Woodwool slabs - production, properties and use

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Woodwool Slabs
– Manufacture, Properties and Use

by Erik Johansson

Erik Johansson was born in Sweden in 1963. He holds a master's degree in Civil Engineering from Lund University. Since graduation he has done research on building materials, and has participated in development research projects on building technique and building materials in Tunisia, Algeria and Ethiopia. He is engaged as a researcher at Lund Centre for Habitat Studies and at the Division of Building Materials, the Institute of Technology, Lund University.

His master's thesis dealt with water leakage in flat roofs in Tunisia, and he wrote a Building Issue on the topic in 1989. He is the house expert on football and spends all his free time out in the Swedish rain cheering on his home team Malmö FF.

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Erik Johansson

1 Introduction

Problem

Thermal insulation is important to improve indoor climate and save energy in a building. The use of thermal insulation materials are, however, often limited in developing countries. There are several reasons, for example:

- The advantages of thermal insulation materials are not known.
- Local thermal insulation materials are not available.
- Imported thermal insulation materials are expensive and require foreign currency.
- Use of thermal insulation materials requires modification in current building methods.

This reports deals with woodwool slabs, a well tested thermal insulation material that can be made locally in most countries. Because of their versatility, woodwool slabs are easy to integrate with most construction techniques.

Many of the materials traditionally used in contemporary buildings – bricks, concrete, stone, soil block, etc. – have poor thermal insulation capacity. To reach the same thermal insulation as 100 mm of woodwool slab requires about 4 m natural stone, 1.8 m concrete, 700 mm soil block or concrete hollow block and 500 mm hollow brick.

Method

This report is primarily based on the experience gained from a research cooperation between Lund University, Division of Building Materials and LCHS, and the National Centre for Building Research and Studies (CNERIB) in Algeria during the period 1991–1993. This project, which included test production of wood-wool slabs with Algerian woods and full scale tests of the slabs in building components, laid the foundation for introducing woodwool slabs on the Algerian market.

Visits were made to modern, completely automated factories in Sweden and the Netherlands. A semi-automated, labour intensive factory was studied in Brazil. Detailed studies were also made on the use of woodwool slabs in these countries.

The report is also based on a study of the literature, including a large part of all the material on woodwool slabs written over the years.

Organization of the report

The report is divided into two parts. The first part includes Chapter 1, the background to the study, Chapter 2, a short description of the production, properties and use of woodwool slabs, and Chapter 3, a description of how woodwool slabs can be produced industrially in developing countries.

The second part includes Chapter 4, choosing an appropriate wood, Chapter 5, the properties of woodwool slabs, Chapter 6, quality control, and Chapter 7 examples of use.

2 General considerations

History of woodwool slabs

Slabs of woodwool (excelsior), gypsum and water were patented in Germany already in 1880. During the 1910s production of woodwool slabs with magnesite as the binding agent (patented 1908) started in Austria. Magnesite[1] gave better durability than gypsum.

Portland cement was introduced at the end of the 1920s, and is the most common binder today, which is why they are commonly called woodwool *cement* slabs and, in North America, cement excelsior boards (CEB). For a long time woodwool slabs were made in Germany with either gypsum, magnesite or cement as binder. Gypsum slabs are no longer made.

The technique to produce woodwool slabs – mainly cement-bonded, but even magnesite-bonded – spread quickly from Austria and Germany to other European countries and North America. A great increase in production occurred during the years before and after the second world war, and woodwool slabs were spread even farther geographically.

At first cement-bonded woodwool slabs were produced by hand in small plants. The equipment was limited to wood shredding machines, to make the woodwool, and a mixer. Manufacture became more and more mechanized over the years, with significantly high production capacity. Modern factories are normally fully mechanized, and about 15 persons can produce up to 150 m^3 slabs a day.

The most commonly used wood for woodwool slabs comes from conifers, mainly pines and firs. During the 1960s a great number of other species were tested, including tropical woods, to see if they could be used for woodwool slabs. A number of species were suitable, which led to production of woodwool slabs on other continents. There is currently production in Africa (Ghana, Malawi, Namibia, Zambia), Asia (Burma, India, Indonesia, Japan, Malaysia, the Philippines, Taiwan, Thailand) and Latin America (Brazil, Mexico, Panama, Peru, Venezuela). Production in these countries varies in the degree of mechanization – everything from manual to completely automated.

Production

The components needed for woodwool slabs are woodwool, binder (Portland cement or magnesite) and water. Normally a small amount of binder additive is added to speed up setting.

Making woodwool

Woodwool can be made from a number of woods. To make production easier, the wood should allow easy shredding (have a low density) and not contain compounds that seriously inhibit the setting of the slab.

Usually the tree trunks are air-dried (seasoned) before cutting into logs and shredding to woodwool. This reduces the amount of sugar and other compounds in the wood that inhibit setting of the slabs, and lowers the moisture content (shredding is more difficult with green wood).

Fig. 1 Making woodwool in a vertical wood shredding machine (Tepro, Sweden). Shredders sold today are horizontal. See Figs 9 and 10.

To make woodwool, a half metre long log is placed in a shredding machine (Fig. 1) fitted with scoring knives perpendicular to the planing knives. The cross section of the woodwool is determined by adjusting the speed with which the log is fed toward the planing knife, and the distance between the scoring knives. The thickness of the woodwool can vary between 0.2 – 0.5 mm, and the width between 1.5 – 5 mm depending on how the slab will be used. The amount of woodwool in a slab varies between about 75 – 200 kg depending on the density of the slab.

Binder

The most commonly used binder in woodwool slabs is Portland cement, but magnesite can also be used. The Portland cement is normally of ordinary type (OPC), although rapid-hardening cement can be used to make the setting faster. Sometimes white cement is used for aesthetic reasons.

For magnesite-bonded slabs the binder can be said to be magnesium oxide (MgO), one of the components of magnesia cement.

The amount of binder depends on the density of the woodwool slab, and varies between about 150 and 400 kg/m^3.

Binder additives

Normally some kind of binder additive is necessary. The setting of the Portland cement and water mixture can be inhibited to greater or lesser extent by sugars and other chemicals in the woodwool. An accelerator is therefore often added so that the slabs set within 24 hours. The most common accelerator is calcium chloride ($CaCl_2$). The amount of accelerator depends on the kind of wood, but is usually about 2% by weight of the water.

For magnesite-bonded slabs the binder additive is either magnesium chloride ($MgCl_2$) or magnesium sulphate ($MgSO_4$).

1 The binder is actually *magnesia cement*, produced by mixing magnesium oxide (MgO) with a solution of magnesium chloride ($MgCl_2$) or sulphate ($MgSO_4$). The magnesium oxide is produced by heating minerals such as magnesite ($MgCO_3$) or dolomite ($Ca(MgCO_3)_2$).

Fig. 2 Mould filled to overflowing with a mixture of woodwool, cement and water before compressing (Tepro, Sweden).

Water
The water should not contain anything that would inhibit the setting of the slabs. The amount of water required is about 50% of the cement by weight.

Mixing
Before the woodwool is mixed with the binder, it is soaked in a water bath containing the binder additive. The wet woodwool is transferred to a mixer, where dry binder is added.[2]

The ratio by weight of binder to woodwool is about 2:1. There are small variations from this ratio. Since the binder normally is the most expensive part of the woodwool slab, attempts are made to use as little as possible. Too little binder, however, means that not all the woodwool is coated, which results in poorer binding and strength.

Making the slabs
The mixture of woodwool, binder and water is put into moulds which are filled with the required amount of mixture by weight (Fig. 2). The moulds are then stacked on top of each other and put under pressure so that the mixture in each mould is compressed.[3]

After the slabs have hardened, usually in 24 hours, they are demoulded and the edges trimmed with a saw. They cure for two to three weeks before they are delivered.

Properties

Thermal insulation
Woodwool slabs give good thermal insulation. Thermal conductivity is, however, relative to their density (see Fig. 23). At a density of 400 kg/m^3 the thermal conductivity is about 0.085 W/mK in practice. A comparison of the thermal conductivity of woodwool slabs and some other materials is shown in Table 1.

Material	Density (kg/m^3)	Thermal conductivity (W/mK)
Woodwool slab	400	0.085
Cellular plastic, mineral wool	20 – 50	0.036
Lightweight concrete	400	0.10
Softwood	500	0.14
Hollow brick	800	0.47

Table 1 Comparison of density and thermal conductivity (values in practice) for woodwool slabs and some other materials.

Other properties
Woodwool slabs have very good acoustic properties and are often used to absorb sound in, for example, factories, public gathering places, sports and concert halls.

The material is known for its good durability. It has very good fire resistance, tolerates damp and is not attacked by mould or rot. Woodwool slabs have good resistance to insect pests, as termites.

Compared to many other insulation materials, woodwool slabs have good bending and compression strength. They are easy to saw, drill and nail. They have good adhesion to rendering/plastering mortars and concrete. The material is considered to be healthy, since it has very low emissions of harmful compounds.

Products and uses

Insulation slabs
Insulation slabs are normally made of relatively coarse woodwool (3 – 5 mm wide). They are used for thermal insulation, and are normally not visible but rendered/plastered. The slabs can be 2 – 3 m long, 500 – 900 mm wide and 15 – 150 mm thick. Their density ranges from 250 – 700 kg/m^3 depending on use. If thermal insulation capacity is important, they are made with low density; if strength is important, they are made with high density.

Acoustic slabs
Woodwool slabs meant for sound absorption are often made of finer woodwool (1.5 – 3 mm). These slabs are visible, and they are often painted for aesthetic reasons. They might also be made with white cement which gives them a whitewood colour. Acoustic slabs are usually 15 – 50 mm thick.

Special products
There are also a number of special products. To increase the loadbearing capacity for use in roof structures, the slabs might be reinforced with wooden poles or bars, or the sides of the slabs can be strengthened with galvanized steel channels (Fig. 4). These reinforced slabs can even be used as standing, loadbearing wall elements.

In many countries the slabs are sold with a finished surface. These might be a layer of cement-based mortar or gypsum plaster. The surfacing can be done so thinly that the texture of the slab still shows (Fig. 5).

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2 Less commonly the binder and water are mixed before the woodwool is added. A small-scale process using this method of mixing is described in Hawkes and Cox (1992).

3 Magnesite-bonded woodwool slabs can also be produced industrially in a continuous process during which the slabs are compressed and heated to 400°C to make them cure faster (see Kollmann 1955).

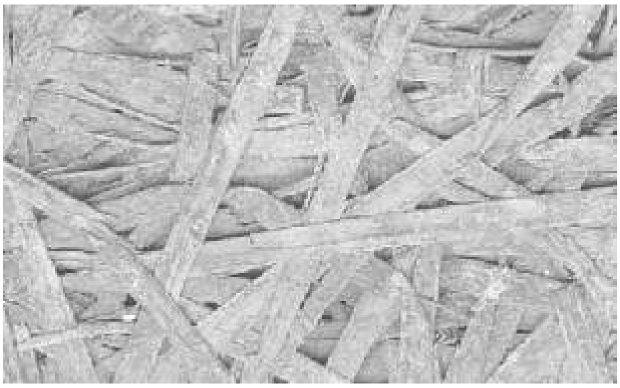


Fig. 3 Example of an insulation slab (above) and an acoustic slab (below), life-size photographs. (Tepro, Sweden).

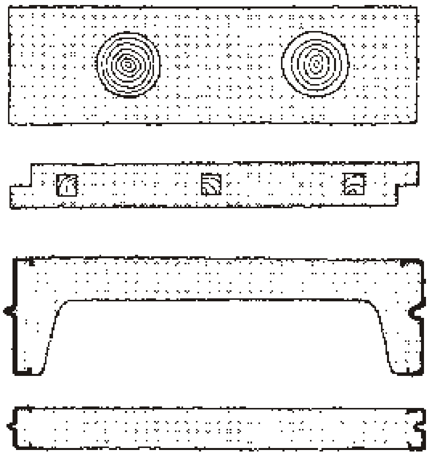


Fig. 4 Cross section of slabs reinforced with wood (above) and galvanized steel channels (below).

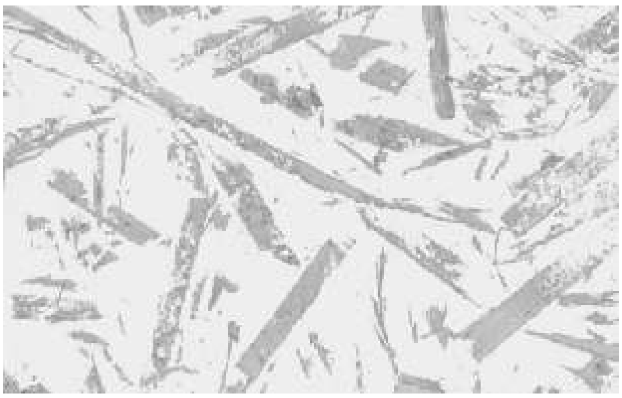


Fig. 5 Slab coated with gypsum plaster, resulting in a smooth surface that retains the texture of the slab (Climatex, Brazil).

