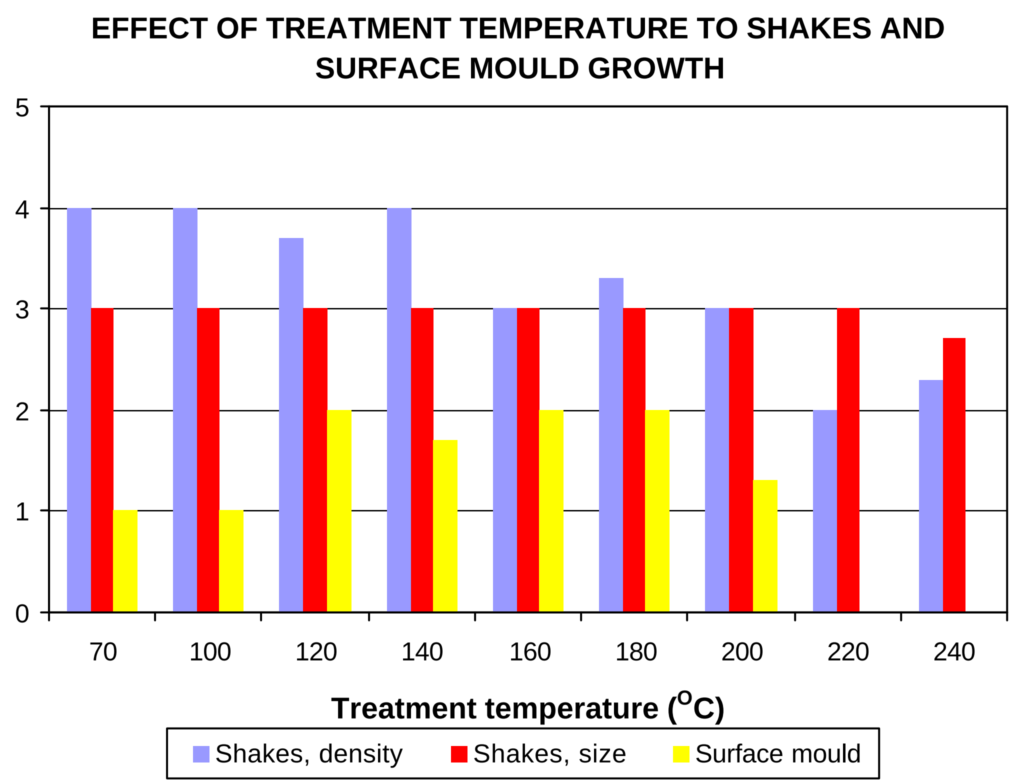


Figure 17-4. Effect of heat treatment temperature on surface shakes and fungal growth of pine panels. Heat treatment time of 3 hours. Outdoor exposure time of 6 months (source: VTT).

It can be easily concluded from the effects of sunlight (ultraviolet radiation) that, with the application of surface treatments containing pigment ThermoWood performs to a good level with respect to surface shakes. Surface treatment is therefore highly recommended.

Weather resistance of surface-treated ThermoWood

Field testing with five years' outdoor exposure was carried out by VTT to study the performance of coatings on the surface of ThermoWood and to compare it with untreated wood. The panels were visually graded in accordance with the ISO 4628 series during weathering.

It was found that the moisture content of ThermoWood was about half that of untreated wood. The unpigmented or low-build stains and oils protected neither ThermoWood nor untreated wood. These coatings wore away and annual rings started to loosen just as in the panels without coating. The panels coated with the low-build stains showed a strong tendency to crack.

The effect of the ThermoWood substrate on the joinery paint performance was observed after five years of exposure. The acid-curable and water-borne acrylic paint had better performance on the heat-treated panels than on the untreated panels. The panels coated with these paints showed no flaking on the ThermoWood substrate (Figure 18-4).

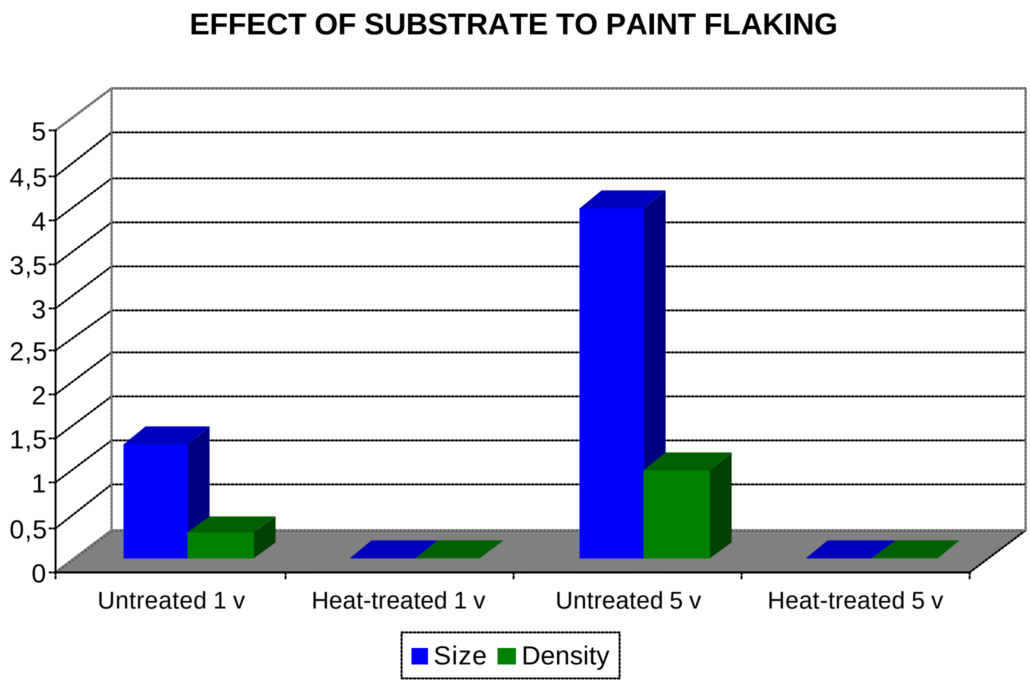


Figure 18-4. The effect of substrate on flaking of water-based joinery paint on pine (source: VTT)

The exterior wall paints performed well on both ThermoWood and an untreated substrate, and no significant effects could be found. The results indicated that the best coating systems for ThermoWood consisted of the priming oil and solvent-based alkyd or water-based acrylic topcoat.

