

Inorganic binder for wood composites: feasibility and limitations

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Abstract

Wood composites fabricated with inorganic binders of gypsum, portland cement, or magnesia cement may contain between 10 and 70 percent by weight of wood particles. The individual wood particles must be fully encased by the binder to attain acceptable board properties. The required quantity of inorganic binder is therefore much higher than that needed in bonding of composites with thermosetting resins. Strength of the composite is dependent on the interaction of the cement/wood ratio with the water/cement ratio.

The setting of inorganic binders is the result of a series of chemical reactions causing a succession of crystallization stages. Crystallization is inhibited to a varying degree by various woods and their extractives. The inhibiting effect can be reduced by aging the wood and counteracted to some degree with chemical additives.

Manufacturing methods are distinguished by the amount of water present in the furnish. Methods vary from the wet process where the mixture is a slurry, to the dry process where the moisture released from the wood particles during pressing makes up a portion of the necessary water of hydration. Hardening of portland cement particleboard, which occurs as a result of the hydration process, usually takes between 6 to 8 hours at ambient conditions. This necessitates long pressing or clamping periods. New

processes incorporating solid, liquid, or gaseous additives have been developed to promote the rapid curing of inorganic bonded boards. Raw material for the binder is in some cases obtained as a by-product of other processes, thus lowering the costs.

Worldwide expansion of inorganic bonded board markets depends not only on an increased need for building homes and the availability of materials, but on changes in established building practices and regulatory codes.

Introduction and general principles

Inorganic bonded wood composites are molded products or boards which contain between 10 and 70 percent by weight of wood particles or fibers and conversely 90 to 30 percent of inorganic binder. Acceptable properties of an inorganic bonded wood composite can only be obtained when the wood particles are fully encased with the binder to make a coherent material. This differs considerably from the technique used to manufacture thermosetting resin bonded boards where flakes or particles are "spot welded" by a binder applied as a finely distributed spray or powder. Because of this difference and because hardened inorganic binders have a higher density than most thermosetting resins, the required amount of inorganic binder per unit volume of composite material is much higher than resin-bonded wood composites. The properties of inorganic bonded wood composites are significantly influenced by the amount and nature of both the inorganic binder and the

woody material as well as the density of the composites.

Inorganic binders are either gypsum (plaster of paris), magnesia cement, portland cement, or a mixture of at least two of these compounds. Raw gypsum (calcium sulfate dihydrate, $\text{Ca}(\text{SO}_4)_2 \cdot 2\text{H}_2\text{O}$) is derived from natural sources or is obtained from the desulfurization of flue gases (desulfo gypsum), or as a byproduct in manufacturing or refining processes (phosphogypsum). Magnesia cement (MgO), also known as Sorel cement, is a two-component inorganic binder. The major and minor portions are caustic magnesia and a magnesium salt, respectively. Caustic magnesia (MgO) is obtained from magnesium carbonate, magnesium hydroxide, or dolomite. The major ingredients of portland cement, a complex mixture of compounds, are given in Table 1. Three of these, tricalcium silicate, dicalcium silicate, and tricalcium aluminate comprise 87 percent of the total weight.

All of the inorganic materials must be heated ("calcined") to make them suitable as a binder. Gypsum, dehydrated during calcination, is rehydrated during the binder curing process. Magnesia, obtained during the calcination process, "sets" when it is hydrated with a magnesium salt. The setting and hardening process of portland cement is shown schematically in Figure 1. The water in the furnish dissolves part of the binder component forming a saturated solution. Tricalcium silicate hydrolyzes and forms small amounts of calcium hydroxide. Calcium hydroxide crystallizes from the solution as hexagonal particles

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Table 1. - Principle components of portland cement.

Name	Chemical form	Percent
Tricalcium silicate	$3\text{CaO} \cdot \text{SiO}_2$	50
Dicalcium silicate	$2\text{CaO} \cdot \text{SiO}_2$	25
Tricalcium aluminate	$3\text{CaO} \cdot \text{Al}_2\text{O}_3$	12
Tetracalcium aluminoferrite	$4\text{CaO} \cdot \text{Al}_2\text{O}_3 \cdot \text{Fe}_2\text{O}_3$	8
Calcium sulfate dihydrate	$\text{CaSO}_4 \cdot 2\text{H}_2\text{O}$	3

(Fig. 1). Moreover, portions of the tricalcium aluminate and calcium sulfate (a minor but important ingredient

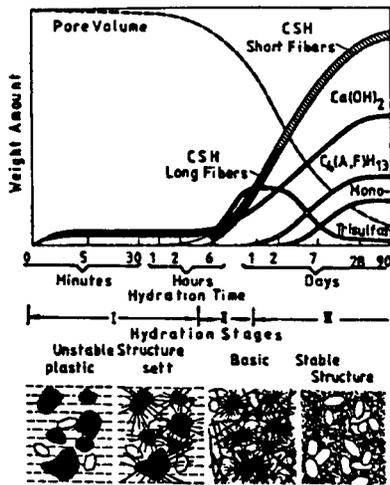


Figure 1.—Scheme of the hydration of cement (CSH = calcium silicate hydrate; trisulfate = $3CaO \cdot Al_2O_3 \cdot 3CaSO_4 \cdot 3H_2O$).