3 Recommendations for production

The manufacturing process recommended is in principle the same as for more automated production. This means the proposed plant can be gradually mechanized with more equipment without alterations in the plant layout.

This description assumes the binder is Portland cement. Magnesite can also be used according to Chapter 2.

Manufacturing process

Debarking and air-drying (seasoning)
Immediately after felling, or at least before stacking in the wood yard, the bark is removed from the trunks with a debarking tool, such as a steel scraper.

The tree trunks should then be air dried until the moisture content of the wood drops to the right level, usually about 20 – 30%. This normally takes three to six months and has to be done in open air.

Making woodwool
The trunks are cut into logs of about half a metre long and moved to the wood shredding machine on carts. During shredding, the planing and scoring knives are adjusted to produce the desired width and thickness of woodwool strands.

Weighing and soaking woodwool
Dry woodwool is taken to the scales in a wheelbarrow and the right amount for a batch is weighed. It is then carried by hand and fed into an immersion tank. The immersion tank is also filled with accelerator solution from an attached container. (The amount and type of accelerator in the solution depends on the type of wood, and it can happen that no accelerator is needed).

Before the wet woodwool leaves the immersion tank, it passes between rubber rollers to remove the excess liquid. The woodwool is then carried by conveyer belt to the mixer.

Adding the cement
Cement is delivered to the plant in bags. The bags are emptied into a container and the cement is transferred to the mixer through screws. The correct amount of cement for a batch is controlled by a cement dosing unit next to the mixer.

Mixing and moulding
Wet woodwool and dry cement are mixed continuously in a horizontal mixer. The homogenous mix is then spread in oiled moulds that are pushed into place under the mixer on a line of rollers. The amount of material in the moulds depends on the density of slab to be produced. The mixture must be spread evenly in the mould and pressed down along the edges. Note that gloves must be used to avoid skin contact with the mixture, since cement is corrosive. (Skin contact with cement might even lead to chrome allergy.)

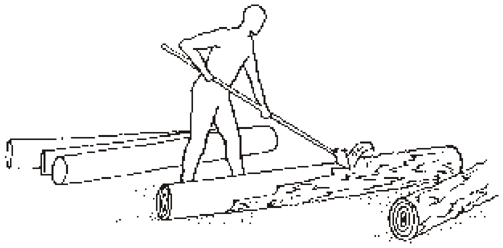


Fig. 6
Debarking the tree trunks before they are air dried.

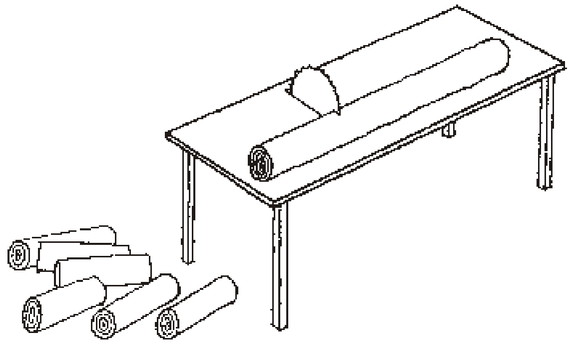


Fig. 7
Cutting the trunks into half a metre long logs.

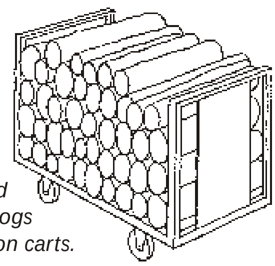


Fig. 8
Debarked and cut logs stacked on carts.

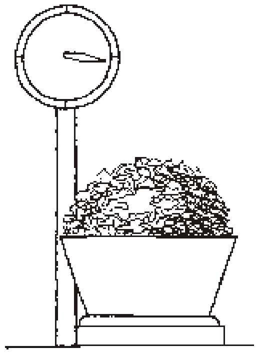


Fig. 11
Woodwool is weighed manually before soaking.

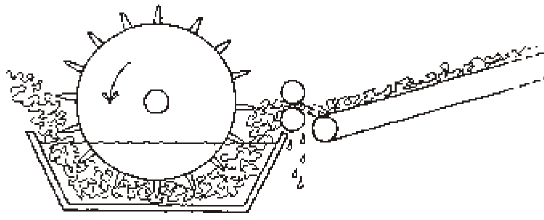


Fig. 12
Dry woodwool is soaked in an immersion tank and transported to the mixer.
Before the wet woodwool reaches the conveyer belt, it goes between rubber rollers to press out excess liquid.

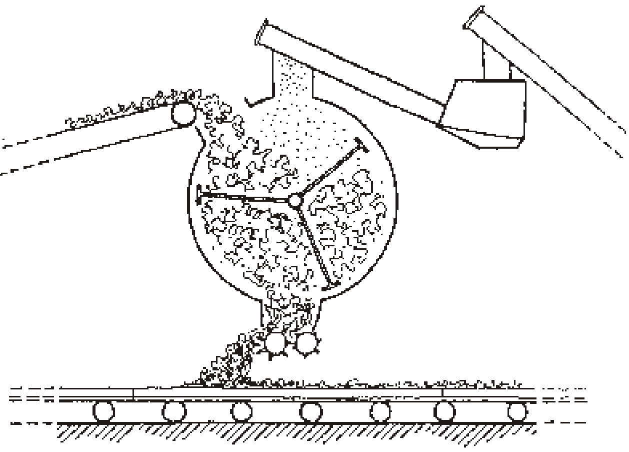


Fig. 13
Continuous mixing of wet woodwool with cement, and filling the moulds. The mixture must be spread uniformly in the moulds and pressed down along the edges.

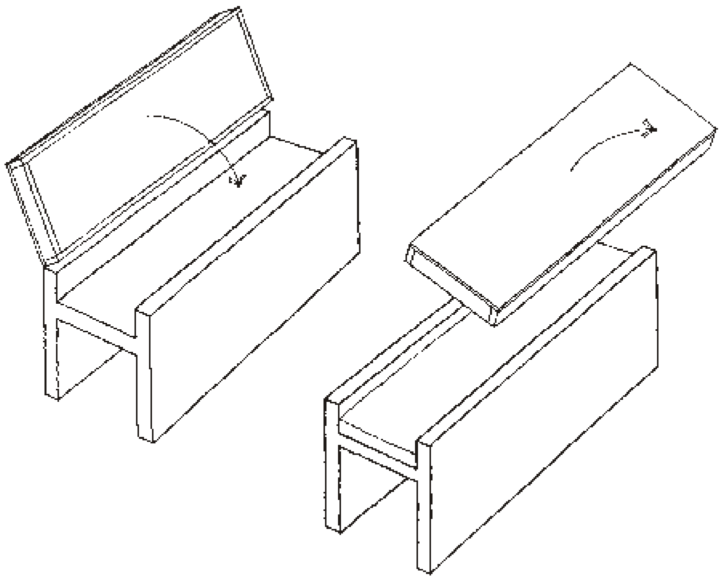


Fig. 17
Stripping the 24 hour old slabs.

Fig. 18
Stripping 24 hour old slabs (Climatex, Brazil).

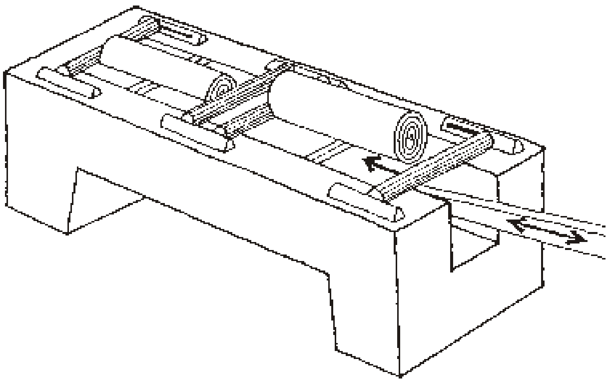


Fig. 9
Producing woodwool in a horizontal wood shredding machine. The logs are fastened and pressed down against the planing and scoring knives by toothed rollers.

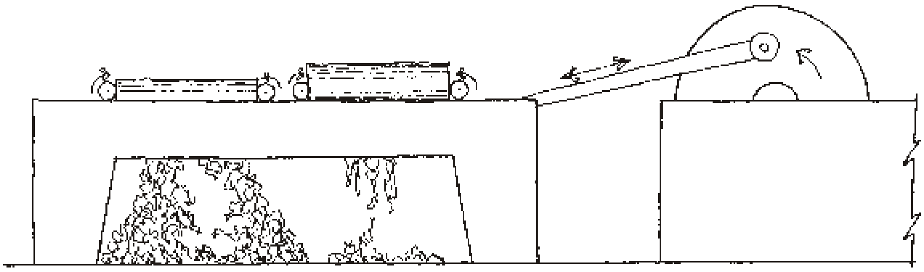


Fig. 10
Shredding woodwool. As the log is fed down, the planing and scoring knives go back and forth horizontally at high speed.
The woodwool falls down under the shredder.

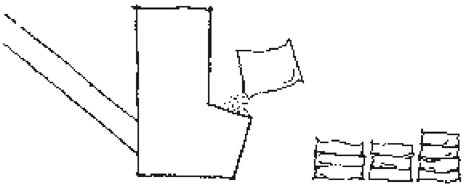


Fig. 14
Filling the cement container that is connected to the mixer by cement screws.

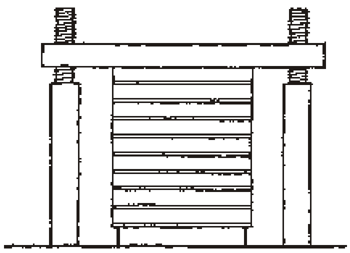


Fig. 15
Compression of filled moulds in a hydraulic press.

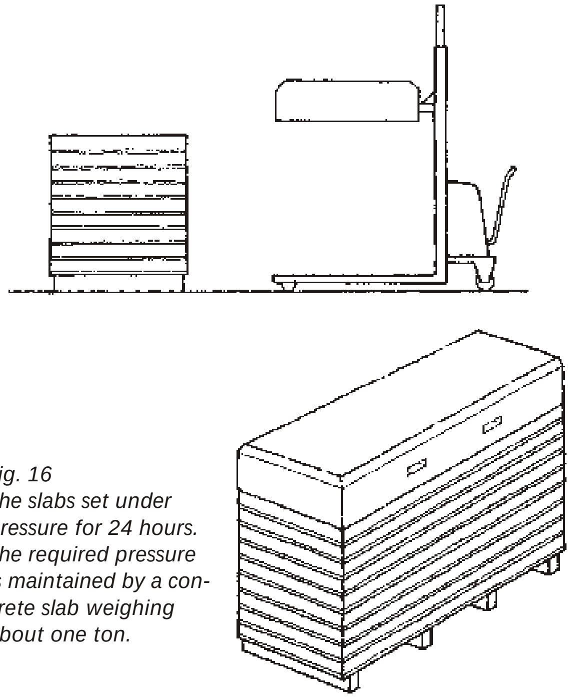


Fig. 16
The slabs set under pressure for 24 hours. The required pressure is maintained by a concrete slab weighing about one ton.

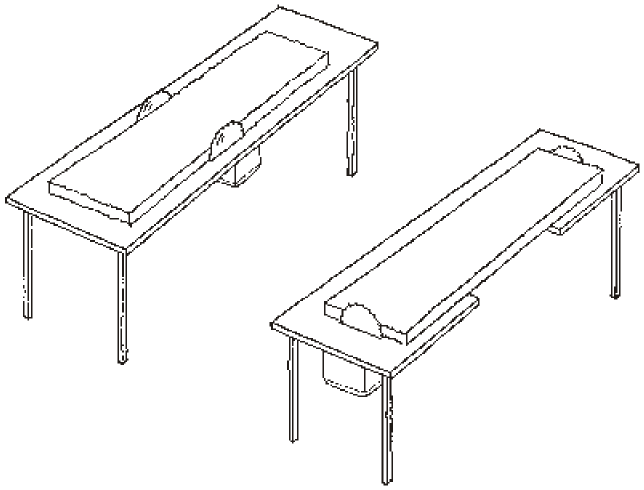


Fig. 19
After a weeks curing, the slabs are sawn to trim the edges and ensure the correct length and width.