4.2.12. Colour

The colour of ThermoWood is affected by the treatment temperature and time. The higher the temperature, the darker the appearance. As with all softwoods, the colour consistency is affected by normal variation due to density and also depends on whether springwood or latewood is used. In principle, the colour can be well replicated in the process and is measured using the L component. The possibility of including measurement of the L component value in process quality control criteria is being studied.

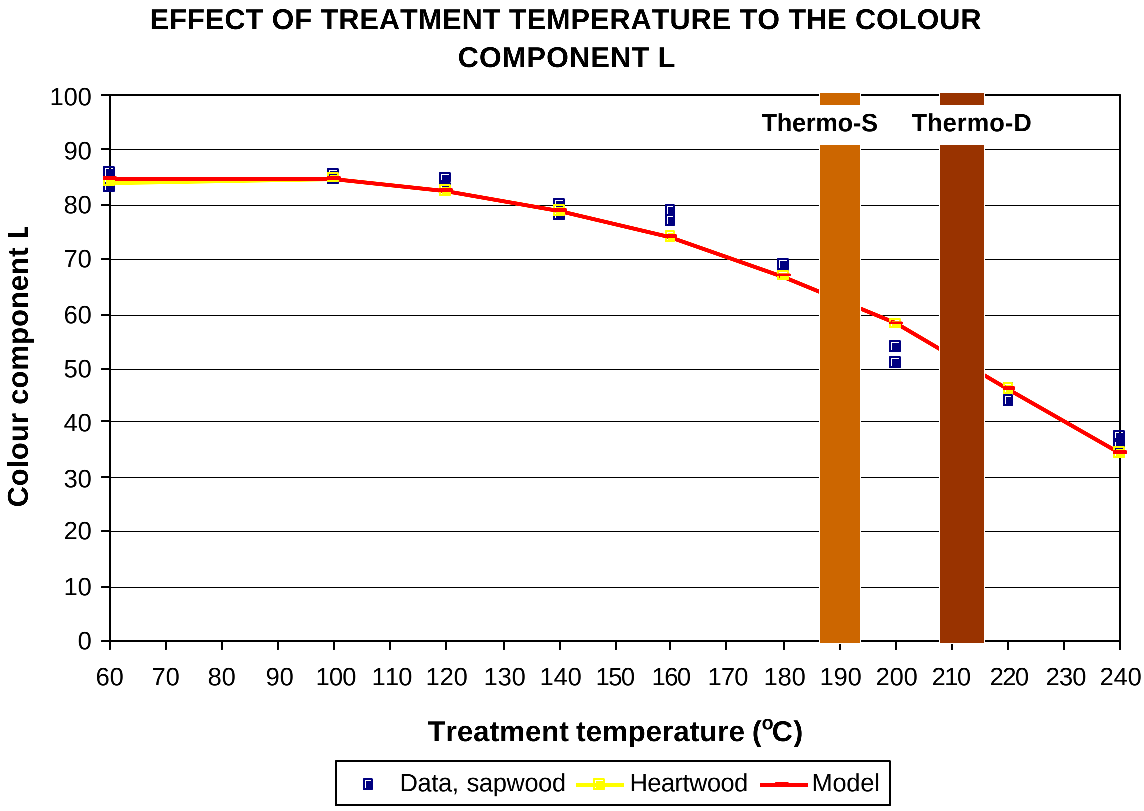


Figure 19-4. The effect of heat treatment temperature on colour component L. Pine boards, treatment time of 3 hours (source: VTT)

The following picture shows the colours of pine boards treated at different temperatures.