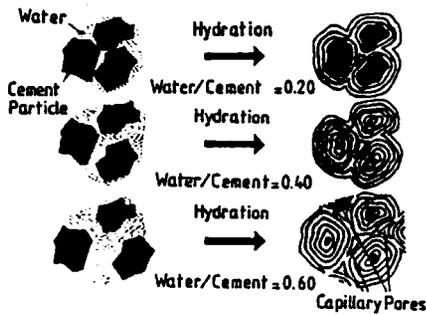


Figure 2.—Influence of water/cement ratio on the porosity of hardened cement

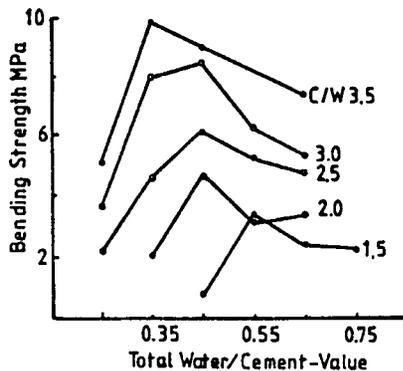


Figure 3. — Influence of the total water/cement ratio on the bending strength of cement-bonded particleboards. C/W = cement/wood ratio.

of portland cement) go into solution and form trisulfate or ettringite ($3CaO \cdot Al_2O_3 \cdot 3CaSO_4 \cdot 32H_2O$). These crystals are very small at first, but following hydration the trisulfate recrystallizes and forms longer needle-like crystals. Such crystals bridge the remaining cement particles during the second stage and give the slurry its initial stiffness. During the next 1 to 3 hours the paste becomes stiffer as the cement sets. The hardening process starts with the formation of long fiber-like crystals of calcium silicate hydrate. These crystals bridge the water-filled pores between the cement particles and provide the mixture with its initial strength. During the following or third hydration stage the pores are filled with small crystals of calcium silicate hydrate and calcium aluminate hydrate. The structure of the matrix becomes more dense until the ultimate strength properties are attained (8). Following the hardening process, which takes approximately 28 days, the excess water evaporates and leaves the pores.

The binders are applied as a powder or as a slurry. Water is required as a homogenizer during the mixing process, as a solvent during the hardening reactions, and also as a component in the chemical hydration process. Gypsum requires about 17 percent (by weight) of water for the hydration process.

Magnesia cement and portland cement require about 20 and 25 percent water of hydration, respectively. The weight of this chemically bonded water is added to the weight of the original binder when calculating the weight of the hardened inorganic binder. Moisture in the woody material can provide a portion of the water requirement, however, additional water must be added in order to obtain a homogeneous mixture. The influence of the ratio of water to binder (water/cement ratio) on the porosity of the cement is shown schematically in Figure 2. At a ratio of 0.2, the available water is insufficient for the hydration. On the other hand, at a ratio of 0.6 too much water is present and pores are left when the water evaporates. These pores reduce the strength properties of the board. The optimum water/cement ratio is approximately 0.4.

The influence of the total water/cement ratio on the bending strength of cement-bonded particleboards is shown in Figure 3. The optimum range for the water/cement ratio is dependent, in part, on the cement/wood ratio. As the cement/wood ratio decreases from 3.5 to 1.5, the optimum total water/cement ratio increases from 0.35 to 0.55. Table 2 lists the appropriate ratios of binder to wood for selected wood composites.

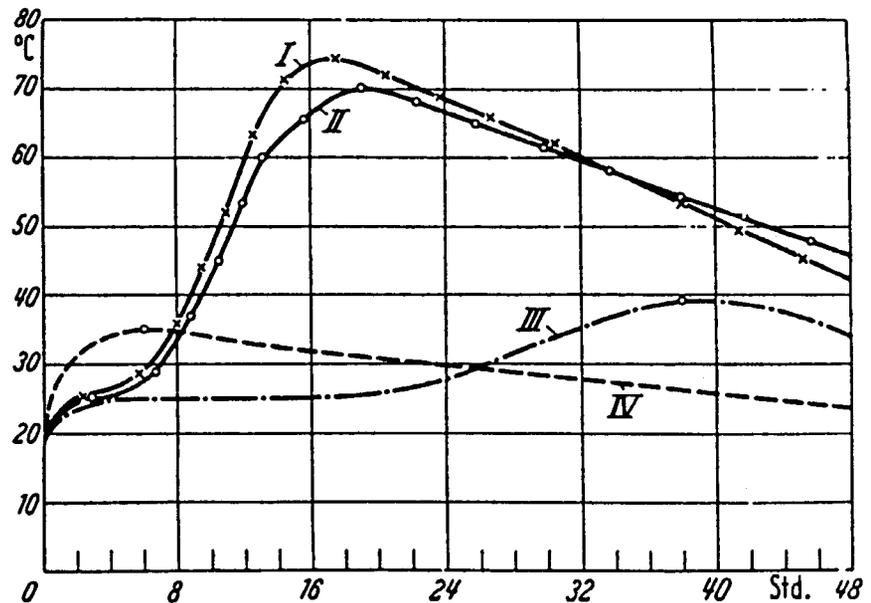


Figure 4. —Temperature rise due to hydration in portland cement paste mixed with wood particles: I = *Tetrameles nudiflora*; II = *Berlinia grandiflora*; III = *Acacia decurrens*; IV = *Chlorophora exelsa*.

Table 2. – Ratio of binder to wood in some wood composites and their technological properties.

