Kirk-Othmer Encyclopedia of Chemical Technology.

BUILDING MATERIALS, SURVEY

This article discusses traditional building and construction products, ie, not made from synthetic polymers (see Building materials, plastic), including wood, asphalt, gypsum, glass products, Portland cement, and bricks. The article presents information about each basic material, the products made from it, the basic processes by which the products or materials are produced, estimates of the quantity or dollar value of the quantities produced or used in the United States, and some pertinent chemical or physical properties related to the material. More detailed chemical and physical property data can be found in articles devoted to the individual materials (see Asphalt; Cement; Glass; Wood).

1. Wood

Wood (qv) is arguably the oldest building material used by humans to construct their dwellings. It is a natural product obtained from trees, used in both structural and decorative applications. The chemical composition of wood is largely cellulose (qv) and lignin (qv). Today there are a variety of composite or reconstituted wood products, such as plywood, particle board, wood fiber boards, and laminated structural beams, where small pieces of wood or wood fiber are combined with adhesives to make larger sheets or boards (see Laminates).

Woods are classified as either hardwoods or softwoods, based on the seed- and leaf-type of the trees from which the wood comes. Softwoods come from trees that are classified as gymnosperms, or naked seeds, whereas the hardwoods are angiosperms, or covered seeds. The common softwoods, such as pine, spruce, fir, cedar, and hemlock, have specific gravities between 0.30 and 0.55, which make them ideal for construction purposes. They can be worked, ie, cut and shaped easily, with simple tools and can be nailed without splitting. Common hardwoods, such as oak, maple, and fruit woods, have higher specific gravities. They are harder to cut with hand tools and tend to split when nailed. Lower specific gravity hardwoods, such as balsa, are too weak for structural application. Because of these properties, softwoods are the common construction wood rather than the generally stronger hardwoods.

1.1. Manufacture

The manufacture of lumber or sawn wood starts with cutting the tree and removing the limbs (limbing), followed by sawing the log into slabs parallel to the long direction of the log. Most softwoods are cut either by sawing through and through or around the log (Fig. 1). Through and through sawing is done by cutting slabs of the desired thickness one after the other across the diameter of the log. Sawing around the log is done by cutting slabs of the desired thickness about one-third the way across the diameter of the log, rotating the log 90°, cutting more slabs, and then repeating the process. This leaves a solid center section that also can be cut. Quality hardwood is cut through and through or by sawing around, but it is also quartersawn. Quartersawn wood is considered to be more dimensionally stable. First the log is cut into quarters, then each quarter is sawn at a 45° angle to the flat sides (Fig. 1). The slabs can then be cut to width prior to or after drying.

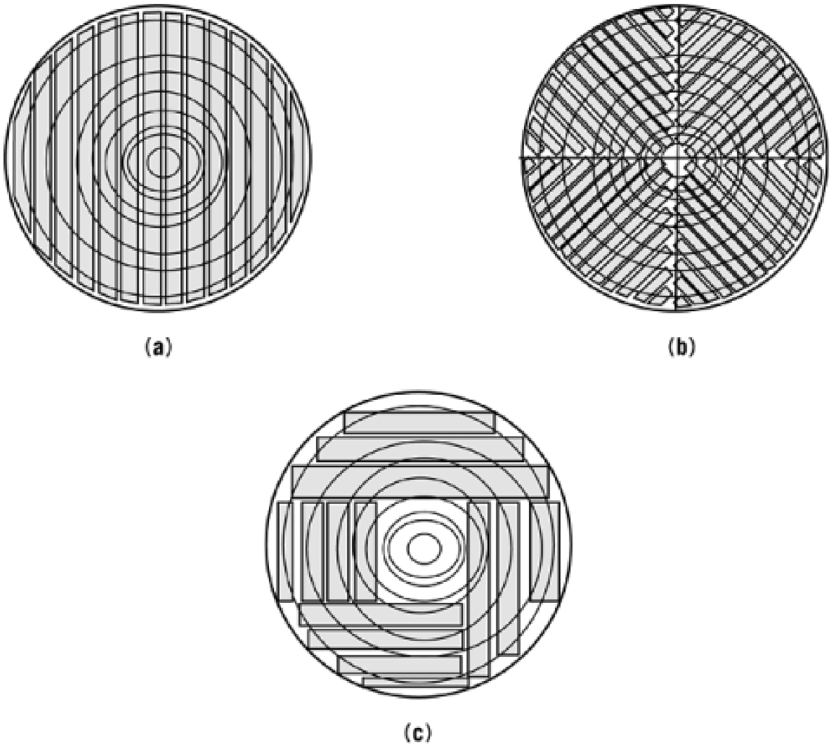

Fig. 1. Methods of sawing logs into slabs, where (**a**) is through and through, (**b**) is quartersawn, and (**c**) is sawing around.