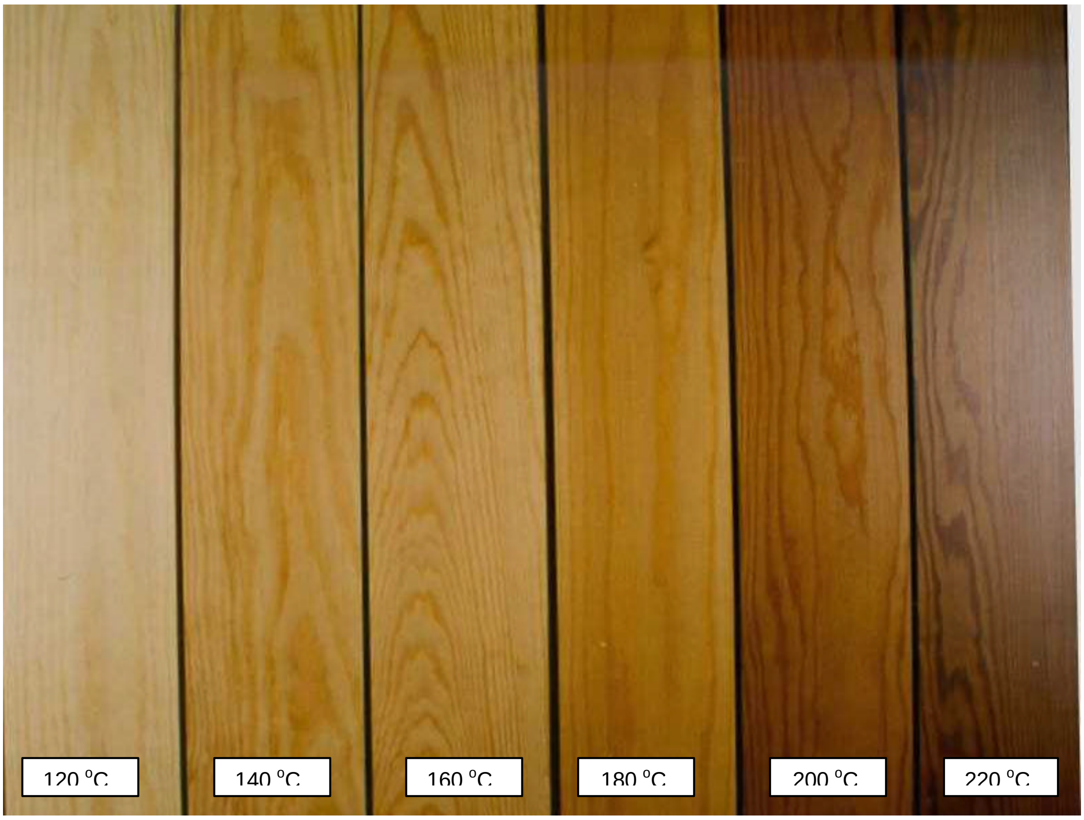


Figure 20-4. The colour of heat-treated pine. Treatment temperatures from 120 to 220°C at 20°C intervals. Treatment time (photo: VTT).

4.2.13. Emissions

Emissions were measured from heat-treated pine boards. The samples were heat-treated at 180 °C and 230 °C for 4 hours. The test was carried out for 7 weeks (180 °C) or 8 weeks (230 °C) after the treatment.

The emission measurements were carried out at the VTT chemical technology unit according to the KET 3300495 test method. Untreated pine showed the largest quantity of volatile organic compounds, 1486 µg/m^{2}h. The majority of this consisted of terpenes, and significant amounts of alpha-pinene, camphene, and limonene were found. Untreated pine contained hexanal and small amounts of furfural and acetic acid too.

The total emission for heat-treated pine treated at 180 °C was 828 µg/m^{2}h. The sample contained terpenes, furfurals, hexanal, and acetic acid. The total emission of heat-treated pine treated at 230 °C was the lowest, at 235 µg/m^{2}h. This consisted mostly of acetic acid (110 µg/m^{2}h). This sample contained only small amounts of terpenes. The emissions are presented in Figure 21-4.

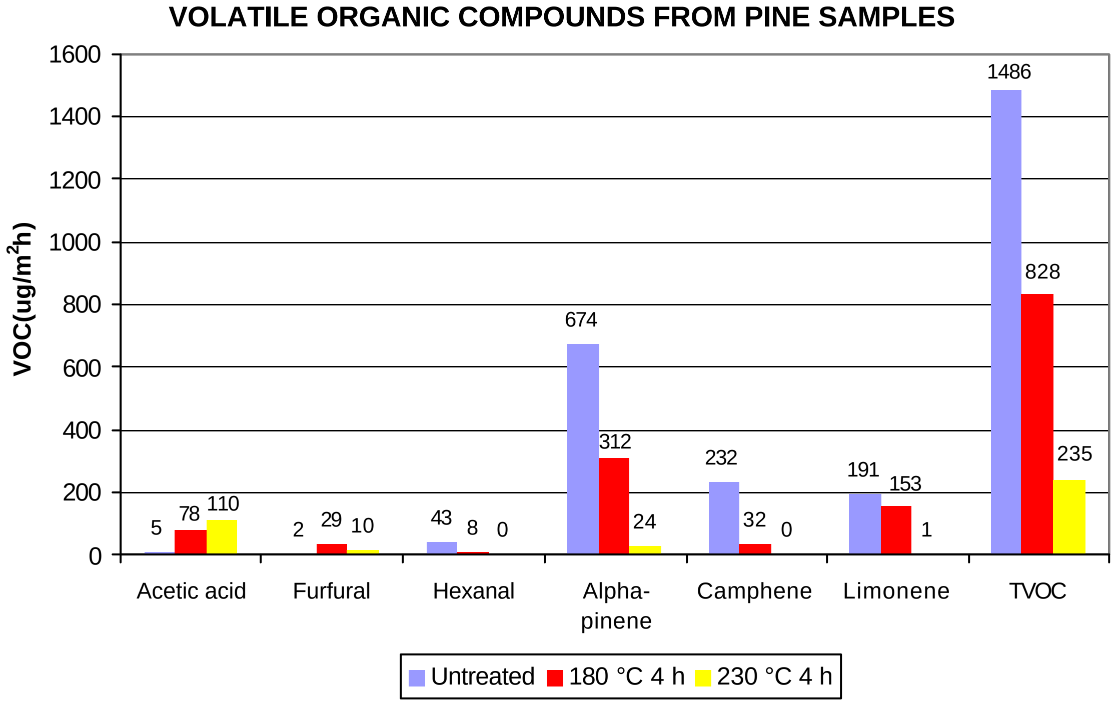


Figure 21-4. Volatile organic compounds from pine samples, age 2 months (source: VTT).

The smoke-like smell of heat-treated wood most likely comes from furfural. Results of tests have not yet been published concerning the smell. The smell has been found to disappear over time, and when surface treatments are applied the smell is removed.

5. Working with ThermoWood in industrial plants

5.1. General

In principle, the handling of ThermoWood requires a bit more care than that of normal kiln dried softwood, it is more susceptible to mechanical damage when it undergoes further processing. Similar handling procedures as when working with hardwoods is recommended. Sharp tools are highly recommended when working with ThermoWood. As when working with all wood materials pre-conditioning of the moisture content in relation to the sites relative humidity improves the results.

5.2. Sawing

The internal stresses of wood are released during an appropriate heat-treatment process, and therefore no distortion occurs after the pieces are split.