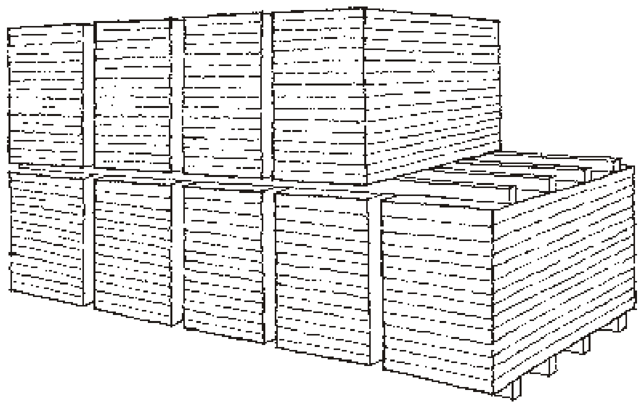


Fig. 20
Storing of slabs stacked on top of each other.

Compressing and setting
The filled moulds are stacked on top of each other and compressed in a hydraulic press. The bottom of one mould becomes a lid on the mould under. Then the entire stack of filled moulds is moved and allowed to set for 24 hours. Pressure is maintained by, for example, placing a concrete slab (weighing about one ton) on top of the stack.

Stripping
When the slabs have set they are stripped from the moulds, and the moulds are cleaned and oiled for reuse.

Curing and trimming the edges
The stripped slabs must be cured indoors or under cover, protected from direct sunlight. The best curing occurs if the surrounding air is somewhat moist, so the slabs are not allowed to dry out. It is recommended that each stack of boards be covered with a plastic sheet during the first week. To avoid high temperatures due to hydration, spacers could be put between the boards.

When the slabs are sufficiently hardened, say after one week, they can be sawn along both long and short sides to the correct size.

After a total of two to three weeks curing the slabs are ready for delivery.

Quality control

Quality is monitored by inspecting randomly selected samples and should be routine at the plant (proprietary inspection) and, if possible, at an accredited testing centre. Chapter 6 gives recommendations on how to determine the quality of woodwool slabs.

Proprietary inspection
The *size* and *weight* of one sample slab, of each product made, should be checked each production day, and the findings entered in a permanent record.

Monitoring by a testing centre
The plant's own inspection should, if possible, be corroborated by an independent testing centre, perhaps twice a year.

An overall inspection of each product should be done regularly, perhaps once a year, by an accredited testing centre. The most important checks are size, density, bending strength and compression strength.

Plant

For the production process described, it is recommended that the plant be about 55 × 40 m with a height of at least 5 m. See the design in Fig. 21. This building is large enough to permit increase automation without major alteration. There will be unused space at first, but this space might well be used to produce prefabricated elements.

The plant should be serviced by roads suitable for lorries. It needs to be connected to water and electricity. Lighting is necessary, and possibly even heating. Some partition walls are needed to separate the workshop, offices, etc. Some of the machines require cast concrete foundations. The plant should have sanitation facilities and fire equipment.

The plant yard should be large enough to allow air-drying of tree trunks.

Equipment

The equipment needed for the suggested production process is shown in Tables 2 – 4. Some of it must be imported, and some should be available locally. The prices given are estimates for new imported equipment. The placement of the equipment in the plant is shown in Fig. 21.

> Note that the equipment to make woodwool slabs is very robust, and it is recommended that used equipment be bought if available.

Item	Number	Code	Cost (US$)
Wood shredding machines	2	*2*	130,000
Immersion tank	1	*5*	56,000
Cement bag tipping unit	1	*7*	14,000
Cement screws	2	*8*	19,000
Cement dosing unit	1	*9*	16,000
Continuous mixer	1	*10*	54,000
Distribution station (mould supplier, spreading machine, stripping table)	1	*11*	32,000
Switch box	1	*12*	28,000
Hydraulic press	1	*14*	54,000
Grinding machine for wood shredding machine planing knives	1	*18*	20,000
Set of spare parts and tools	1	–	27,000

Table 2 Equipment to be imported. Approximate cost 1 Dec 1994 according to Elten Systems, the Netherlands. The code number shows the placement of the equipment in the plant (Fig. 21).

Item	Number	Code
Bark removers (steel scrapers)	5	–
Saw to cut logs	1	*1*
Manual fork-lifts	3	*15*
Saw blade grinding machine	1	*17*
Air compressor	1	*19*
Concrete blocks (for compressing slabs in the moulds)	20 – 30	–
Delivery pallets (for storage of slabs and delivery to the customer)	–	–
Oil for the hydraulic system	600 litres	–
Oil and grease for machine maintenance	–	–
Main transformer station with distribution station	1	–
Distribution system for process water	–	–
Tools for the workshop	–	–
Laboratory equipment for testing slabs	–	–
Basic electric installation material	–	–
Equipment for plant cleaning	–	–
Containers for transport of waste	–	–

Table 3 Equipment normally available locally.

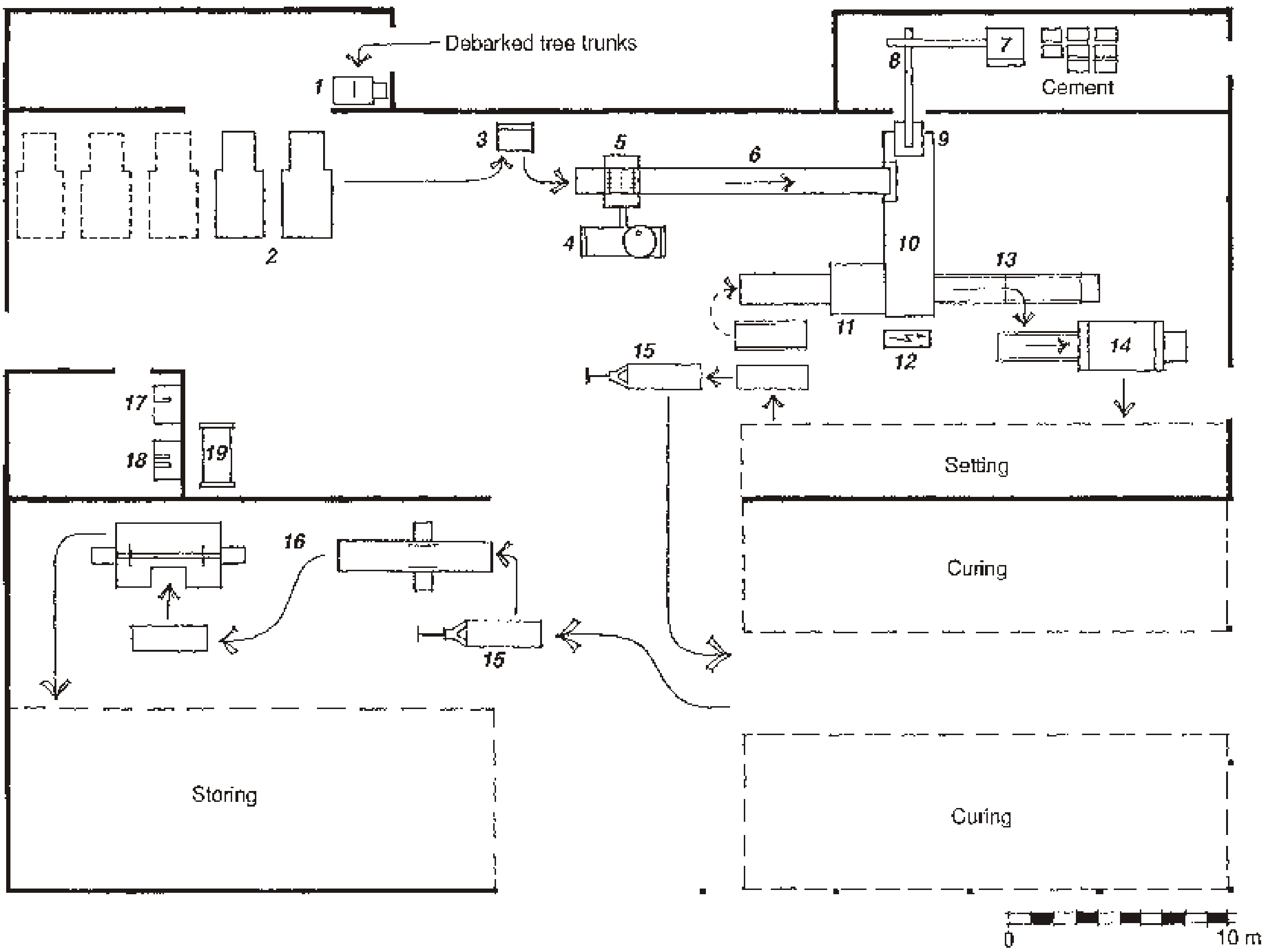


Fig. 21 Design for a semi-automated plant.
(Detailed proposals for plants with different degrees of automation are available from Elten Systems, the Netherlands.)

Item	Number	Code	Cost (US$)
Scales for woodwool	1	*3*	10,000
Salt solution preparation unit	1	*4*	20,000
Woodwool conveyor	1	*6*	28,000
Roller conveyor	1	*13*	6,000
Edge trimming station	1	*16*	47,000

Table 4 Equipment that might be purchased locally. Approximate cost 1 Dec. 1994 according to Elten Systems if the equipment is imported.

Moulds

It is recommended that the moulds have bottoms of water-resistant plywood and sides of wood strips, see Fig. 22. The plywood should be about 20 mm thick and preferably be surface treated with phenolic resin. The edge strips should be about 50 mm wide. The recommended inside dimensions for the moulds is 2 – 3 m long, 500 – 600 mm wide, and 15 – 150 mm high.

The number of moulds needed depends on the production volume and the thickness(es). With a daily production of 32 m^3, if the slabs are 50 mm thick and 1 m^2 in area (for example 500 × 2,000 mm), the theoretical number of moulds needed is 640. However, there should always be some spare moulds, and one should have about twice as many, that is 1,300. A mould should last about five years with good care and maintenance.

Staff

For production 22 labourers (see Table 5), a supervisor and a maintenance engineer are needed, which makes a total of 24 production staff. There are also administrators, sales and marketing staff, etc.

Tasks	No. of workers
Slab production	
Debarking tree trunks, sawing into logs, shredding and transport of woodwool to scales.	3
Weighing woodwool and loading the immersion tank	1
Preparation of accelerator solution, filling cement, cleaning, oiling, etc.	2
Filling and spreading the mixture in the moulds	4
Transport of filled moulds with a manual fork-lift	1
Stacking the moulds, compression in the hydraulic press	2
Stripping the set slabs from the moulds	2
Transport of the stripped slabs and trimming the edges	3
Stacking the slabs on pallets	2
Delivery	
Transport with manual forklift	1
Maintenance	
Maintenance of machines, sharpening the shredder knives and saw blades	1
Total	22

Table 5 Labour needed for production.

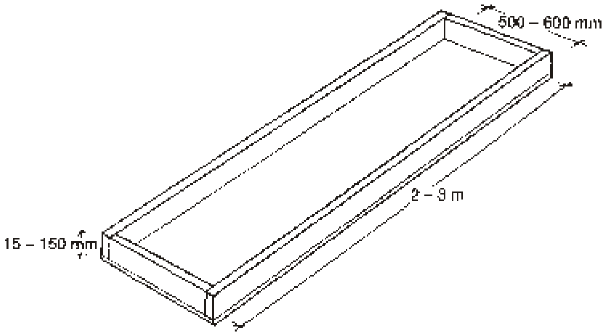


Fig. 22 The moulds are normally made with a plywood bottom and wooden strips on the sides.

Setting up the plant

Before starting production, the equipment must be set up and tested. Mechanical and electrical installations are supervised by qualified professionals with help of the future labourers. Installations can take 1.5 – 2 months.

Each machine must be tested after installation. When all machines work well, the plant starts pilot production, while the staff is trained by experts. This training takes 2 – 3 weeks.

Consumption of raw materials and energy

Raw materials

Production capacity is usually governed by the number of shredders. With a normal thickness of woodwool (about 0.3 mm) each shredder has a capacity of 300 – 400 kg of woodwool per hour.

The production method described here makes slabs with a density of 250 kg/m^3 or more. With an air-dry density of 400 kg/m^3, about 32 m^3 of woodwool slabs can be made during an 8 hour shift (7 hours effective work). This gives a year's production of 7,700 m^3 (reckoning 240 work days per year).

To produce 8,000 m^3 of woodwool slabs per year requires about 2,000 m^3 wood. An annual felling of this volume of wood requires a plantation of an estimated 200 – 500 hectares.

It is important that production of woodwool slabs does not lead to deforestation. The wood must be taken from well-managed forests and plantations, with continuous replanting.

Industries using wood do not necessarily lead to a decrease in forests. On the contrary, commercial forestry can promote wood plantation, if replanting is seen to pay.