Table 1. Softwood Nominal vs Actual Sizes, in.[a]

Nominal	Actual
1	$\frac{3}{4}$
2	$1\frac{1}{2}$
3	$2\frac{1}{2}$
4	$3\frac{1}{2}$
6	$5\frac{1}{2}$
8	$7\frac{1}{4}$
10	$9\frac{1}{4}$
12	$11\frac{1}{4}$

[a] To convert inches to cm, multiply by 2.54.

The green wood of a fresh cut tree can have a moisture content of 60 to over 150%, depending on species and weather conditions. Hardwoods tend to have lower moisture contents than softwoods. These moisture levels are too high for most construction applications as the wood can rot and undergo relatively large dimensional and shape changes as it dries out. Most construction wood is dried to below 19% moisture content, often to about 8%, to reduce these problems. As wood drys, it typically shrinks 5–8% perpendicular to, ie, across, the grain and less than 1% with, ie, parallel to, the grain.

Construction lumber is milled, ie, smoothed, after it has dried to its finished dimensions. These dimensions are less than the nominal size of the lumber which is based on the size of the green wood cut during the sawing operation. Nominal versus actual sizes of construction lumber in the United States is given in Table 1.

Table 2. Softwood Gradings[a] by Wood Type

Grade classification			
Douglas fir	Redwood	Pine	Uses
C and better	clear all heart	C and better, 1 and 2 clear	exposed wood and where best weather resistance needed
C select	heart C	select, choice	contains slight defects; use for painted surfaces
construction	construction, construction heart	D select	some knots, some warping and cupping; use for finish construction
standard	merchantable	1–5 common	visible surface irregularities; use for framing

[a] As the use description shows, the quality of the wood decreases reading down each column.

Finished lumber is visually sorted or graded based on industry organization standards. These standards consider the number of knots, ie, tree limb locations, straightness, and overall quality of the wood. For example, pine lumber graded #3 is full of knots whereas select-grade has almost no knots. Construction lumber is graded and stamped on the end of the boards. General grading classifications are given in Table 2, which shows that these gradings are qualitative and subjective.

1.1.1. Shake Shingle

Whole wood products are used in shake shingles for residential and light commercial application. Cedar is the most common wood used because it splits easily and is rot-resistant, but pine is also used. The logs are cut into approximately 12 in. (30.5 cm) lengths, split by hand or machine into slabs parallel to the grain, and classified as lightweight, medium weight, or heavyweight shingle based on thickness. The shingles are then nailed over a waterproofing felt, typically a nonperforated asphalt saturated organic felt, to provide water tightness to the roofing system. To obtain a class C fire rating, which is the lowest possible, from Underwriters Laboratory, a fire-retardant treatment is given to the wood shingles.

1.1.2. Annual Production

The United States is the largest single producer of lumber with about 25% of all the logs cut in the world. The current soft housing and construction markets as well as environmental pressures to limit logging are reducing the percentage. Still the value of wood harvested was about $12.6 billion in 1989.

The value of lumber produced in 1989 was estimated to be $17.3 billion, of which softwood lumber represented about 58%. The other 42% was composed of hardwood lumber (12%), woodchips (10%), and a variety of wood products (20%).

1.2. Wood Products or Composite Wood Materials

The wood products or composite wood materials consist of products where the wood is cut into small and/or thin pieces and then the cut pieces are glued together to form a larger piece of wood product. The most common example is plywood. This category also includes reconstituted wood products subclassified into wood flake boards, particle boards, or wood fiberboards depending on the size of the wood particle glued together. Products in these categories include low density fiberboard (wood fiberboard), medium density fiberboard (MDF), high density fiberboard (hardboard), flake board, oriented strand board (OSB), and particle boards.

1.2.1. Plywood

Plywood is made up of thin layers (plies) of wood laminated together. The plies alternate the grain direction to balance both the structural strength and the dimensional movement of wood. An odd number of plies is used to give an even number of adhesive lines and hence reduce warpage. The adhesive lines shrink during the curing process and cause warping; by having an even number of adhesive lines uniformly spaced throughout the cross section of the plywood panel, the shrinkage forces balance out. Plywood is considered to be more dimensionally stable than wood itself because of the dimensional stability of the cured resin adhesive and the cross-directional plies that balance and/or cancel out most of the wood movement. Plywood is also favored for its resistance to splitting and punctures in normal construction applications. Thicknesses range from $\frac{1}{4}$ (0.63 cm) to $\frac{3}{4}$ in. (1.9 cm) with the common sheet dimension of 4×8 ft (1.2×2.4 m). The number of plies commonly range from three to five, but hardwood plywoods may have more. The outermost plies are called faces or face plies. Inner plies with the grain parallel to the face are called core(s) or center, whereas those with the grain direction perpendicular to the face are called the crossbands.