Wood composites	Density (kg/m ³)	Bender/wood ratio	Bending strength (MPa)	IB (MPa)	Thickness swell ^a (%)	Linear expansion ^b (%)
Gypsum-bonded: particleboards	1,000 to 1,200	4	6 to 9	0.3 to 0.6	delam	0.05
fiberboards	1,000	5 to 6	4 to 7	0.3 to 0.5	delam	0.06
Magnesia-bonded: particleboards	900 to 1,250	1.5	7 to 14	0.4 to 0.6	4 to 8	0.25
fiberboards	700 to 1,100	5	8 to 10	--	--	0.10
Cement-bonded: wood wool boards	360 to 570	1.4	0.4 to 1.7	--	3.5	0.7
particleboards	1,000 to 1,350	2.9	6 to 15	0.4 to 0.6	1.2 to 1.8	0.1 to 0.4
fiberboards	1,350	10	21	0.8	0.25	0.15
Resin-bonded particleboards	500 to 800	0.08	17 to 21	1.0 to 1.4	15.0	0.35

^a 24-hour soak.

^b 30 to 90 percent relative humidity.

Compatibility of inorganic binders with wood

The woody material in the composite can act both as an aggregate and as a reinforcing material. In either case the interaction between the organic binder and the woody material is very important. Certain woods and their extractives retard the cure of inorganic binders. Since cement hydration is exothermic, it is possible to trace the reaction by monitoring temperature increase. The relative reaction rates for four different species bonded with portland cement are indicated in Figure 4. Inhibited reactions are characterized by a lower hydration temperature or by a longer hydration time. Species compatibility varies with the type of binder. Relative hydration times of gypsum, magnesia cement, and portland cement as affected by selected wood species and specific extractives are shown in Table 3. Portland cement is more sensitive to wood extractives than either gypsum or magnesia cement, i.e., in most cases the hydration times are the longest.

To obtain quantitative data about the bond between wood and inorganic binders, the shear strength is determined using the specimen shown in Figure 5. The binder is first mixed as a paste and is then cast in the mold. Air is dispelled by vibration. The shear strength properties of pure gypsum, portland cement, and various magnesia cement test samples are compared with the shear strength of samples containing spruce veneer in Figure 6. A shear strength of 100 percent is 4.5

Table 3. – Compatibility of some woods and wood extractives with various inorganic binders.

Wood or extractive	Relative hydration time		
	Plaster	Magnesia cement	Portland cement
	----- (%) -----		
Inorganic binder	100	100	100
Glucose 1%	120	120	inhibited
Hydrolyzable tannin 1%	1,124	163	inhibited
Spruce wood	133	135	135
Spruce bark	1%	128	inhibited
BeechWood	146	153	255
Birch wood	162	175	255
Oak heartwood	208	150	150

MPa, corresponding to that obtained for pure gypsum. Magnesia cement made with magnesium chloride has the highest relative shear strength, 380 percent, and magnesium sulfate cement has the lowest relative shear strength, approximately 50 percent. Portland cement has a relative shear strength of 120 percent (15). Even though the effect of spruce on the hydration rate of inorganic binders has been shown to be relatively minor (Table 3), the shear strength between spruce veneer and the binders is only about 25 to 30 percent of those of the pure binders.

Wood extractives retard the hydration of the inorganic binders and alter crystalline structures. Normal calcium sulfate dihydrate or gypsum crystals are relatively long and have a hexagonal form. The length to width ratio is approximately 17. Under the influence of wood extractives, the form and dimension of the crystals are altered. Between birch veneer and normal gypsum three layers of crystals can be

distinguished (Fig. 7). They are, progressing from the birch to the gypsum, the contact layer, the middle layer, and the transition layer. The crystals in the contact layer are very small. The crystals in the middle layer are somewhat longer whereas the crystals in the transition layer resemble those found in normal gypsum. All three layers are characterized by a lack of interlocking crystals. Because there are less inhibiting extractives in spruce than in birch, only two layers of altered crystals can be distinguished. The crystals are longer than those found adjacent to birch, and interlock to some degree (20).

The same test specimen shown in Figure 5 can also be used to determine internal bond. Internal bond is only about 20 percent of the corresponding shear strength (Fig. 8) (23). In test samples containing wood veneer, failure usually occurs at the weak interfacial layer between the wood and the binder. Wood failure, however, has been observed in spruce veneer test

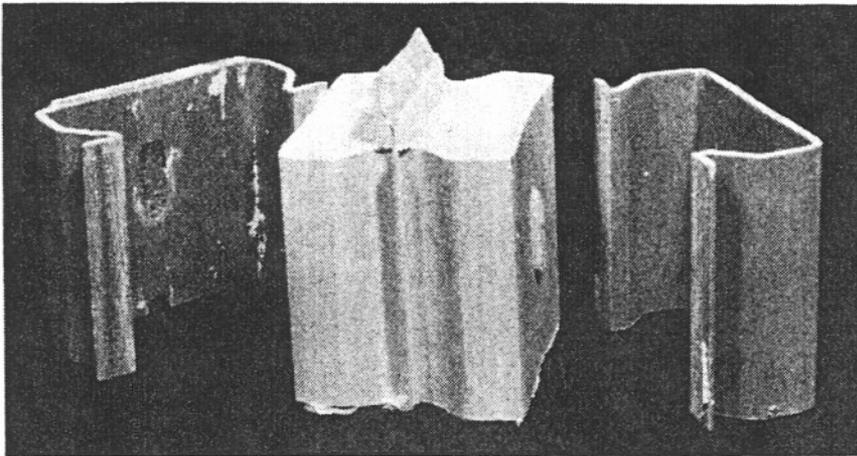


Figure 5. - Specimen for the determination of shear or internal bond strength between wood veneer and gypsum.