Since ThermoWood does not contain resin, the power requirement for cutting equipment is reduced and the life span of the equipment is significantly increased.

Sawing of ThermoWood does not differ from sawing of untreated wood. Where knots are concerned, no special tearing is distinguishable compared with normal kiln dried softwood. The only problem encountered thus far in sawing is the wood dust. Since ThermoWood is very dry, the wood dust is very fine and spreads easily to the environment.

For the reasons mentioned above, special attention has to be paid to the operation of an appropriate dust extraction system. The system must be well-sealed and sufficiently effective.

Since gap-toothed saw blades can cause chipping in the edges of ThermoWood pieces, fine-toothed blades are recommended. Blades with carbide or similar tips extend the saw blade's maintenance and sharpening intervals.

5.3. Planing

As a result of the ThermoWood heat-treatment process, cupping can occur in the pieces although, as referred to in the section discussing stretching and contracting of wood due to moisture, post-treatment movement is very limited. As a result of cupping, it is recommended that when planing timber pieces which have not been re-cut before planing, the infeed roller be changed to one that has two narrow wheels so the contact with the piece is at the outer edges of the convex face - see figure below. Alternatively, a single narrow wheel could be used so that the piece is turned with the convex face down. Both methods enable a flat surface to be formed as the piece proceeds through the planer, thus reducing the risk of surface cracking and enabling higher infeed roller pressure.

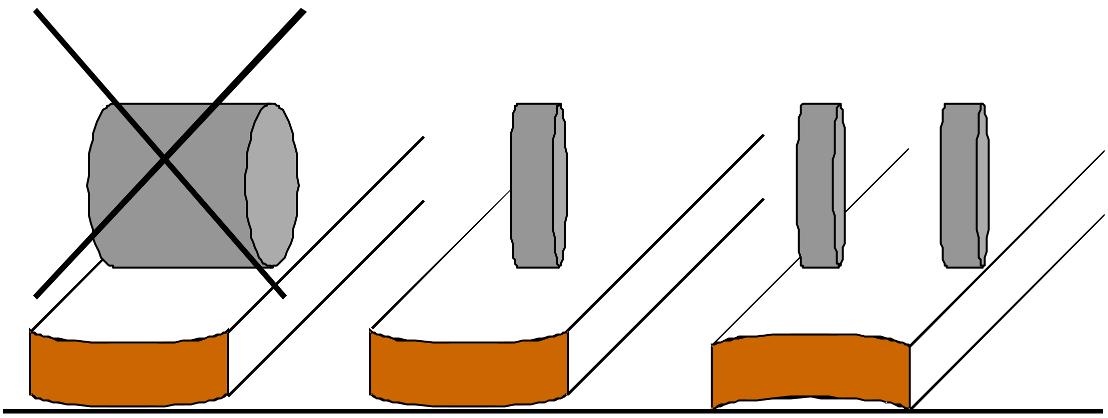


Figure 1-5. Recommended infeed rollers to avoid cracking of the boards.

In order to avoid cracking of the boards, it is advisable to make a flat base surface with a planer or band saw first before profiling. Seinäjoki Polytechnic has performed a series of tests concerning the planing of ThermoWood. Several cutter angles were tested. In these tests, all angles worked well and the surface quality was good too. The best results are achieved with carbide-tipped cutters, as when working with hard types of wood.

It has also been reported that ThermoWood pieces cause less friction during infeed and enable a smoother planing process. This is due to the lack of resin in the wood. On the other hand, since the strength of the material is lower, the infeed rollers must be adjusted to lower pressures to avoid cracking of the boards. Good results have been achieved by replacing the rollers as shown in the picture above. In some planing lines, the speed must also be decreased - for example, in one case from 80 m/min to 60 m/min and in another case from 100 m/min to 80 m/min. If the infeed speed is decreased, the rotation speed of the cutters must be decreased accordingly. Too high a ratio of rotation speed to infeed speed can cause the wood surface to burn.

The pressure of rollers, as well as speed and other parameters, is highly dependent on the planing line and machinery. Therefore, no general values can be cited. In the planing of ThermoWood, the parameters are set separately for each planing machine.

It has been reported that machines (cutters and other surfaces) are very clean after working with ThermoWood due to the lack of resin in the wood. ThermoWood can even clean the machines of the resin-containing dust from previous production lots.

To achieve the best possible planing results and minimise loosening of the wood's annual rings, it is recommended to use material that has been cut as parallel to the grain as possible. In addition, considering the best face of the board when planing improves the result. There is a close connection between the infeed roller type and pressure, the grain direction, cupping, cutter sharpness, and throughput speed. When these variables are carefully harmonised, the best results are achieved.

5.4. Milling

Milling tests were performed by VTT using a CNC machine. In order to achieve a good surface quality – especially in milling – the cutters must be sharp; otherwise tearing will occur. A higher level of tearing was observed when the wood was milled across the grain. The greatest problems with tearing occurred at the start of the milling and at the end, when the cutter comes out of the wood. Milling heat-treated wood can be regarded as similar to working with hard, brittle hardwoods.

It was found that the working order has an influence on the working properties of wood. The best results were achieved when there was enough solid wood material behind the cutter. Therefore, working must be planned carefully beforehand.

The cutters wear more slowly than with normal wood.

5.5. Sanding

General working is equivalent to working with untreated wood; no problems have been reported. In many cases there is no need for sanding, as ThermoWood has a good surface quality after planing or milling.

The dust generated has a small particle size, which is to be taken into account in planning dust extraction. On the other hand, it is a light and dry dust which does not impose any special requirements for dust extraction systems. As in working with any type of wood dust, there is a risk of dust explosion in certain conditions.

5.6. Industrial gluing and jointing

Gluing

In gluing ThermoWood, the adhesive manufacturer's specific instructions must always be followed. Appendix 1 presents the recommendations of one manufacturer.