The maximum capacity of a plant is thus 23,000 m^3 (with 3-shift production). To increase production capacity per shift requires more shredders and moulds. (Proposals for larger plants than that described here can be obtained from Elten Systems, the Netherlands.)

The ratio between woodwool, cement and water (including accelerator) is about 1:2:1. For slabs with a air-dry density of 400 kg/m^3, the wet density is about 470 kg/m^3. An annual production of 7,700 m^3 requires the following raw materials.

Wood	1,000 metric tons	(including wastage)
Cement	1,875 metric tons	
Water	1,100 metric tons	(including general use)
Accelerator[1]	18 metric tons	

1 The accelerator can be calcium chloride or any other accelerating salt. A solution of 2% is assumed. However, the amount of accelerator depends on the type of wood.

Note there are several advantages in making slabs with a density lower than 400 kg/m^3: thermal conductivity decreases (see Fig. 23), the slabs are easier to handle (lighter) and the production volume is greater for the same amount of raw materials.
A lower density however means that strength decreases. This makes no difference in most applications. Lower density however requires good quality woodwool, which must be elastic and strong.

If slabs are made with a density of 300 instead of 400 kg/m^3, thermal conductivity improves from about 0.085 to about 0.072 W/mK, and the volume of production increases about 30% for the same amount of raw materials.

Energy consumption

The equipment recommended requires a total of about 75 kW. The most demanding machine is the shredder which draws about 20 – 30 kW depending on the brand. Energy consumption for the plant with one shift per day is about 75,000 kWh per year (240 work days and a load factor of about 60%).

Production costs

Estimated production cost

An example is given of the calculation of production costs for 1 m^3 of woodwool slab with an air-dry density of 400 kg/m^3. The calculation is done for the plant recommended in this chapter and assumes one work shift per day, equivalent to an annual production volume of 7,700 m^3. The current prices for imported equipment were used. Other prices and costs, which vary greatly between countries, were estimated in this example. The calculation is set up so that the correct values can easily be put in.

The calculation is done for the first year of production. Over time bank interest will go down, but the cost for maintenance will go up. Therefore it is not expected that the total production costs will change very much. Possible import taxes on the equipment are not in-cluded in the calculation. It is assumed that there is continuous production, that is the demand is rather constant and there are no big technical problems.

The calculated production cost for 1 m^3 woodwool slab is 52 US dollars (see Table 6). If 50 mm thick slabs are produced, the cost per m^2 is 2.6 US dollars.

Calculations

Cost of raw materials[1] (in US dollars)

	Quantity	Unit price	Total annual cost
Cement	1,875 tonnes	50	94,000
Wood	1,000 tonnes	25	25,000
Water	1,100 tonnes	1	1,000
Calcium chloride	18 tonnes	100	2,000
Sum			122,000

1 Including transport

Cost of consumables (in US dollars)

	Quantity	Unit price	Total annual cost
Moulds	1,300 pcs	50	13,000[1]
Other			2,000
Sum			15,000

1 With an expected lifetime of 5 years

Salaries (in US dollars)

	Number	Cost/person[1]	Total annual cost
Engineer	1	8,000	8,000
Supervisor	1	6,000	6,000
Labourers	22	4,000	88,000
Sum			102,000

1 Annual salary including insurance, employers tax, etc.

Energy cost (in US dollars)

	Quantity	Unit price	Total annual cost
Machines	75,000 kWh	0.04	3,000
Other	25,000 kWh	0.04	1,000
Sum			4,000

Capital costs for equipment (in US dollars)

	Investment cost
Imported equipment	450,000
Transport (6%)	30,000
Other equipment	160,000
Total	640,000

		Total annual cost
Amortization	640,000 / 15 years	43,000
Interest	640,000 × 10%	64,000
Sum		107,000

Note that if second hand or locally produced equipment are used as much as possible, investment costs will be significantly lower.

Capital costs for plant and site (in US dollars)

	Investment cost
Plant building	300,000
Site (8,000 m^2)	50,000
Total	350,000

		Total annual cost
Amortization	350,000 / 30 years	12,000
Interest	350,000 × 10%	35,000
Sum		47,000

Type of cost	Cost/m^3 (US$)
Raw materials	16
Consumables	2
Salaries	13
Energy	1
Capital costs for equipment	14
Capital costs for plant and site	6
Total production costs	52

Table 6 Estimated total production costs during the first year (in US dollars) for 1 m^3 woodwool slab with an air-dry density of 400 kg/m^3 with an annual production of 7,700 m^3.

Note that if the slabs are made with a density of 300 instead of 400 kg/m^3 (which means production increases from 7,700 till 10,000 m^3/year), the calculated production cost decreases from US dollars 52 to 40 per m^3 (a decrease of 23%).

Note also that if the interest rate is 5% instead of 10% the calculated production cost drops from US dollars 52 to 46 (a decrease of 12%).

Comparison with other materials

The actual cost for the material will be significantly greater than the estimated production cost. Overhead costs include costs for management, administration, sales and marketing, taxes, profit, etc. When the production starts for the first time, there are also costs for installation, training and the pilot production.

It is difficult to compare prices of woodwool slabs and other building materials since the prices vary greatly between countries. In general woodwool slabs are somewhat more expensive per m^2 than thermal insulation materials such as mineral wool and cellular plastic to give equal thermal insulation.

Compared to traditional construction using, for example, hollow blocks, building components containing woodwool slabs are often cheaper. This is because construction is faster with the material, and it combines good thermal insulation capacity with high strength.

4 Choice of wood

This chapter deals only with cement-bonded slabs, but the procedures to choose a suitable wood are the same for magnesite-bonded slabs.

Technical requirements for the wood

Ease of shredding

The wood must allow shredding at a reasonable cost. This means it should not be too hard and/or contain much silica, which causes excessive wear on the knives. Woods with an air-dry density over 750 kg/m^3 are not normally suitable. The most suitable species have few branches and trunks that grow relatively straight.

> Wood species that give long, strong and elastic strands are best to achieve good thermal insulation capacity. This type of woodwool allows production of slabs with low density and sufficient bending strength. On the other hand if the woodwool easily breaks into short strands, it is difficult maintain both low density and good bending strength in the slabs.

The diameter of the tree trunk should normally be greater than 100 mm and less than 400 mm. (There are also special shredding machines that handle diameters under 100 mm).

The wood's effect on setting

Cement-bonded woodwool slabs consist of organic woodwool enclosed in inorganic cement paste (Portland cement and water). Like all cellulose materials, wood to greater or lesser extent inhibits the setting of the cement. This is caused by wood sugars and other compounds that leach out of the wood in contact with the cement paste. If the species of wood prevents setting, or delays it too much, the wood is not suitable.

Availability of the wood

If a wood species is to be considered suitable for production of woodwool slabs, it is not enough that the technical requirements are met. It is also important that the wood is available in adequate quantity and at a reasonable price. The proximity to the source of wood is important, since transport costs would otherwise be high. Quick growing species are often preferable, since these woods are normally the cheapest.

An annual production of 8,000 m^3 woodwool slabs, as assumed in Chapter 3, requires a plantation of about 200 – 500 hectares, assuming it is well maintained and replanted after felling. The precise area depends on how quickly the species grows.

> Tree species with little commercial value might be used in woodwool slabs. Quick growing species, such as pulpwood, that are not appropriate for furniture, etc. are often suitable.

Improving the compatibility of the wood with cement

Air-drying (seasoning)

Air drying lowers the content of sugars and other compounds that inhibit setting, and normally takes 3 – 6 months.

Addition of an accelerator

The inhibition of the cement setting by the wood can be compensated by the use of an accelerator. Dissolved in water, these are often called "mineralizing fluids." They work by making the slab set before the "cement poisons" in the wood have time to diffuse into the cement paste.

The most common accelerator is calcium chloride ($CaCl_2$). Other possible accelerators are magnesium chloride ($MgCl_2$), water-glass (sodium silicate, Na_2SiO_3, or potassium silicate, K_2SiO_3), aluminium sulphate ($Al_2(SO_4)_3$) and lime water. The accelerator is usually added to the water bath that the woodwool is soaked in before it is mixed with the cement. The normal concentration is between 1 – 5% by weight of the water in the mix.

There are several reasons to keep the amount of accelerator low. One is production costs, especially if the accelerator is expensive or must be imported. If the slab contains chloride, which it will if calcium chloride or magnesium chloride was used as accelerator, there is a clear risk of corrosion and galvanized nails and screws must be used.

Rapid-hardening cement

The amount of accelerator can be reduced – perhaps none is needed at all – by using rapid-hardening (quick setting) Portland cement. It is more finely ground than ordinary cement and thus more expensive.

Leaching

Another, often economical, way to improve the compatibility of the wood with cement is leaching. This is done by pre-soaking the woodwool in water for 24 hours (possibly 48 hours with a change of water after the first day). Sometimes the woodwool is soaked for some period in hot water or in solution of calcium chloride, water-glass or sodium hydroxide (NaOH).

Tests of suitability

Full-scale tests

The only way to be sure that a wood species is suitable for woodwool slabs is to produce test slabs on full scale. Such a test requires access to a woodwool shredder.
If this is not available, logs can be sent away for shredding, and the woodwool shipped back. It might be possible to conduct tests at the closest woodwool slab factory, which gives one access to the factory's practical experience, which can be very valuable. Full-scale tests can also be conducted by Elten Systems, the Netherlands.

Observe how the wood shreds. The wood should be easy to shred so that the knives do not wear out too fast.

(Normally the knives should last for eight hours production before they need sharpening.)

The slabs themselves can be made by hand. The ratio of woodwool : cement : water should be 1:2:1. First soak the woodwool in water (perhaps with an accelerator), then sprinkle on the cement. (Alternatively the dry woodwool can be put into a cement slurry.) Mixing can be done with a pitchfork in a trough or in a cement mixer. The mix is packed into a mould of appropriate size, such as 50 × 500 × 1,000 mm.

The main aim of making test slabs is to see if the slabs hold together and how long time they take to set before they can be stripped from the mould. If the test slab sets satisfactorily, in a reasonable time, one can examine its bending strength and compression strength. For these, and other tests, see Chapter 6 *Quality control*.

A large number of wood species have already been tested by production of full-scale slabs. They are listed in Appendix (Table A1).

Screening tests

There are several small-scale tests to determine the suitability of a wood. **Note that it is not possible to establish suitability with these tests; they only help eliminate completely unsuitable woods**.

A rather good method is to make small test slabs with woodwool, cement and water (perhaps containing accelerator). This gives an impression of the shredding quality of the wood, and if the slabs set satisfactorily. If these tests are promising, then full-scale tests are done and the slabs are tested for strength. Woods tested by this method are shown in Appendix (Table A2).

There are other more or less simple screening tests, but since they are not reliable they are not described here.

5 Properties

Thermal properties

Thermal conductivity

The thermal conductivity of woodwool slabs is mainly a function of their density and moisture content; it increases as density and/or moisture content increases. Fig. 23 shows thermal conductivity in practice as a function of air-dry density. (Thermal conductivity for oven-dry material is significantly lower.) Table 7 compares the thermal conductivity of a woodwool slab, with 400 kg/m^3 density, with other materials.

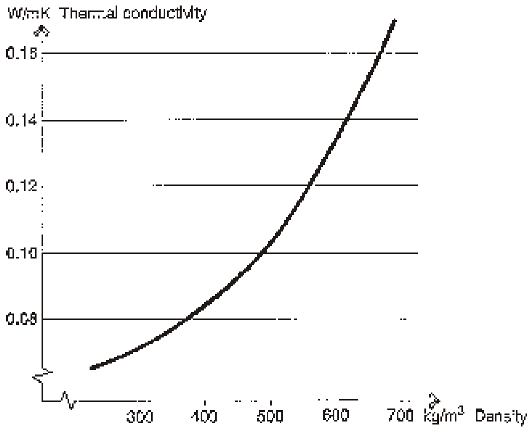


Fig. 23 Approximate values for the thermal conductivity (λ) as a function of air-dry density for woodwool slabs (moisture content 8 – 10%). (Sources: Information from different manufacturers and Cammerer (1962): Der Wärme- und Kälteschutz in der Industrie).

Woodwool slabs allow air to pass easily, which could increase the thermal conductivity by forced convection when the material is left unplastered (acoustic applications as in Fig. 44). Studies show however that if one side of the slab is sealed, normal values for thermal conductivity apply as well to this kind of construction.

Thermal capacity

Woodwool slabs have a high specific thermal capacity (about 1,600 J/kgK at 10% moisture content). The relatively high thermal capacity of roofs and walls constructed with woodwool slabs can significantly improve indoor comfort, since indoor temperature changes are attenuated, when there are large diurnal variations in outdoor temperature.

The thermal capacity of woodwool slabs is compared with other materials in Table 7.