Scheme of the crystals of $\text{CaSO}_4 \cdot 2\text{H}_2\text{O}$ at the interfacial layer between wood/gypsum

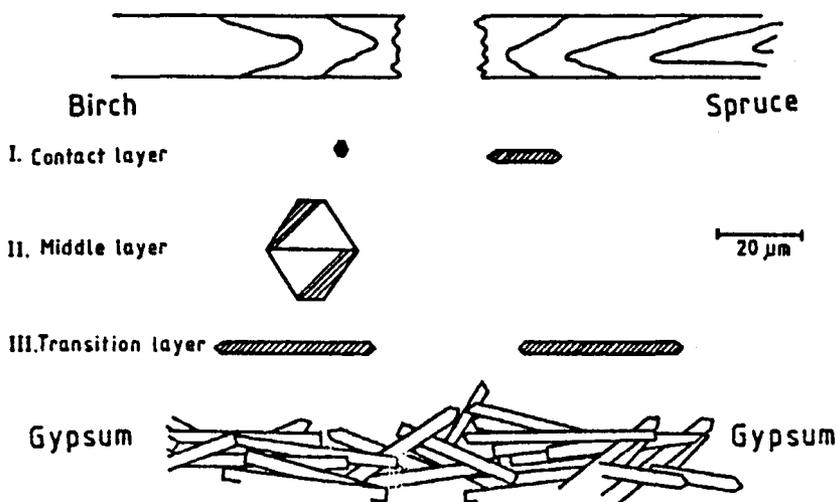


Figure 7. - Scheme of the crystals of gypsum at the interface between wood veneer of spruce or birch with gypsum.

samples made with the magnesium chloride activated magnesia.

Many methods are described in the literature to increase the compatibility of various woods with cement. Aging or seasoning is a method often used by industry to lower the concentration of inhibiting compounds. A plant in Japan sprays liquid paraffin, lubricating oil, or phosphoric acid ester on larch wood particles in order to increase their compatibility with cement (26). Substitution of condensed silica fume or rice husk ash for a portion of the portland cement binder has also

been proposed as a method to improve compatibility (17,18).

Properties of the composites

Gypsum, magnesia and portland cement have all been used to manufacture medium density (360 to 800 kg/m^3) wood wool (excelsior board) and medium-high density (800 to 1,350 kg/m^3) particleboard and fiberboard. In addition portland cement is used as a binder for high-density (above 1,350 kg/m^3) fiberboard and hollow core (extruded) panels (21).

A partial listing of the mechanical

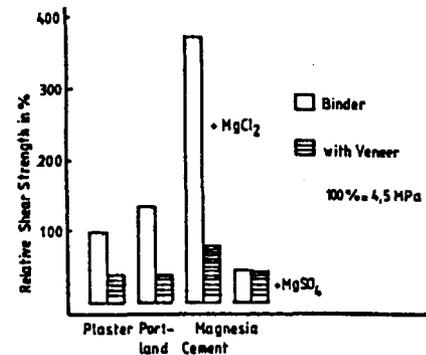


Figure 6. - Relative strength of inorganic cement shear specimens, with and without spruce veneer.

and physical properties of these board types is compared to those of a resin-bonded board in Table 2. Bending properties, along with other important properties like fire resistance, sound absorption, and insulation behavior, are primarily influenced by the density of the product and the binder/wood ratio. However, the swelling properties are determined by the type of binder. Conventional gypsum-bonded board is characterized by a relatively low resistance to thickness swelling and is therefore limited to indoor applications. Portland cement on the other hand shows very small dimensional changes in the soak test and is well suited to outdoor use. Magnesia-bonded boards occupy an intermediate position in this exposure regime. Magnesia boards can be used outdoors but must be protected from direct exposure to the weather. Both portland cement- and magnesia cement-bonded composites are considered to be resistant to wood destroying fungi and insects, including termites.

Manufacturing processes

A general scheme for the production of composites bonded with inorganic binders is shown in Figure 9. The process, similar in many respects to that used for fabricating panels bonded with thermosetting resin, can be divided into several operations including: wood particle or fiber preparation, mat formation, pressing, and curing and drying. The moisture content to which the wood particles or fibers are dried depends on whether the blending and forming operations are wet or dry. Because the process requires water of hydration particle moisture content, even for the dry

methods, is usually higher than that employed in making panels with thermosetting resins. Mat formation and pressing can be continuous or discontinuous.

A major difference in the processing of inorganic compared to organic bonded composites is the long hardening time required for the inorganic binders. Whereas the rate of strength development in hot pressed thermosetting resin bonded boards permits the release of compression forces in a relatively short time (4 to 5 min. for 3/4-in.-thick urea-bonded boards), inorganic bonded boards, usually cured at ambient conditions, may require up to 8 hours of press time. This is usually accomplished by pressing and clamping stacks of boards which are then set aside to harden. The hardening (hydration). times of some normal and modified inorganic binders are compared to that of synthetic resins in Table 4. Following the release of the clamping forces most inorganic binders need additional time to develop full strength. For portland cement this cure period is 28 days.