VTT has studied the glueability of heat-treated wood with 1- and 2-component PVAc adhesives, 1- and 2-component polyurethane adhesives (PU), resorsinol-phenol adhesives (RF), and emulsion-polymer-isocyanate adhesives (EPI). The glueability test was carried out in accordance with DIN 68603. The strength of the glue line was determined in accordance with EN 392 (block shear test). The moisture durability was determined in accordance with the delamination test EN 302-2. The penetration of the adhesive into ThermoWood was studied with a microscope.

The glueability is dependent on the heat-treatment class. The shear strength of the glue line decreases with increased treatment temperatures. This is due to change in the strength properties of the material. It also explains the high wood failure percentages (90–100%). The glue line broke up from the wood, not from the adhesive.

The penetration of the EPI adhesive into heat-treated wood was high, which can have some effect on the strength values. The EPI adhesive is mildly alkaline, and also a long cold pressing time of several hours can improve the penetration of the adhesive.

Experiences in one glulam beam plant using heat-treated pine as raw material were good. Both MUF and RF adhesives worked well. Normal production parameters (pressing time, pressure, etc.) were used. Finger joints were made with MUF adhesive.

With regard to gluing, the results are better with wood treated at lower temperatures. In working with PVAc adhesives, the water content in adhesive should be minimised. Since the heat-treatment process changes wood's water-bonding capability, the absorption rate of adhesive and water into the wood is decreased.

Some PVAc adhesives can cause problems in the form of significantly prolonged drying times due to the requirement for the water to penetrate the wood, i.e,. the curing of the adhesive is based on the absorption of water into the wood. Chemically curing adhesives have a normal drying time.

All tests carried out with PU adhesives have been successful, but it must be kept in mind that the curing reaction of PU requires water. The water can be absorbed from either the wood or the surrounding air. The required amount of moisture is dependent on the adhesive, but if both wood and air are very dry, there exists a chance of unsuccessful gluing.

As always in wood gluing operations, attention has to be paid to correct working conditions when working with ThermoWood. These include wood temperature, the wood's moisture content, and surface cleanliness.

Finger jointing

The Seinäjoki Institute of Technology has performed finger-jointing tests with

- Four different adhesives: MUF, PVAc, 2 x PU;
- Three open times: 15 s, 30 s, and 60 s;
- Six pressures between 1.3 and 7.8 N/mm^2 (corresponding pressure in the glue line 0.2–1.2 Mpa).

The joints were firm with all tested parameters. According to the tests, the maximum pressure was 22 N/mm^2, which is over ten times the pressure that a firm glue line needs.

Carbide-tipped cutters are recommended for machining the fingers for the joints. It is also recommended that adhesive be applied to both ends in order to ensure a firm joint.

Since working with blunt cutters can easily lead to chipping of the finger joints, sharp cutters are essential. It was also found that using slightly lower speeds caused less chipping of the joint fingers.

Various finger jointing methods have been tested successfully.
Industrial tests have shown that due to the cupping of ThermoWood caused by the treatment process, pre-planing of the material before finger jointing yields a much better result and allows for higher throughput speed and fewer stoppages. In addition, pre-planing improves the performance of machine vision devices in automated cutting lines.

Mechanical joints

Splitting of the material can be avoided by using self-tapping and countersinking screws or by pre-drilling the holes.

Figure 2-5. Self-tapping screw.

The hardware must be selected according to the application. For outdoor applications and similar conditions, stainless steel hardware is recommended.

Good jointing results are achieved with pneumatic nailers. Attention must be paid to the correct pressure and the nailer's drive length.

The decreased splitting strength and also slightly decreased bending strength of the material is to be taken into account when designing the joints. It is recommended that the critical joints and the details of the products be tested before production. Big knots (especially with respect to the size of the cross-section) are always a risk factor with ThermoWood because the wood lacks the resinous substances that in normal wood act as an adhesive between knot and the surrounding area.

The better dimensional stability of ThermoWood allows joints to be designed with smaller tolerances than joints using normal wood.

5.7. Industrial surface treatment

In terms of its material properties, ThermoWood is comparable to untreated wood as a substrate for coatings. Since the resins have come out of the heat-treated timber, the risk of resin flow from the surroundings of the knots to the paint surface is reduced. Therefore, knot sealer is not required before surface treatment.

In the application of surface treatment products to ThermoWood, the paint manufacturer’s specific instructions must always be followed. Appendix 2 presents manufacturers' recommendations.

Better surface adhesion for ThermoWood occurs with a smooth planed finish, or if springwood is brushed. Otherwise, small splinters are easily detached from the surface sawn with a bandsaw. Surfaces must be clean, as with any other material.

Oil-based substances work as with normal wood. When one works with water-based substances, it has to be taken into account that ThermoWood has a lower water-absorption capacity than normal wood. However, no problems have been reported. Water-based treatment products seem to work well, when they dry slowly and have enough time to penetrate the wood. UV-hardening paints and lacquers have shown good results, as have oils and waxes.

We are still awaiting the results of outdoor tests of Dyrup/Gori paints. In addition, a comprehensive series of water-based industrial application systems with varying colours has been tested. Dyrup has also carried out accelerated weathering tests on ThermoWood with one surface coating without impregnation as well as normally impregnated softwood with a surface coating. These samples have already been in the accelerated weathering test chamber for 2000 hours, and they show no difference in performance. The test will continue for a further 2000 hours to see if any differences will appear.

The tests have shown that there is a larger consumption of primer, but apart from this there are no other significant findings other than the excellent surface results and aesthetic appearance gained with ThermoWood. Paint products which can already be recommend for ThermoWood are mentioned in the appendices.

As always in surface treatment operations, working with ThermoWood requires attention to be paid to correct working conditions, such as appropriate wood temperature, moisture content, and surface cleanliness.