Strength

The standards for strength according to DIN[4] 1101 for cement and magnesite-bonded woodwool slabs are given in Table 8. The minimum values according to DIN are low; modern industrially produced woodwool slabs might have several times the strengths shown.

4 Deutsches Institut für Normung ("German standards institution").

The strength of woodwool slabs, especially if they are cement-bonded, is insignificantly affected by high relative humidity.

Bending strength

The bending strength of a slab is high relative to its weight, because the two components – woodwool and binder – complement each other: the wood strands take the tensile stress, while the hardened cement paste (or magnesia cement) takes most of the compressive stress. The tensile strength of the wood strands is crucial to the slab's bending strength.

Bending strength increases with density. Normally thin slabs are made with higher density than thick slabs to give adequate bending strength.

Load bearing capacity can be increased significantly by reinforcing the slabs. Steel channels or wooden poles or bars can be used, see Fig. 4. These slabs can have a bending moment capacity of over 2 kNm and are about 4 times stronger than an ordinary slab of the same thickness.

Compressive strength

Woodwool slabs have a relatively high compressive strength that, as bending strength, increases with density. The compressive strength perpendicular to the plane of the slab is expressed as compressive stress at 10% compression (see Table 8). Compressive strength of woodwool slabs is compared with other materials in Table 7.

Material	Density (kg/m³)	Thermal conductivity[1] (W/mK)	Volumetric thermal capacity (J/m³K)	Compressive strength (MPa)
Woodwool slab	400	0.085	640×10^3	0.2 – 1.0[2]
Autoclaved aerated concrete	400	0.10	420×10^3	1.7
Glass wool	50	0.036	44×10^3	0.01
Expanded polystyrene	30	0.036	36×10^3	0.1
Hollow brick	800	0.47	700×10^3	–

1 Values in practice.
2 At 10% compression.

Table 7 Comparison of properties for some insulation materials and hollow brick. Note the high thermal conductivity for hollow brick and the low thermal capacity for mineral wool and expanded polystyrene.

Thickness (mm)	Weight[1] (kg/m²)	Density[1] (kg/m³)	Bending strength[2] (MPa)	Compressive strength[2 3] (MPa)
15	8.5	570	1.7	0.20
25	11.5	460	1.0	0.20
50	19.5	390	0.5	0.15
75	28.0	370	0.4	0.15
100	36.0	360	0.4	0.15

1 Maximum value.
2 Minimum value.
3 At 10% compression.

Table 8 Standards for weight and strength of woodwool slabs for different thicknesses according to DIN 1101.

Acoustic properties

Sound absorption

Woodwool slabs have good sound absorption, which makes them suitable for all kinds of public gathering places, industries, etc.

The sound absorption normally increases somewhat with increased thickness, especially for low frequencies. Sound absorption is also affected by proximity to other materials, while painting the slabs has only slight effect.

Fig. 24 shows sound absorption at different frequencies both for a free-standing slab, such as a suspended slab, and for a slab next to a hard material, such as a woodwool slab against cast concrete.

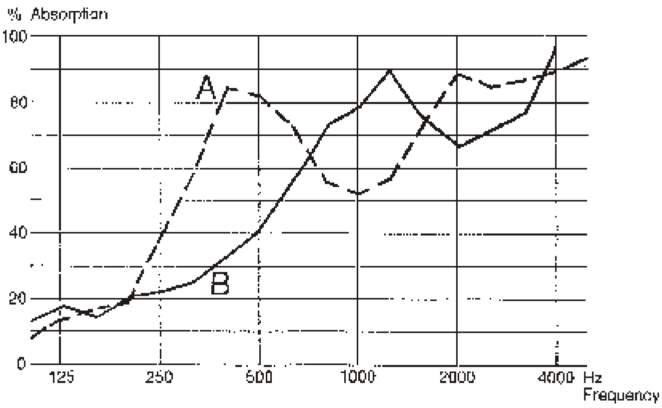


Fig. 24 Sound absorption at different frequencies for a 50 mm thick woodwool slab. Curve A is the slab with at least 50 mm clear space over. Curve B is the slab lying against a hard material. (Source: Anon. 1985).

Sound insulation

A woodwool slab itself gives very moderate sound insulation, but if it is plastered on one side, the sound insulation properties are good (sound reduction of about 30 dB). If a plastered woodwool slab is part of a heavy wall, made of brick or concrete for example, sound insulation is very good; (sound reduction is 35 – 55 dB depending on the weight of the wall). Good sound insulation can also be achieved with a wall made of two plastered woodwool slabs with an air cavity (sound reduction of about 50 dB).

Fire performance

In spite of the wood content, woodwool slabs have good resistance to fire. The material is classed as hard to ignite, and is therefore approved for indoor surfaces according to international standards. A 50 mm thick slab resists fire for 1 hour and a 100 mm thick slab for 2 hours.

The good fire performance of the material is related to the fact that the wood strands are protected by the binder, as well as its thermal insulating capacity and coarse structure. If the material is covered with a layer of cement or gypsum plaster, fire resistance increases further.

Moisture properties

Woodwool slabs have the ability to absorb large amounts of moisture. If the relative humidity in the air exceeds 95%, the moisture content of the slab is more than 20%. (When dipped in water until saturation, the moisture content is about 30%.) Because of their capac-ity to absorb moisture, woodwool slabs are suitable where the relative humidity is occasionally very high, for example in sports halls. The slabs attenuate the variations in the indoor air humidity, by absorbing moisture rapidly when there is a moisture input (when the relative humidity rises) and releasing this moisture when the relative humidity decreases. Most thermal insulation materials lack this ability. Fig. 25 compares the ability of woodwool slab with wood (pine), brick and mineral wool to absorb moisture.

When wet woodwool slabs dry to air-dry (about 50% relative humidity), shrinkage in length is about 3‰.

The vapour diffusivity of woodwool slabs (at 20°C) is about 10×10^{-6} m^2/s, whereas the vapour resistivity is about 20 MNs/gm.

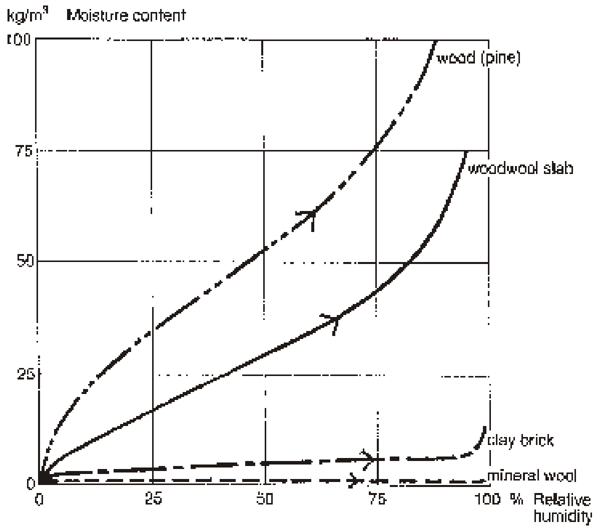


Fig. 25 The ability to absorb moisture. The moisture content (kg moisture per m^3 material) as a function of relative humidity for woodwool slab (density 400 kg/m^3), pine (500 kg/m^3), brick (1,700 kg/m^3) and mineral wool (20 kg/m^3). (These absorption isotherms *are valid at equilibrium at 20°C)*
(Source: Own measurements and Elmarsson and Nevander, 1981: Fukthandbok)

Durability

Resistance to rot and mould
Cement and magnesite-bonded woodwool slabs have surprisingly good resistance to rot and mould. This is because the binder creates a chemically basic environment that protects the wood strands (pH-value ≥9).

Woodwool slabs have been in use for over 80 years, and the experiences of all areas of application are uniformly good. Rendered slabs have sat on facades exposed to heavy rains for over 50 years without rotting or moulding. Experience from swimming halls, where the relative humidity can be over 80%, is also very good. The material has been buried in the ground for 30 years and kept under water for 10 years without destruction.

Mould resistance is an important quality for healthy buildings. Where moisture is high, mould is common on untreated wood and on wooden boards that are *not cement-based*.

Resistance to insects and termites
Because the wood strands are covered by binder, resistance to insects and termites increases significantly. Some studies show however that both cement and magnesite-bonded woodwool slabs might be attacked by termites (see Kumar 1980).

The results are very good in practice. Woodwool slabs have been used at least since the 1960s in countries with severe termite problems, without any reports of termite attack on the slabs.

For safety reasons the risk of termites must however be considered, if the slabs have an active function in the loadbearing construction.

Plastering the slabs will further reduce the risk of termite attack.

Resistance to an aggressive environment
Woodwool slabs have good resistance to aggressive air. The material resists sulphur in the air and has been very successfully used in swimming halls where the air often contains chlorine and chrome. Woodwool slabs in factories where aggressive chemicals are used have not deteriorated.

Emission of harmful compounds

Woodwool slabs have little emissions. Unlike glued wood-based boards, such as plywood and chipboard, the material does not release formaldehyde. The total amount of volatile organic compounds (TVOC) released by a cement-bonded slab was measured at less than 11 μg/m^2h, which is very low (Tests by Swedish National Testing and Research Institute).

6 Quality control

The suggestions in this chapter are largely based on the German standards for woodwool slabs, DIN 1101, but local standards may be established.

Conditions of testing
The tests should be carried out on five randomly selected slabs of each product produced. Before testing, the slabs should be conditioned for at least two weeks under as constant room temperature and humidity as possible.

Size and density

Size
Requirement. The slab is measured and the following variations are allowed: length ±10 mm, width ± 5 mm, thickness ± 3 mm.

Method. Use a steel measuring tape. Measure the length of each slab in three places and the width in four places. Measure the thickness of the slab with callipers in 10 places. The average of the measurements for each dimension should fall within the range specified.

Density
Requirement. A standard for the *highest* density should be established for each type of slab made. See for example Table 8, which gives the DIN standards. The average of the five slabs must be equal to or lower than the chosen standard. The density of an individual slab may not exceed this standard by more than 15%.

Method. Five slabs of the same type, whose dimensions are determined as described above, are each weighed on scales with an accuracy of ± 0.5 kg. The density of each slab is calculated.

Strength

Bending strength
Requirement. A standard for the *lowest* acceptable bending strength should be established for each type of slab made. See for example Table 8, which gives the DIN standards. The average value for the bending strength of the five slabs must not fall below the chosen standard. The bending strength of an individual slab may not be more than 10% below this standard.

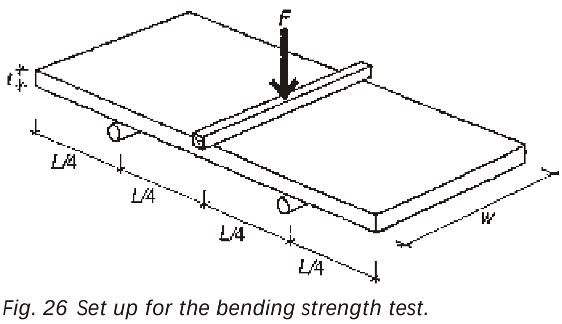


Fig. 26 Set up for the bending strength test.

Method. Five slabs of the same type are tested in a hydraulic press (or the equivalent). Each slab is placed on two supports (preferably rollers) that are at least as wide as the slab (Fig. 26). The slab is placed so that the supports are placed one quarter in from each short end (so that the weight of the slab itself does not affect the test). The slab is loaded with a linear load across its centre (parallel to the supports) as shown in Fig. 26. The load is gradually increased until the slab breaks. The bending strength (the modulus of rupture), σ_b (MPa), is calculated as follows:

$$\sigma_b = 0.75F \times L / (w \times t^2)$$

where F is the breaking load in Newtons (N); L, w and t are the length, width and thickness of the slab respectively (mm).

Compressive strength
Requirement. A standard for the lowest compressive strength (defined as the compressive stress at 10% compression) should be established for each type of slab produced. See for example Table 8, which gives the DIN standard. The average compressive strength of five specimens should not fall below the chosen standard. The compressive strength of an individual sample should not be more than 10% below this standard.

Method. From five slabs of the same type, saw square specimens with an edge L of, say, 200 mm. The specimens are tested in a hydraulic press (or the equivalent). Each specimen is placed between two rigid metal plates with the shorter side at least as long as the edge of the specimen. Each specimen is subjected to a load over its centre (Fig. 27). The specimen is first loaded with a force of 100 N to determine its initial thickness. The pressure is then increased steadily until the specimen is compressed to 90% of its initial thickness. Compressive strength, σ_c (MPa), is then calculated as follows:

$$\sigma_c = F / L^2$$

where F is the load (N) at 10% compression.