Three processes - wet, casting, and semidry - are distinguished by their water-binder ratio. In the wet process a dilute slurry made of wood fibers, binder, aggregates, and additives is formed into a mat and dewatered on a screen equipped with a vacuum chamber. Using a Hatschek machine, a thin web is formed and wound on a cylinder until the desired mat thickness is attained (Fig. 10). The web is then split and transferred to a steel caul. The uncured boards are stacked, compacted by pressure, and allowed to cure and harden. Compared to particles or flakes,

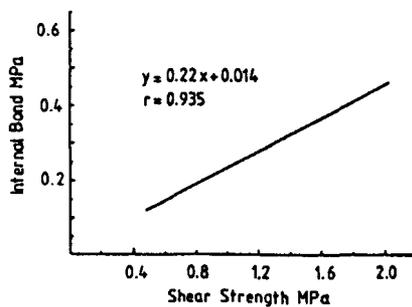


Figure 8. - Correlation between shear and internal bond strength of variously treated spruce wood veneer and gypsum.

the springback forces in boards made with refined wood fibers are negligible after pressing. Therefore fiberboards can harden without sustained compression. The wet process is used to manufacture flat and corrugated boards and molded products.

In the casting process, the water/binder ratio is about 0.6 to 0.8. Following mat formation in molds by mechanical devices, the highly viscous mixture is compacted by vibration or a light pressure. Wood wool boards made with the casting process require sustained pressure following compaction; however, wood cement boards made of shavings do not require prolonged compaction pressure.

In the semi-dry process the water/binder ratio is about 0.4, and the woody material acts as a water reservoir. The furnish is spreadable, and can be formed into a mat with forming devices commonly used in manufacturing particleboards. The water becomes available to the binder forming a coherent material when the furnish is pressed at 1 to 3 Mpa. In the case of fiberboards the pressure can be released after attaining the desired thickness. However, particleboards must be clamped. In a newly developed semidry process, wood particles, fly ash, cement, and water containing water-glass are extruded into hollow core panels (Fig. 11) (21). Due to the

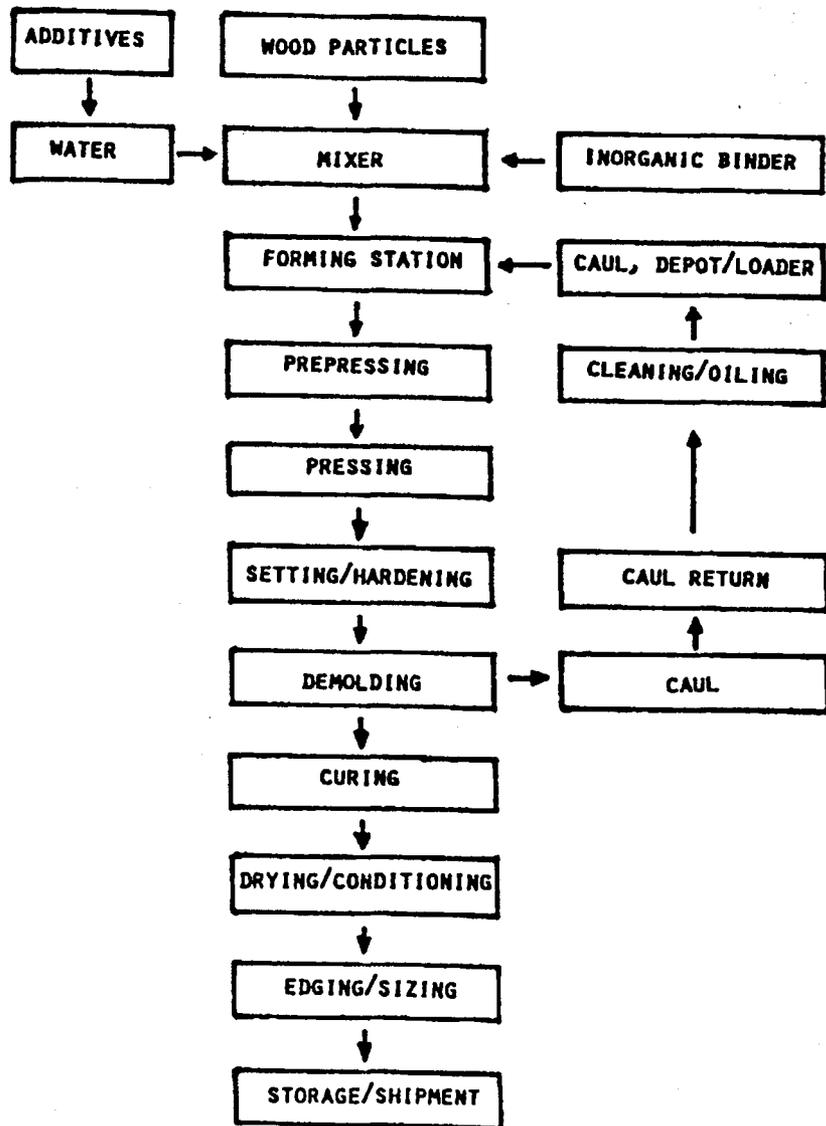


Figure 9. - Schematic flow diagram for the manufacture of cement-bonded particleboards.

low content of wood particles and also the addition of sand, the uncured panels can be stacked without sustained pressure.