5.8. Fire protection

ThermoWood (made of pine) has shown good results in preliminary fire retardant tests. They have been carried out using Moelven Fireguard IV and Injecta F exterior fire retardants. For both substances, the uptake is higher than with normal untreated wood, the reason for that being the lack of resin in ThermoWood. Further testing will be carried out.

5.9. Practical experiences from a Finnish joinery company

The following results are comments by a technical engineer at a Finnish purpose-made joinery company. The company has been working with ThermoWood successfully for several years.

Raw material
The company has worked with heat-treated pine, spruce, aspen, and birch.

- Aspen: the results have been good but availability is poor
- Birch: good results and better availability
- Pine and spruce: small fresh-knotted material good; larger dead knots a problem; availability good
- In most cases, they purchase the timber one dimension module larger than is usual, to ensure sufficient allowance, the problem being distortions due to the heat-treatment process

Sawing

- Normal machines/tools work but must be sharp
- No significant problems with split or cross-cut sawing
- No internal stresses are present in heat-treated wood
- The wood structure is more like that of hardwood, and tools wear accordingly

Planing

- The company uses normal machines/cutters
- The machines and cutters must be well maintained and sharp
- The working result can be affected by cutter techniques
- The cutters wear down in the same way as when working with hardwoods
- Aspen, birch, and pine are very good to work with
- Spruce needs slightly more attention, but the results can be good

Milling

- Risk of breaking when tennoning
- The sharpness of the cutters, correct cutting angles, and cutting speed affect the result

Sanding

- No significant problems when using sanding machines
- Paper wears at a similar rate as when sanding hardwood

Nailing and screwing

- A pneumatic nailer is best for nailing
- For nailing with a hammer, pre-drilled holes are recommended
- For screwing, pre-drilled holes are required
- Handle the wood as with hardwood

Gluing

- Adhesive drying and pressing time notably longer
- Several adhesive options
- Drying time can be shortened with higher temperatures

Surface treatment

- Normal methods are suitable
- Without pigment, the colour becomes light grey after a period
- Good adhesion of surface treatment
- The material is a good base for water-based paints

Storing the raw material

- Do not store where exposed to snow or rain
- Protect the packages with paper wrapping or store in a warehouse
- No need for special warehouse conditions
- Conditioning suggested before use

5.10. Health and safety

There is no major difference in health and safety considerations for ThermoWood as compared to normal softwood or hardwood species. There are still two detectable differences: the smell of the material and the dust generated in the processing of ThermoWood.

ThermoWood has a smoke-like smell, which likely comes from chemical compounds called furfurals. Although the smell is easily detectable by the human senses and seems stronger than that of untreated wood, the tests show opposite results. As mentioned in section 4.2.13, the volatile organic compound (VOC) emissions from ThermoWood are only a fraction of those of normal pine.

There have been no toxic or harmful components found in ThermoWood. It has even been tested as a bone substitute material. In any case, if a wood splinter penetrates the skin, it should be removed as soon as possible, as with normal wood.

The Tampere University of Technology has studied, in co-operation with the Lappeenranta Regional Institute of Occupational Health, the health effects of working with ThermoWood. ThermoWood dust has a slightly smaller particle size than normal softwoods. It is comparable to MDF (although the density is lower) or hardwood dust. No correlation to a risk of cancer was observed when studying ThermoWood dust.

In processing ThermoWood, special attention has to be paid to the operation of an appropriate dust extraction system. The system must be well-sealed and sufficiently effective.

The standard dust extraction systems in industrial environments meet this requirement without requiring special adjustments. Since the dust is fine, light, and resin-free, it is easily sucked into the extraction piping. Persons who are exposed to the dust on a daily basis should protect themselves with, for example, dust masks.

When gluing or painting ThermoWood, always follow the paint or adhesive manufacturers' specific health and safety instructions.

6. Use of ThermoWood

6.1. Working

Sawing ThermoWood is like sawing untreated wood. Where knots are concerned, no special tearing distinct from that of normal wood has been noticed.

Working with all kinds of hand tools - for example, in sanding, drilling, and milling - is easy. Sanding gives excellent results, and drilling – even of knots - is easy.

Because of the brittleness of ThermoWood, attention must be paid to its handling. Dropping the pieces may damage the edges. Long pieces shouldn't be lifted by only one end.

The only problem in working with hand tools is the dust. Because ThermoWood is normally very dry, the wood dust is fine and spreads easily to the environment. The best solution would be an efficient dust extraction system, but that is often not possible; therefore, the use of a dust mask in these cases is highly recommended.

6.2. Joining

Nailing

A pneumatic nailer is recommended for nailing ThermoWood. The pressure must be tested in order to adjust the nail penetration - see the figure below. The best result is achieved by using a small pneumatic nailer with adjustable drive depth.

The use of a normal hammer increases the risk of splitting when the hammer hits the wood. The final 2 to 3 mm of the nail length should be hit with a punch.

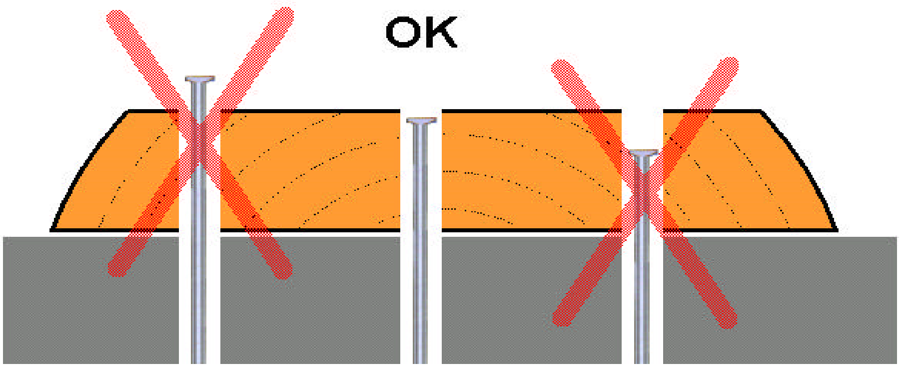


Figure 1-6. Drawing showing the correct nail penetration depth. The correct penetration depth is about 1 mm below the surface of the piece.