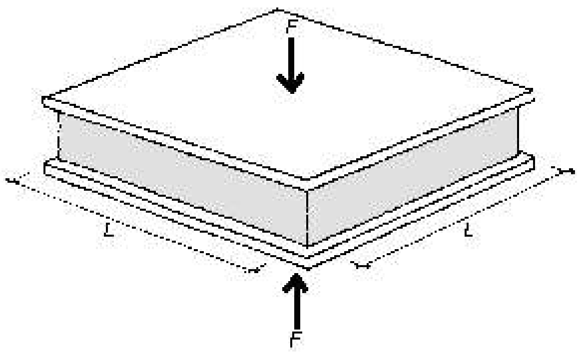


Fig. 27 Set up for the test of compressive strength.

Other tests

Thermal conductivity
Requirement. A standard for the *highest permitted* thermal conductivity should be established with respect to the density of the slab. The same standard can be used

for slabs of different thicknesses but with about the same density. (The DIN standard for slabs with thicknesses ≥ 25 mm is 0.090 W/mK.

Method. Thermal conductivity is closely tied to density (compare with Fig. 23), that is a test of density is an indirect test of thermal conductivity. However, if possible, at least one thermal conductivity test should be done per product in a laboratory. How to measure thermal conductivity is described in, among others, DIN 52 612 part 1 and 2, British Standard (BS) 874 and American Standard (ASTM) C 518. Since thermal conductivity is also related to the moisture in the material, the slabs should be conditioned to a defined moisture content before testing.

Acoustic properties

Slabs intended for sound absorption should, if possible, be tested to produce a profile of sound absorption at different frequencies (see Fig. 24).

The sound insulation properties of the slabs might be tested for the types of walls and roofs they are normally used for. Such tests are described in BS 2750 (sound reduction index).

Fire performance

Fire performance is related to the density of the slabs, that is if the slabs meet the density requirements, their fire performance is also known. If possible the fire performance of each product should be tested at least once. Tests of fire performance are described in, for example, DIN 4102 part 1, BS 476 part 1, 5, 6 and 7.

Chloride content

Requirement. According to DIN 1101 a woodwool slab may not contain more than 0.35% water soluble chlorides (measured in percent weight of the slab's oven-dry weight).

Method. The principle for the test is that chlorides are leached out by distillation and the content is determined by potentiometric titration. The method is described in DIN 1101.

Some national standards for woodwool slabs

Austrian	ÖNORM B6021
British	BS 1105
German	DIN 1101; requirements, testing 1102; application
Indian	IS:3308
Dutch	NBN 638
Swedish	SIS 238101

7 Applications

Exterior walls

Thermal insulation requirements

It is difficult to give a general standard for the thermal transmittance (U-value) of an exterior wall, since it depends on the local climate and on economic factors. Adamson and Åberg (1993) recommend a maximum U-value of 1.0 W/m^{2}K for walls of air conditioned houses in warm and humid climates. The types of walls described here follow this recommendation.

Walls built on site

★ The wall in Fig. 28 is made of elements containing a cavity. Each element consists of two woodwool slabs sandwiching spacer strips of woodwool slab. The spacer strips should be at least 50 mm thick. The parts are assembled with cement slurry. The slabs in the elements might stand vertically or horizontally. In the latter case the distance can be increased between the concrete columns, and each column can be cast in vertical stages.

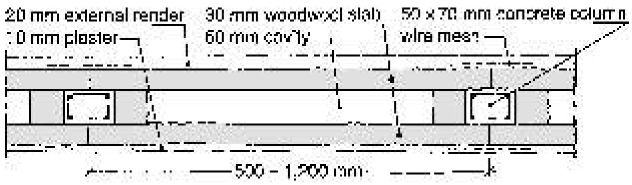


Fig. 28 Wall of vertical (or horizontal) elements consisting of two woodwool slabs sandwiching spacer strips of woodwool slab. The elements are joined by in-situ cast columns of reinforced concrete. (Using 30 mm thick woodwool slabs gives a U-value of 0.9 W/m^{2}K).

Advantages. The walls are light and fast to build. The cavity can be used for electrical cables. The wall has good vertical loadbearing capacity and is stable because of the good adhesion of the concrete columns to the elements. It has no significant thermal bridges and is safe in case of termites, since the load is carried by the concrete.

Disadvantages. Wall elements must be prefabricated, requiring an extra step in the work process.

Calculation of U-value for the wall in Fig. 28

	t (m)	λ (W/mK)	R (m^{2}K/W) = t / λ
External rendering	0.02	1.0	0.02
Woodwool slab	0.03	0.085	0.35
Cavity	0.05	—	0.17
Woodwool slab	0.03	0.085	0.35
Plastering	0.01	1.0	0.01
External + internal surfaces		—	0.17
Total	0.14		1.07

$U = 1/R_{total} = 0.93$ W/m^{2}K

The small decrease in the insulation capacity caused by the concrete columns is ignored in the calculation.

★ The wall in Fig. 29 consists of homogeneous slabs with the ends sawed into a V-shape. A square cavity is created when the slabs are placed next to each other, and reinforcement is placed in the cavity. Concrete of fluid consistency is poured in. The slabs can be placed vertically or horizontally. In the latter case the distance between the concrete columns is greater, and they can be cast in stages.

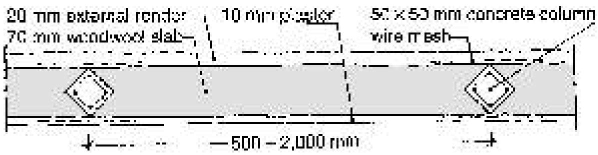


Fig. 29 Wall of vertical (or horizontal) woodwool slabs with V-shaped ends. The slabs are joined by columns of in-situ cast concrete. (Using 70 mm thick woodwool slabs gives a U-value of 1.0 W/m²K).

Advantages. The wall is thin and in spite of that has a low U-value (the U-value is 1.0 W/m²K for a total wall thickness of 100 mm). It has good vertical loadbearing capacity and is stable because of the good adhesion of the concrete to the slab. The wall is light and quick to build, and it is safe in case of termites since the load is carried by the concrete.

Disadvantages. The concrete columns go through the wall and function as thermal bridges, which raises the U-value somewhat.

> Materials with very high thermal conductivity, such as concrete and steel, should not be allowed to go through an outer wall or the roof if possible. They function as *thermal bridges* promoting thermal flow. Also, when it is colder outdoors than indoors, condensation can occur on these thermal bridges causing dirtying.

★ The wall in Fig. 30 consists of prefabricated, I-shaped concrete columns, with woodwool slabs placed horizontally between. The distance between the columns is the full length of the slab (2.4 m). This kind of wall is used in Zambia (see Hawkes and Cox 1992).

Advantages. The wall is thin and in spite of that has a low U-value (1.0 W/m²K for a thickness of 100 mm). It has good vertical loadbearing capacity, is extremely quick to build and is completely termite safe.

Disadvantages. The concrete columns function as thermal bridges and raise the U-value somewhat.

★ Fig. 31 shows a wall of slabs reinforced with galvanized steel channels, which carry the vertical load. This

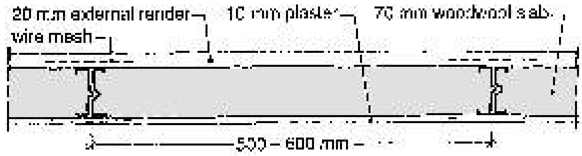


Fig. 31 Wall of vertical slabs reinforced by galvanized steel channels. (Using 70 mm thick woodwool slabs gives a U-value of 1.0 W/m²K).

kind of wall is used in Mexico, Venezuela and Panama, among other places.

Advantages. The wall is thin and in spite of that has a low U-value (1.0 W/m²K for a thickness of 100 mm). It has good vertical loadbearing capacity, is extremely quick and easy to build and safe in case of termites, since the load is carried by the steel channels.

Disadvantages. The steel channels form thermal bridges which raise the U-value of the wall.

★ Fig. 32 shows a wall of slabs reinforced by wooden poles to carry the vertical load.

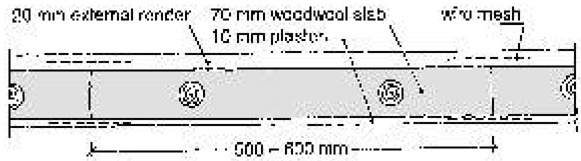


Fig. 32 Wall of vertical woodwool slabs reinforced by wooden poles. (Using 70 mm thick woodwool slabs gives a U-value of 1.0 W/m²K).

Advantages. The wall is thin and in spite of that has a low U-value (1.0 W/m²K for a thickness of 100 mm). It has good vertical loadbearing capacity. The wall has no thermal bridges and is very easy and quick to build.

Disadvantages. The wall is not safe in case of termites, since the load is carried by wood studs.

★ Fig. 33 shows a wall with woodwool slabs nailed on both sides of a wooden loadbearing structure.

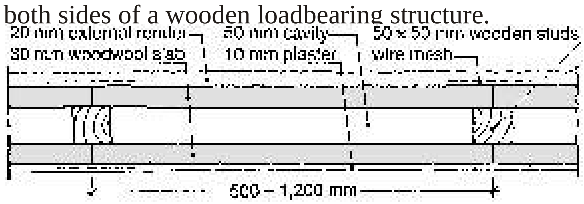
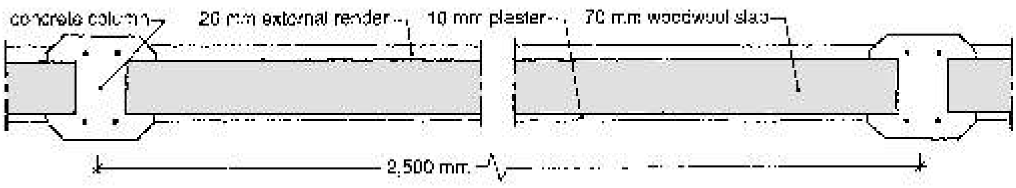


Fig. 33 Wall with a wooden loadbearing structure against which woodwool slabs are nailed on both sides. (Using 30 mm thick woodwool slabs gives a U-value of 0.9 W/m²K).

Advantages. The wall has good vertical loadbearing capacity and is quick and easy to build. The cavity can be used for electrical cables.

Disadvantages. The wall is not safe in case of termites, since the load is carried by wood studs.

Fig. 30 Wall of prefabricated, I-shaped concrete columns, with woodwool slabs placed horizontally between. The slabs are joined by mortar. (Using 70 mm thick woodwool slabs gives a U-value of 1.0 W/m²K).



If the accelerator used in making the woodwool slab contains chlorides, all nails and other metal fittings that come into contact with the slab should be hot-dip galvanized.

★ Fig. 34 shows a wall made of woodwool blocks. (The blocks are sawn from as thick a slab as possible, at least 70 mm). The blocks are laid to bond with lime cement mortar, with thin joints.

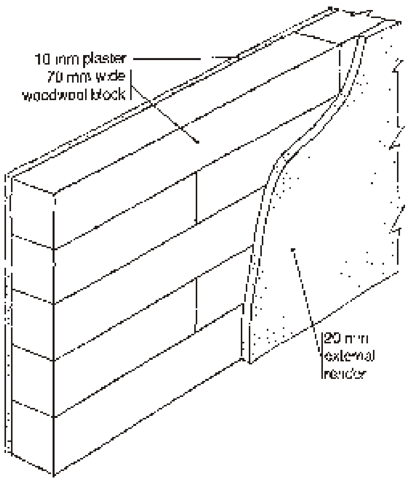


Fig. 34 Woodwool block masonry. (Using 70 mm wide woodwool blocks gives a U-value of 1.0 W/m^{2}K).

Advantages. A very quick and easy technique with great flexibility.

Disadvantages. The wall has limited vertical load-bearing capacity.

★ Fig. 35 shows a wall for a multi-storey building. The wall is made of reinforced concrete, cast in-situ between woodwool slabs which function as permanent shuttering.

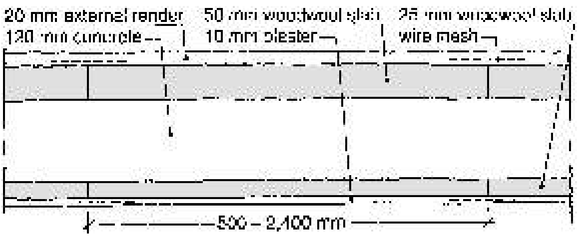


Fig. 35 Concrete wall for a multi-storey building where the woodwool slabs are used as permanent shuttering. (Using 25 and 50 mm thick woodwool slabs gives a U-value of 1.0 W/m^{2}K).

Advantages. Compared to an ordinary concrete wall, this saves the work of taking down the formwork and finishing the surface of the concrete. Electric cables and other installations can be cast in the concrete. The wall has no thermal bridges and is safe in case of termites.