Present situation and outlook

The largest portion of the inorganic-bonded wood composite board market is filled by portland cement-bonded wood wool board and portland cement-bonded medium-high density boards. The boards are used mainly as wall and roof materials in the construction of houses or shelters or in such diverse applications as sound barrier walls bordering highways. Increasingly medium-high density boards, some containing a mixture of glass and wood fibers, are being used as a substitute for asbestos cement boards. Production of gypsum-bonded particleboards and fiberboards is steadily increasing. Most of these board are direct substitutes for paper-wrapped gypsum sheetrock (registered USG trademark). Magnesia-bonded medium-high density boards have been available for a relatively long period of time but are presently facing a declining market due to relatively high costs.

Portland cement boards

Medium-high density portland cement-bonded particleboard was developed in the Elmendorf research laboratory, Palo Alto, Calif., in the early 1960s (4). Presently, there are more than 30 plants worldwide producing portland cement-bonded boards. Ten plants are in Russia and 5 plants are located in Japan. The remaining are in 10 other countries. No plants have ever been built in the United States. This is probably a result of the ready availability of wood sheathing and siding materials and less restrictive residential fire codes. Some cement-bonded board is presently being imported into the United States from Mexico, and it is anticipated that sales of this product will be expanded in the roofing market (13).

Most of the plants making medium-high density cement-bonded composites still utilize the classical Elmendorf process. Accordingly, the press time is long, about 6 to 8 hours. A number of methods incorporating modified cement or accelerators have been developed to shorten the pressing time (Table 5). Use of a special cement mixture has allowed a plant in Japan to

reduce press time for a 15-mm-thick board to 18 minutes (14). The same press time is also reported by a German equipment supply firm, which builds plants of cement-bonded particleboards (11). Both processes probably utilize a mixture of portland cement, gypsum semi-hydrate, and high alumina cement. Such a mixture is not inhibited by sugars and tannins (22). A Finnish plant uses an accelerator of sodium hydroxide and waterglass in conjunction with finely ground blast furnace slag to manufacture a rapid-hardening cement-bonded particleboard. The process requires a press temperature of 150°C. The boards, reported to be suitable for indoor uses, can be produced in slightly modified particleboard plants.

A new casting process has been developed to manufacture cement-bonded glass fiber boards (3). This process is a modification of the spraying method commonly used in applying shotcrete to the wall of tunnels. A cement slurry and an accelerator are sprayed separately and combine in the mat to harden rapidly. The process

could be of major importance in the fabrication of cement-bonded wood fiberboard.

Recently a plant in Hungary has been built to manufacture cement-bonded particleboard using carbon dioxide as an accelerator (6). The gas is injected into the mat during pressing and has reduced the press time to 4.5 minutes. No further compression holding period is needed; however the boards must be allowed to cure for an additional 10 days to attain ultimate strength properties. The plant uses Finnish equipment and technology. It is interesting to note that both the acceleration of cement using CO₂ gas and the injection of resin-bonded wood composite boards with a gas for the purpose of catalysis are processes that have been previously patented in the United States (1,5).

Our own examinations with carbon dioxide injection confirm that press times for cement bonded boards can be dramatically shortened with the use of CO₂ gas. Simatupang has extended this technology by combining a carbonate of either potassium, so-

Table 4. - *Hardening time of some binders used to manufacture wood composites.*

Binder	Temperature	Hardening time
	(°C)	(min.)
Gypsum + accelerator	ambient	30
	ambient	1 to 3
Magnesia cement	ambient	240
	120	1
Portland cement + accelerators + CO ₂	ambient	800
	80	10
	ambient	4
Urea formaldehyde resin + catalyst	ambient	200
	100	1
Phenol formaldehyde resin + catalyst	ambient	600
	100	1

Table 5. - *Specific press time of some wood composites.^a*

Binder components	Specific press time	Reference
	sec./mm board thickness	
Portland cement:		
+ carbonates + waterglass + high-frequency heating	30	(20)
+ CO ₂ (gas)	20	(6)
+ high alumina cement	50	
Magnesia cement:		
+ magnesium chloride	50	(9)
+ magnesium sulfate + steam injection	15	(19)
High furnace slag cement + NaOH + waterglass	50	(9)
Gypsum:		
particleboards + accelerator	180 (total)	(2)
fiberboards + accelerator	20	
Urea formaldehyde resin	12	
Phenol formaldehyde resin	15	

^a Press time of gypsum-bonded boards are independent of board thickness.

dium, or ammonium with the cement. The carbonate emits carbon dioxide on heating. The most promising additive is ammonium carbonate. The ammonium carbonate, unlike the potassium or sodium carbonate which leave cations in the cement and can raise the pH of the pore water, releases ammonia which is dissipated during the reaction.

Gypsum board

Both gypsum-bonded fiberboards and particleboards are commercially manufactured. Presently 11 gypsum fiberboard plants exist worldwide. Ten plants use the Fermacell-Siempelkamp process, a method intermediate between the wet and the semidry process. One plant is designed to use the Wurtex semi-dry process to produce a fiberboard on a continuous press using recycled materials for both the furnish and the binder (24,25). Newsprint is used as the fiber and calcined gypsum from a flue gas desulfurizing unit is used as the binder. No gypsum fiberboard plants are under construction in North America. Both of these plants will use recycled newspapers in the furnish.