Nail types
To reduce the risk of discoloration of the wood, stainless steel nails should be used. However, if a pneumatic nailer is used, galvanised nails are suitable since in this method no metal-to-metal contact occurs and breaks the galvanised surface. Galvanised nails are also best if a topcoat is applied to the cladding. To prevent splitting, small oval-head nails would be the most suitable.

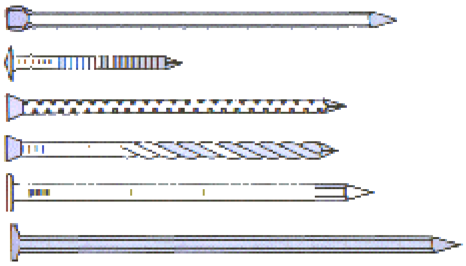


Figure 2-6. Some suitable nail types, the most recommended being the small oval-head nail shown at the top.

Screwing
Pre-drilling (close to ends) and countersinking is essential, just as when working with hardwood, MDF, or other brittle materials. Stainless steels screws with countersunk heads are most suitable in outdoor usage or other humid environments. For the best holding strength, coarse-thread screws perform best. Self-tapping screws can be used in ThermoWood without pre-drilling.

Figure 3-6. Self-tapping screw.

6.3. Gluing on-site

In gluing ThermoWood, the adhesive manufacturer's instructions must always be followed. Appendix 1 presents recommendations from one manufacturer.

Where gluing is concerned, the results are better with wood treated at lower temperatures, such as the ThermoWood class for interior applications. In assembly, high compression pressures cannot be used, as the material is more brittle than untreated wood.

Heat-treated wood absorbs water and water-based adhesives, such as PVAc, slowly. That is why longer pressing times than normal are needed when using water-based adhesives. Some PVAc adhesives can cause problems in the form of significantly prolonged drying times due to the requirement for the water to be absorbed by the wood, i.e., the curing of the adhesive depends on the wood's absorption of water. When one works with PVAc adhesives, the water content in adhesive should be minimised.

It is reported that PU (polyurethane) adhesives work well with ThermoWood. Although all tests carried out with PU adhesives have been successful, it must be kept in mind that the curing reaction of PU requires water. The water can be absorbed from either the wood or the surrounding air. The required amount of moisture is dependent on the adhesive, but if both wood and air are very dry, there exists the possibility of unsuccessful gluing.

Chemically curing adhesives, such as MUF and RF resins, allow drying times and other gluing parameters to remain unchanged.

As always in wood gluing operations, attention has to be paid to correct working conditions when working with ThermoWood; these include wood temperature, moisture content, and surface cleanliness.

6.4. Surface treatment

As a general rule, ThermoWood® is analogous to normal wood as a base for surface treatment. However, the ThermoWood® process affects some properties related to surface treatment. The decreased equilibrium moisture content of the wood improves its stability, which in turn reduces the cracking and flaking of the surface coating in changing environmental conditions. Water-based surface treatment products require slightly longer drying/absorbing times since ThermoWood's water-absorbing capacity has decreased along with the equilibrium moisture content. Since the high temperature of the treatment process removes the resin from the wood, knots do not necessarily require special procedures during the surface treatment.

Without surface treatment, the surface of ThermoWood acts like the surface of untreated wood. Due to the UV radiation in sunlight, the surface turns grey, microscopic cracks are formed on the surface, and the surface ages to an antique appearance over time. To retain the original colour and surface quality, surface treatment is recommended. If priming paint is to be applied manually, the best surface treatment results are achieved by using oil-based paints. If the material has been delivered to the site primed, the corresponding topcoats can be applied without problems manually with a brush using either oil- or water-based paint, depending on the primer type and the manufacturer's recommendations.

To prevent colour changes, the treatment substance should contain pigment. In most cases, the surface treatment is done with a transparent wood preservative with brown pigment added to match the original ThermoWood colour as closely as possible. This usually results in a slightly darker appearance. Different surface treatments have different maintenance intervals. The more pigment used, the longer the maintenance interval. If opaque paint is used, the original ThermoWood colour and features are obscured.

It is recommended that the material be treated once before installation, with the finishing treatment applied after the installation. If vegetable-oil-based surface treatment products are used for applications exposed to the elements, it is recommended that products containing anti-mould agents be used.

In carrying out surface treatment of ThermoWood, the instructions of the surface treatment product manufacturers must always be followed.

6.5. ThermoWood in sauna benches

Due to its highly hygienic nature, colour, and decreased thermal conductivity, ThermoWood® is well suited for sauna benches. However, fast wetting and drying cycles in a high-temperature environment can cause benches to split at the ends. To avoid this, it is recommended to seal the ends with oil, wax, or varnish.

6.6. Product maintenance

Different surface treatments have different maintenance intervals. The more pigment used, the longer the maintenance interval. However, if opaque paint is used, the original ThermoWood colour and appearance are obscured. As a rule of thumb, pigment-containing transparent surface treatment has a doubled or tripled maintenance interval in comparison to a treatment product without pigment. Furthermore, opaque paints have maintenance intervals twice as long as pigment-containing transparent paints.

The environment and climate have a crucial effect on the life span of a surface treatment. UV radiation from sunlight and moisture are major obstacles that must be surmounted by surface treatment. These factors mean that, for example, the south side of a building needs maintenance more often than the north side. Moreover, buildings in a continental climate have a longer life span for their surface treatment than buildings by the sea.