Prefabricated wall elements

In Porto Alegre, Brazil, a building system is used for single-storey houses – the "Climatex system" – with both exterior and partition walls of prefabricated wall elements made of woodwool slabs and concrete. During production in the factory, slabs are placed in a mould and

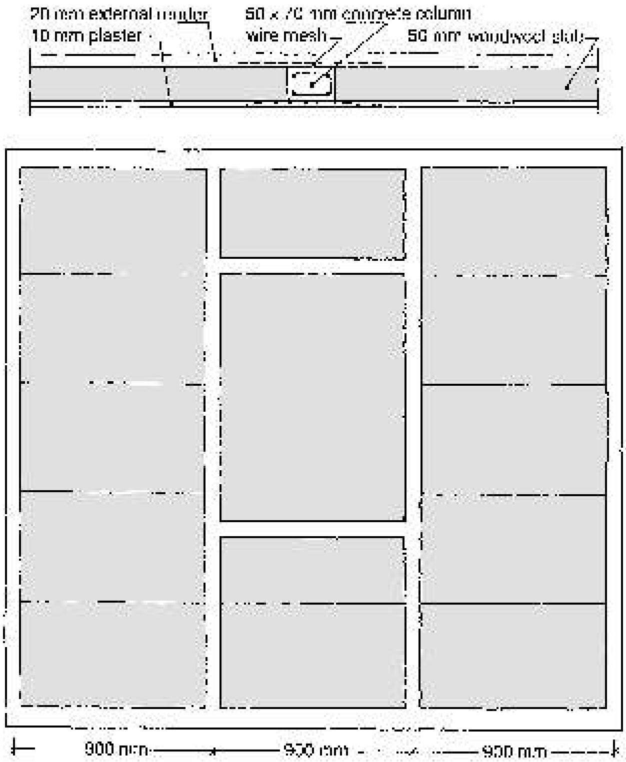


Fig. 36 Wall element in the "Climatex system" consisting of 50 mm thick woodwool slabs with columns and beams of reinforced concrete. The elements are rendered and plastered (U-value = 1.3 W/m^{2}K).

Fig. 37
Above: House in Porto Alegre, Brazil, built with the "Climatex system" (Fig. 36) with prefabricated wall elements of woodwool slabs and concrete.

Left: Interior showing plastered walls and a ceiling of gypsum coated woodwool slabs (see Fig. 5).

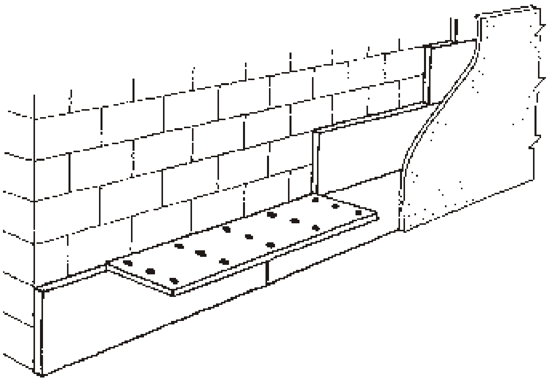


Fig. 38 Supplementary insulation on a masonry wall. The slabs are fixed by mortar.

reinforced concrete cast around them, leaving space for windows and doors (Fig. 36).

During assembly the elements are tied together with reinforcement bars sticking out from the elements (the joints between the elements are later covered with concrete). When all walls are up, they are rendered and plastered.

The wall elements are currently made of 50 mm thick woodwool slabs and have a U-value of about 1.3 W/m^{2}K. To reduce the U-value to a maximum of 1.0 W/m^{2}K, the thickness of the slabs must be increased to 70 mm.

Corrugated asbestos sheets have been the main roofing material together with a ceiling of 25 mm woodwool slab. Over 7,000 houses have been build with this system in southern Brazil since the 1970s. The houses are largely maintenance free and the residents are very pleased with them (Fig. 37). See also van Elten (1982).

Supplementary insulation

Woodwool slabs are very suitable for both external and internal supplementary insulation of walls. Against masonry (with or without rendering) or concrete walls, the material can be fixed with cement slurry, lime cement mortar or gypsum plaster (Fig. 38). The material can be nailed or screwed to wood walls.

Roofs and ceilings

Thermal insulation requirements

A roof should have at least as good insulation as the walls. In tropical climates, with high solar elevation and strong solar radiation, much of the heat transmission is through the roof, and here the roof should be better insulated than the walls. In air conditioned houses in tropical climates, Adamson and Åberg (1993) recommend a maximum U-value for the roof of 0.5 W/m^{2}K. Most of the roofs described here meet this recommendation.

Pitched roofs

A common use for woodwool slabs in pitched roofs is to nail them to the rafters as a base for the roofing material, such as roofing tiles, metal sheets, or similar (Figs 39A and 40). Before applying the roofing material the slabs are normally coated with a cement-sand screed.

The woodwool slabs can also be nailed to the ceiling joists (Fig. 39B).

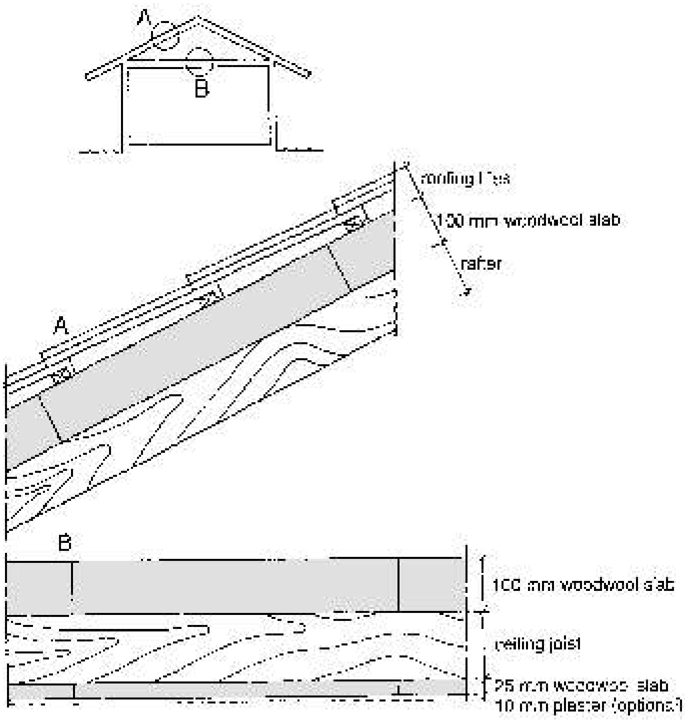


Fig. 39 Woodwool slabs used in pitched roofs.
A. Slabs nailed to the rafters as a base for the roofing material. (Using 100 mm thick woodwool slabs gives a U-value of 0.6 W/m^{2}K).
B. Slabs nailed to the ceiling joists. A thinner slab is used as a ceiling. (Using 100 and 25 mm thick woodwool slabs gives a U-value of 0.5 W/m^{2}K).

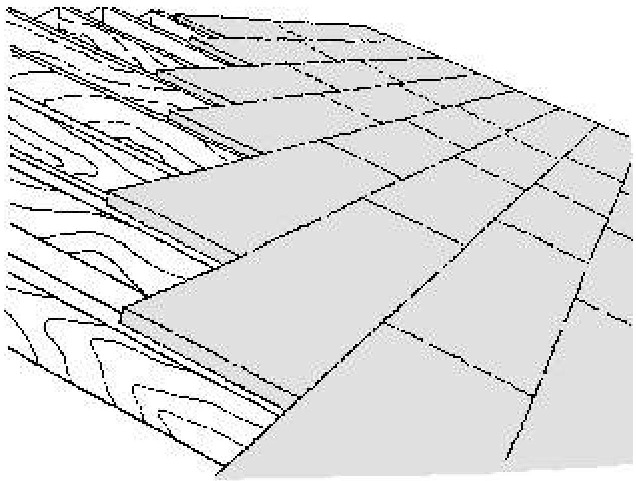


Fig. 40 Nailing woodwool slabs to the rafters on a pitched roof.

Reinforced slabs are often used in roof applications, because they are stronger than ordinary slabs and allow a greater distance between the supporting beams.

Flat roofs

The roof shown in Fig. 41 is a variant of a type of flat roof that is very common in many countries. It normally consists of prefabricated (often prestressed) concrete beams with hollow blocks (of either concrete or burnt clay) in between and is covered with a reinforced concrete slab cast in situ. By replacing the hollow blocks with woodwool slabs, and by increasing the distance between the beams, the U-value of the construction can be improved significantly.

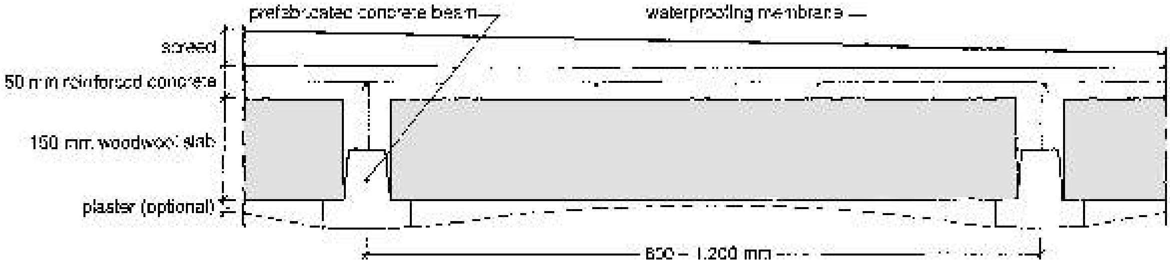


Fig. 41 Flat roof with woodwool slabs laid between prefabricated concrete beams. A slab of reinforced concrete is cast over the woodwool slabs and beams. The ceiling can either be left as it is, which give good sound absorption, or plastered.
(Using a 150 mm thick layer of woodwool slabs gives a U-value of 0.5 W/m²K).

★ The roof in Fig. 41 was used in two buildings in Tunisia (Fig. 44). The cost for the roofs was less than for a traditional roof using hollow blocks, even though the woodwool slabs were imported. The reason for the lower cost was mainly that it was quicker to build.

Advantages. The roof is very quick to build and needs no formwork, only posts. It has good thermal insulation (U = 0.5 W/m²K).

Disadvantages. The beams must be prefabricated and they function as thermal bridges.

★ Fig. 42 shows a variation of the roof in Fig. 41 using two layers of woodwool slabs. In this roof, entirely cast in-situ, the thermal bridges created by the concrete beams are broken by the underlying woodwool slab.

Advantages. The roof is quick to build. It requires no formwork when cast, only support consisting of beams and posts. It has no thermal bridges and excellent thermal insulation (U = 0.5 W/m2K).

Disadvantages. This roof requires more support when casting than the roof in Fig. 41.

Note that for the roofs in Figs 41 and 42 it is very important to calculate the shear reinforcement in the beams. This vertical reinforcement, which should be anchored in the concrete slab, increases with the distance between the beams.

Both roofs met the strict Algerian and Tunisian requirements for loadbearing capacity and deflection in full-scale laboratory tests (see Åstrand et al., 1994).

Ceilings
One of the most common uses for woodwool slabs is as acoustic ceiling panels in public gathering places, corridors, etc. The slabs can either be fixed to the roof (cast against concrete or screwed in as in Fig. 39B) or suspended (Fig. 43). The air space between the slabs and the roof influences the sound absorption somewhat (Fig. 24).

Surface finishes

Woodwool slabs provide and excellent base for rendering and plastering because of their coarse texture.

Reinforcement
Before applying render or plaster, all joints between slabs, or between slabs and another material (for example a concrete column), should be reinforced. This is done to avoid cracks in the material caused by movements in the woodwool slabs due to temperature and moisture changes. Reinforcement can be done with galvanized steel wire netting, preferably welded netting (chickenwire can be used, but because it is elastic, it does not pre-

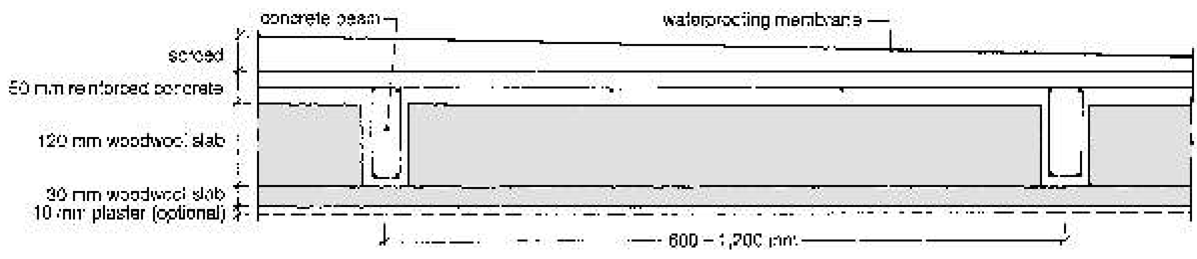


Fig. 42 Flat roof consisting of two layers of woodwool slabs. Space is left in the top layer for reinforced concrete beams. These beams and the concrete slab are cast at the same time. The under layer of woodwool slab breaks the thermal bridges created by the concrete beams. The ceiling can either be left as it is, which gives good sound absorption, or plastered. (Using 30 and 120 mm thick woodwool slabs gives a U-value of 0.5 W/m²K).