Two plants, one in Finland and one in Norway, manufacture gypsum-bonded particleboards according to the Kossatz process (7). This semidry process uses spruce particles in the furnish and consequently the boards must be stack-clamped for 2 hours. Phospho-gypsum used as the binder in the Finnish plant is obtained as a byproduct from a phosphorous processing plant.

Magnesia boards

The first industrially made inorganic bonded wood composites were magnesia-bonded wood wool boards (10). In Europe the Heraklith boards and in the United States the Tectum boards are well known. Both kinds of boards were originally manufactured on continuous presses. However, the European processes are now similar to that used in making cement-bonded wood wool boards. The boards are clamped in a stack for a minimum of 8 hours. Magnesia-bonded particleboards are also manufactured in Finland.

Recent studies show that half-calcined dolomite can be partially substituted for the magnesia (22). Additional work by Paszner (12) shows that wood composites can also be made

using a mixture of heavy magnesia and ground dolomite in combination with a solution of ammonium polyphosphate as the binder. The process is further simplified by using caustic calcined magnesia or half-calcined dolomite in combination with a sparingly soluble ammonium polyphosphate. Simatupang has shown that physical and mechanical properties of magne-

sium oxyphosphate-bonded particleboards are similar to those obtained with magnesium sulfate and vary directly with the binder/wood ratio (Table 6). Magnesium oxyphosphate boards, however, are more water resistant than magnesium sulfate boards.

The cure of magnesia binders can be readily accelerated by the addition of heat. Wood composite boards made

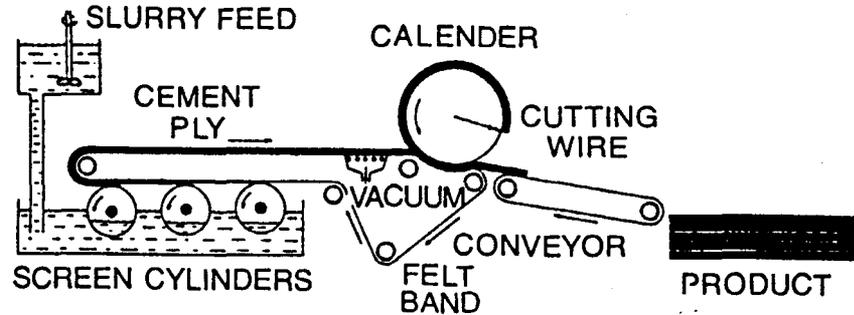


Figure 10. - Schematic of a Hatschek machine for the manufacture of inorganic-bonded wood composites, according to a wet process.

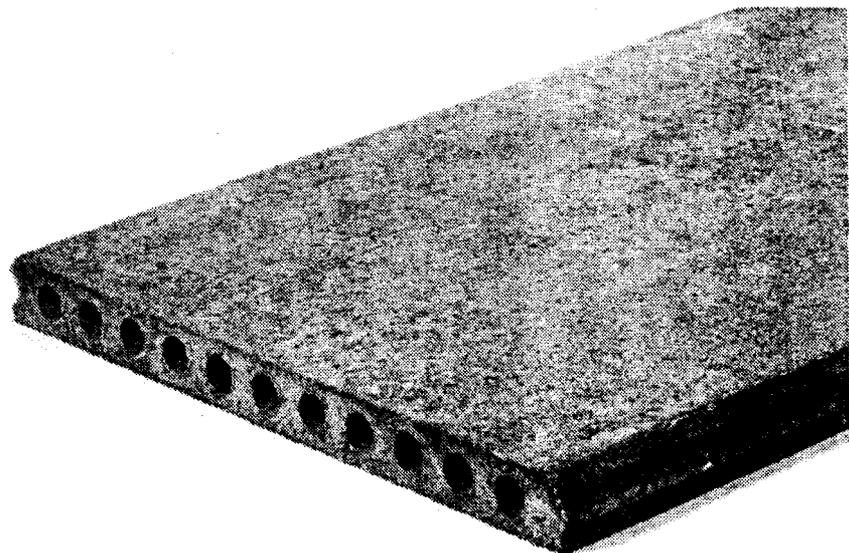


Figure 11. - Ecopanelboard manufactured using an extrusion process.

Table 6. - Properties of magnesia oxyphosphate-bonded particleboards.^a

Ratio binder/wood	SG	Bending strength		Thickness swelling	
		Internal bond		2 hours	24 hours
		----- (MPa) -----		----- (%) -----	
1.5	1.057	11.7	0.57	3.55	4.35
2.2	1.049	8.1	0.54	2.49	2.92
3.0	1.055	7.68	0.40	2.42	2.78
4.0	1.100	5.81	0.32	0.93	1.55
4.5	1.089	5.03	0.31	0.82	1.10

^a Binder components - caustic calcined magnesia: ammonium polyphosphate 5:1. Press time and temperature - 15 min., 120°C.

with this material are therefore compressed in a heated press. As with resin-bonded wood composites, total press time can be reduced by rapidly transferring heat to the center of the board. Steam injection pressing, a process whereby saturated steam is forced into a mat during pressing, is being successfully used to raise the center-line temperature of resin-bonded boards to curing temperatures in less than a second. This process can also be used with magnesia-bonded boards (10). However, the difference in a number of board variables, including binder/wood ratio, particle geometry, moisture content, precure, and steam pressure/temperature relations, must be considered in adapting the process to magnesia-bonded board. Using modified techniques the specific press time for magnesia-bonded particleboards can be reduced from 1 minute per mm of board thickness to about 15 seconds per mm (19).