To ensure maximum performance of coating and avoid damages, the surfaces should be cleaned and checked annually, with any defects repaired immediately.
Always refer to the paint manufacturer’s specific maintenance instructions, if available.

6.7. Health and safety

There is no significant difference between the health and safety considerations for ThermoWood and those for normal softwood or hardwood species. There are still two detectable differences: the smell of the material and the dust resulting from the processing of ThermoWood.

ThermoWood has a smoke-like smell, which likely comes from chemical compounds called furfurals. Although the human senses can easily recognise the smell and it appears stronger than that of untreated wood, the volatile organic compound (VOC) emissions from ThermoWood are only a fraction of those of normal pine.

There have been no toxic or harmful components found in ThermoWood. It has even been tested as a bone substitute material. However, if a wood splinter penetrates the skin, it should be removed as soon as possible, just as with normal wood.

ThermoWood dust has a smaller particle size than dust from normal softwoods. It is comparable to MDF (although the density is lower) or hardwood dust. The dust can cause problems for people suffering from asthma. For the reasons mentioned above, one has to pay special attention to the utilisation of an appropriate dust extraction system.

If the dust extraction system is not sufficient, a dust mask must be used.

When gluing or painting ThermoWood, always follow the paint or adhesive manufacturers' specific health and safety instructions.

7. Handling and storage of ThermoWood

7.1. General

ThermoWood must be stored in a dry place. Since no special storage temperature is required, cold warehouses are among the suitable locations. The product should be carefully covered or stored in a covered warehouse.

The packages should be stored horizontally with a sufficient number of supports under the packages to prevent the lowest boards from distortion. The packages must be stored so they do not touch the ground

Before use or further working where gluing and/or surface treatment is taking place, the material must be allowed sufficient time for conditioning to the suitable MC and temperature as per the manufacturer's recommendations. When ThermoWood packages are lifted with a crane, forklift, or similar device, the forks should be adjusted to their maximum distance apart because of the slightly decreased bending strength of the material.

The bundles are not to be opened before use.

7.2. Handling of residual and discarded products

ThermoWood is a natural wood product without any chemicals added to it. When not glued or painted, ThermoWood waste can be handled like any other untreated wood waste.

ThermoWood can be burned. It produces about 30% less energy than untreated wood because the majority of the energy containing extractives has already been removed in the heat-treatment process. ThermoWood burns with a smaller flame and produces less smoke and harmful gases because of the factors mentioned above. Flammability is normally better due to the lower equilibrium moisture content of the wood; i.e., the wood is drier. There is no significant difference between the compounds in smoke from ThermoWood and those in the smoke from normal wood.

Pelletising and briquetting is possible, if a mixture with normal sawdust is used. Due to the dryness and lack of resin with ThermoWood, normal softwood dust is required to hold the pellets together.

ThermoWood can be taken to the landfill. It is non-toxic.

8. Frequently asked questions and answers

1. Can you heat-treat different wood species?

The manufacturing and use of both softwood and hardwood species, such as pine, spruce, birch, and aspen, has produced highly positive results.

2. How long does ThermoWood last?

Although evidence from long-term experience of the use of ThermoWood is not yet available, tests have shown that the material's resistance to decay is far superior to that of untreated softwoods and equal that of many tropical hardwoods. In addition, good dimensional stability increases the wood's life span. The service life can be affected by many factors other than resistance to decay - such as the level of maintenance, especially for the surface treatment, and general wear and tear. Following the guidelines presented in this handbook should also assist in lengthening the life expectancy of the product.

3. What are the guarantees?

Although there are no specific guarantees for the product, tests conducted by several independent research institutes have shown consistently positive results where durability is concerned.

4. Why is ThermoWood so durable despite the resin and extractives having boiled away?

The durability of ThermoWood is based on the changes in chemical compounds in the wood. Wood's hemicellulose (sugar compound) is degraded, leaving no nutritive matter for fungi.

5. Are any chemicals added as part of the process?

No chemical additives are used in the ThermoWood production process; only energy and steam are required. Hence, ThermoWood can be utilised/discarded like normal wood after its life span is complete.

6. Can ThermoWood be used in contact with the ground?

Results have shown that even in ground contact ThermoWood does not decay; however, when constantly immersed in water or making soil contact, it loses its strength properties due to certain chemical reactions. The mechanisms are yet unknown, and further research is needed. This is why it is recommended that ThermoWood not be used in continuous direct contact with moist soil.

7. What kind of surface treatment is needed for outdoor use?

ThermoWood can be used outdoors without surface treatment, but this will lead to greying and shaking of the surface, as with normal wood. The type of surface treatment desired varies with the end use application. Products that require the original ThermoWood appearance should be treated with transparent paint containing some brown pigment.

8. Is the smell of ThermoWood harmful?

Tests have shown that there are no harmful emissions from ThermoWood, but the smell might not be appreciated by everyone.

9. Does the smell disappear?

If surface treatment is applied to a product made of ThermoWood, the smell will disappear and not return. If ThermoWood is used without surface treatment, the smell will gradually dissipate until reaching a level where it is no longer noticed except when smelled from a very close distance.

10. Can ThermoWood be glued?

Practical experience has shown that gluing of ThermoWood is possible with all adhesive types. If water-based adhesives, such as PVAc adhesive, are used, the decreased water absorption capacity of ThermoWood must be taken into account where drying time is concerned. In the case of PVAc in particular, the adhesive manufacturer's specific instructions for the product and its use with ThermoWood must always be followed.

11. Can ThermoWood be used in load-bearing structures?

So far, most of the strength tests have been carried out with small, defect-free test pieces. Further testing is required with larger test pieces and with varying numbers of knots and different knot types. Due to insufficient information, we recommend that ThermoWood **NOT** be used structurally for load-bearing purposes for the time being.

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