Fig. 43
Ceiling of suspended woodwool slabs.

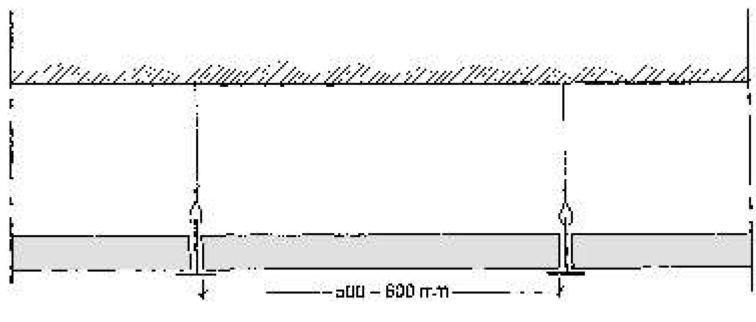


Fig. 44 The roof in Fig. 41 as built in the youth centre of Tameghza, Southern Tunisia. Woodwool slabs provide both thermal insulation and sound absorption.

vent small cracks). The net, which should cover at least 100 mm on each side of the joint, is fixed to the slab with hot-dip galvanized nails.

External rendering
The slabs should be neither too damp nor too dry at finishing. A dry slab, for example exposed to direct sunlight, can be dampened a little before finishing. A damp slab, for example one that has been in the rain, must dry before finishing.

The external rendering should be in two or three coats: spatterdash coat (a preparation of the base, maximum 2 mm, optional), undercoat (10 – 15 mm) and a finishing coat (paint or render 0 – 5 mm). The mortar of a previous coat should be stronger (contain more cement) or as strong as the mortar for the next coat. A suitable spatterdash coat is lime-cement mortar with a small amount of lime. A suitable material for the undercoat and the finishing coat is lime-cement mortar with equal parts (by weight) lime and cement, or with more lime than cement. (See also Anon. 1985 and Anon. 1990).

Internal plastering
Internal plastering should be done on air dry slabs. The plastering material can be cement mortar, lime-cement mortar or gypsum mortar. If a lime-cement mortar is used, a thin preparation of the base is preferable before the undercoat (10 – 15 mm) is applied. Plastering with gypsum mortar should be done in two or more coats starting with a thin undercoat.

> Vapour barriers are often recommended in air conditioned buildings to improve tightness and avoid moisture transport that could damage organic materials. Woodwool slabs are moisture resistant, so there is no need for a vapour barrier in these applications. Finished woodwool slabs meet the requirement for air tightness.

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1994 *Matériaux thermiquement isolants – béton mousse et panneaux en laine de bois*. Report 2. LCHS, Lund University, Sweden. (In French)

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Conversion factors

from SI units to British and US units

1 m	= 3.281 ft
1 mm	= 3.937×10^{-2} in
1 m²	= 10.76 ft²
1 hectare = 10,000 m²	= 2.471 acres
1 m³	= 35.31 ft³
1 kg	= 2.205 lb
1 tonnes = 1,000 kg	= 1.102 short tons = 0.984 long tons
1 kg/m³	= 6.243×10^{-2} pcf (lb/ft³)
1 N	= 0.2248 lb f
1 Nm	= 8.850 in lb f
1 MPa = 1 N/mm²	= 145.0 psi (lb f/in²)
1 J	= 9.485×10^{-4} Btu
1 kWh	= 3.414×10^{3} Btu
1 W = 1 J/s	= 3.414 Btu/hr
1 kW	= 1.341 hp
$T_K = T_{°C} + 273$	= $5/9 (T_{°F} - 32) + 273$
1 W/mK	= 6.938 Btu in/ft² hr °F
1 W/m²K	= 0.1762 Btu/ft² hr °F
1 J/kgK	= 2.390×10^{-4} Btu/lb °F

from SI units to CGS units

1 N	= 0.102 kp
1 MPa	= 10.2 kp/cm²
1 W/mK	= 0.860 kcal/m h°C
1 J/kgK	= 2.39×10^{-4} kcal/kg°C

Addresses

Manufacturers of equipment for woodwool slab production

Elten Systems
P.O. Box 15
NL-3770 AA BARNEVELD, The Netherlands

Manufacturers of wood shredding machines

MECCAT
Zona Industriale
Via Braille 5
I-391 00 BOLZANO, Italy

Some Manufacturers of woodwool slabs

Österreichische Heraklith AG
A-9702 FERNDORF, Austria
(Manufacturer of magnesite-bonded woodwool slabs. Factories in Austria, Germany and Greece)

S.A. DHENACLITE
35, rue Emile Claus
B-8798 SINT-ELOOIS-VIJVE, Belgium

Climatex Indústria de Madeira Mineralizada Ltda.
Caixa Postal 7054
91130-040 PORTO ALEGRE – RS, Brazil

FIBRALITH GIE
Zone Industrielle
F-68190 UNGERSHEIM, France

E. Schwenk Dämmtechnik GmbH & Co. KG
Isotexstraße 1
D-86899 LANDSBERG/LECH, Germany

Nederlandse Bouwplaten
en Isolatiematerialen Industrie BV
P.O. Box 375
NL-4900 AJ OOSTERHOUT, The Netherlands

Träolit AB
Box 20
S-570 60 ÖSTERBYMO, Sweden

Torvale Building Products
Pembridge
LEOMINSTER
Herefordshire HR6 9LA, United Kingdom

Organizations with information about woodwool slabs

Bundesverband der Leichtbauplattenindustrie e.V.
Beethovenstr. 8
D-80336 MÜNCHEN, Germany
(Trade association for the 14 woodwool slab manufacturers in Germany)

Forest Research Institute
P.O. New Forest
DEHRA DUN 248 006
Uttar Pradesh, India

Appendix

Botanical name	Suitability
*Abies pindrow**	s
Agathis borneensis Warb	n
Ailanthus malabarica DC.	n
Albizia falcataria	s
Albizia lebbek	s
Anisoptera costata Korth.	s
Anisoptera marginata Korth.	n
Anogeissus latifolia	n
*Araucaria araucaria**	s
Azadirachta indica	n
Bombax cieba	s
Bridelia retusa	s
Calophyllum inophyllum	s
Calophyllum soulatri Burn. f.	s
Cassia siamea	r
Cedrela toona	s
Cedrus deodara	s
Cinnamomum seylanicum	n
Cordia myxa	s
Cratoxylon sp. ("geronggang")*	s
Cunninghamia lanceolata Hook.	s
Dacryodes excelsa	s
Dalbergia sisoo	s
Dehassia caesia Bl.	s
Delonix regia	s
Dialium platysepalum Baker.	n
Diospyros macrophyla Bl.	s
Dipterocarpus sp. ("gurjan")	s
Dipterocarpus appendiculatus Scheff.	n
Dipterocarpus condiferus Merr.	n
Dipterocarpus costulatus V. Sl.	n
Dracontomelon dao Meer & Rolf.	n
Dracontomelon mangiferum Bl.	n
Drypetes longifolia Pax & Hoffm.	n
Durio zibethinus Merr.	r
Emblica officinalis	n
Eperus falcata	n
Eschweilera sp.	n
*Eucalyptus globulus**	s
Eucalyptus grandis	r
Ficus sp. ("gular")	s
Ficus sp. ("bar")	s
Ganua motleyana Pierre	n
Garcinia sp. ("manggis hutan")	n
Gonystilus brunescens A. Shaw.	n
Gossweilerodendron balsamiferum Harms.	s
Grevillea robusta	s
Haplolobus celebicus H.J.L.	s
Holoptelia integrifolia	n
Hopea dryobalanoides Miq.	s
Hymenodictyon excelsum	s
Irwingia malayana Olive	n
Koompasia excelsa Tamb.	n
Koompasia malacencis Maing	n
Koordersiodendron pinnatum Meer	s
Lannea coromandelica	n
Larix leptolepis	s
Licania laxiflora	n
Liquidambar styraciflua L.	n
Liriodendron tulipifera L.	s
Maesopsis eminii	n
Mangifera foetida Lour	n
Mangifera indica	s
Mangifera minor Bl.	n
Melanorhoea wallichii Hook.	n
Miristica lowiana King	n
Mora excelsa	n
Morus sp. ("shehtoot")	n
Octomeles sumatrana Miq.	n
Ougeinia oojeinensis	n
Palaquium ferox H.J.L.	n
Palaquium hexandrum Baill	n
Palaquium obovatum	s
Palaquium obtusifolium Burck	s
Palaquium rostratum Burck	n
Parastemon versteeghii Meer & Perry	n
Parinari corymbosa Miq.	n
Payena leerii Kurz	n
Pericopsis elata	n
*Picea abies**	s
*Picea smithiana**	s
*Pinaceae sp.**	s
Pinus sp. ("southern pine")*	s
Pinus caribaea	s
Pinus densiflora	s
*Pinus elliottii**	s
Pinus kesiya	s
Pinus khasya	s
Pinus mercusii	s
*Pinus nigra**	s
Pinus patula	s
*Pinus roxburghii**	s
*Pinus sylvestris**	s
Pinus taiwanensis Hay.	s
*Pinus wallichiana**	s
Polyathia hypoleuca HK. & TH	n
Populus deltoides	s
Populus tremula	s
Pterocarpus indica	n
Pterospermum celebicum Miq.	s
Quercus alba L.	n
Quercus falcata Michx.	n
Salmalia malabarica	s
Sandoricum indicum	n
Santiria laevigata Bl.	n
Shorea bracteolata Dyer	n
Shorea elliptica Burck.	n
Shorea gibbosa Brandis	n
Shorea gysbertsiana Burck.	s
Shorea hopeifolia Sym	n
Shorea koordersii Brandis	n
Shorea leprosula Miq.	n
Shorea ovalis Bl.	s
Shorea palembanica Miq.	s
Shorea pauciflora King.	s
Shorea pinanga Scheff.	n
Shorea sp. ("Meranti")	r
Simaruba amara	r
Spondias cytherea Sonn.	n
Swietenia macrophylla	n
Syzygium cumini	s
Tarrietia javanica Bl.	n
Tectona grandis	r
Terminalia spread	n
*Tetrameles nudiflora**	s
Toona ciliata	s
Tsuga chinensis Pritz.	r
Xylopia malayana HK. f. & TH	n

Table A1. Woods tested by production of full-scale slabs.
A wood is considered suitable if the slab meets the requirements for bending strength of DIN 1101 or an equivalent standard.
(Information from different sources. Information about other woods can be obtained from Elten Systems, the Netherlands.)

s suitable
n not suitable
r restrictive suitability
* This wood species is used commercially for woodwool slab production

Botanical name	Suitability
Afzelia bipindensis	n
Antiaris africana	n
Antrocaryon micraster	n
Berlinia grandiflora	s
Canarium schweinfurthii	r
Cedrela odorata	s
Ceiba pentandra	n
Celtis zenkeri	n
Chlorophora excelsa	n
Chrysophyllum africanum	s
Chrysophyllum albidum	s
Cola gigantea	r
Cylicodiscus gabunensis	s
Daniellia ogea	r
Distemonanthus benthamianus	n
Entandrophragma angolensis	s
Entandrophragma cylindricum	r
Entandrophragma utile	s
Eucalyptus camaldulensis	r
Eucalyptus gomphocephala	s
Guarea cedrata	n
Khaya sp. ("khaya, mahogany")	n
Lovoa trichilioides	s
Mansonia altissima	r
Mitragyna stipulosa	r
Musanga cecropioides	s
Nauclea diderrichii	n
Nesogordonia papaverifera	r
Ongokea gore	n
Piptadeniastrum africanum	n
Pterygota macrocarpa	n
Tarrietia utilis	r
Tectona grandis	r
Terminalia ivorensis	r
Terminalia superba	s
Tieghemella heckelii	n
Triplochiton scleroxylon	r

Table A2. Woods tested by production of small test slabs.
The wood is considered suitable if it can be shredded easily and if the slabs set satisfactorily. If these tests are promising, then full-scale tests are done and the slabs are tested for strength.
(Information from different sources.)

s suitable
n not suitable
r restrictive suitability