Concluding remarks

Inorganic-bonded wood composite boards have many desired qualities. Besides being highly fire resistant, they provide excellent protection against decay and insect attacks. Boards produced with portland cement are dimensionally stable in high humidities and durable in outdoor applications.

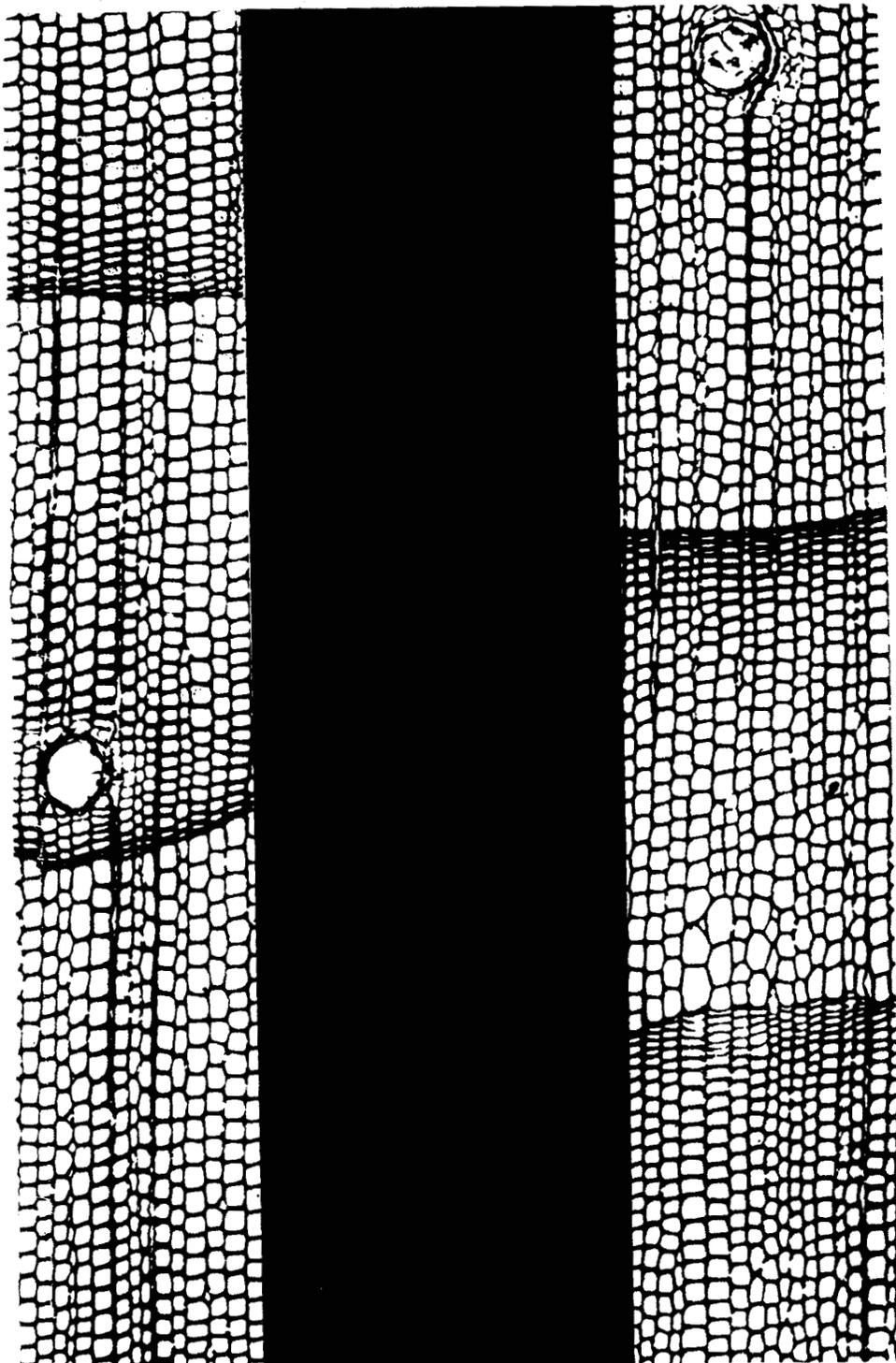
New technologies have helped to improve the economics of manufacturing inorganic composites. Use of accelerators, and novel methods of introducing heat and catalysts via a vapor phase has remarkably decreased press times. New manufacturing techniques have been devised to permit semi-dry and dry methods of forming. The processes have been adapted to use recycled materials, thereby reducing raw material costs.

Markets for inorganic-bonded wood composites vary throughout the world. In Europe, residential buildings built with masonry walls do not require sheathing. Common construction practices do not use sheathing beneath cement or clay roof tiles. Substantial markets for inorganic-bonded wood panels have been developed for such diverse end uses as sound barrier walls and fire rated partitions. In the United States, inorganic-bonded boards

could be easily adapted to the wood frame construction techniques used for residential housing. Their use, however, has been precluded by the abundance of resin-bonded structural panels and the lack of strict fire codes. In contrast, relatively large residential housing markets for cement-bonded sheathing and siding have developed in Japan (16). Increased use of inorganic-bonded composites is highly dependent on building codes, safety and fire regulations, construction techniques, esthetics, availability of materials, and all the other underlying factors which determine public acceptance of a product.

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