Some of the newer structural plywoods are called four-ply plywood, implying that they have an even number of plies. To get stability, two center crossbands are glued with the grains of the plies parallel, making it effectively one ply with the adhesive line in the neutral axis, and removing the warping tendency. These products can be considered a three-ply plywood. In general, the more plies the stronger the plywood is at a given thickness.

Plywood is also divided into softwood and hardwood plywood products. The classification depends on the type of wood the face plies are made from. The principal application for 1 cm and thicker hardwood plywoods are cabinets and furniture. The thinner grades are used to make paneling and doorskins, which represent approximately 56% of the total hardwood plywood products. The total market in 1989 was estimated to be $2.1 billion.

Softwood plywood is usually used for construction application and is the type commonly found in local lumber and home center stores. The face plies are generally fir. Shipments in 1989 were estimated at $5.02 billion. The Pacific Northwest represented 42% of the total whereas 36% came from the South.

Hardwood and softwood plywoods are manufactured by the same basic process. The first step is to make the veneers that are used as the plies. They are produced by slicing off thin layers of wood from presoftened logs that have been debarked and soaked in hot water for a period of time. The most common method of slicing the veneer is the rotary process, which uses a lathe to turn the log while a long sharp knife blade is pressed against the log. The knife is indexed to keep cutting at the desired thickness of veneer as the diameter of the log is reduced. Veneer comes off the log in a continuous sheet that is then cut into usable sizes and dried. Some hardwood plywood veneer is made by flat slicing. Flat slicing involves cutting the log quarter, then the flat side is forced against the cutting knife using hydraulic rams to slice off slabs or a sheet of veneer. These slabs of veneer are generally less than the width of the finished plywood and need to be edge-joined into larger sheets. The rotary cut veneer is also edge-joined when the sheet breaks. The veneer is inspected when dry, and holes are patched to make it ready for the adhesive application step.

Adhesives (qv) used to make plywood are classified as either the exterior adhesive or the lesser quality interior adhesive. The terms relate to the ability of the adhesive to survive exposure to moisture and weather. Phenolic resins (qv) are commonly used as adhesives to make plywood. The difference between interior and exterior phenolic resin adhesive is the filler level. Exterior rated plywood uses higher resin content adhesives. Interior rated plywood uses either highly extended (below 24% resin solids) or protein-based adhesives. The adhesive is applied to the veneer by roll coating, spraying, curtain coating, or foam extrusion.

The adhesive-coated veneers are then stacked in the correct order (thickness and number of plies) to make the desired product and sent to a cold press. The pressure applied by the cold press assures uniform adhesive distribution across the plies and full adhesion later. From the cold press the assembly is moved to a hot press. The hot presses have up to 50 openings between steam heated plates. Depending on the thickness of the plywood being manufactured, one or more (up to three) layers of uncured plywood assemblies are loaded into each opening. The press is closed and pressure of 1.2–1.38 MPa (175–200 psi) and temperatures of 110–166°C are applied for the period of time needed to cure the adhesive. The cured plywood panels are removed from the hot press and sent past trim saws that trim the panels to final size. A- and B-grade veneer products are sent on for sanding, whereas structural panels with C- and D-grade veneers (lowest quality, the most holes) are not. Following the sanding step, the panels are inspected again and any new defects are patched.

1.2.2. Reconstituted Wood Products

This category includes three general varieties: wood flake board, particle board, and wood fiberboard. The manufacturing processes are similar for all these products except for the size of the wood particles that are glued together.

1.2.2.1. Wood Flake Boards. This category covers a range of products depending on the size and orientation of the wood flakes used. The earliest product was made in the 1950s using low density wood species, such as aspen and pine, with the flakes bonded together with phenolic resins. Today there are two types of flake board, waferboard and oriented strand board (OSB).

Waferboard is made almost exclusively from aspen wood and the flakes are roughly square in shape, up to 2 in. (5 cm) on a side. They are used for low end structural sheathing applications.

OSB is a product from the 1980s and differs from the waferboards in the shape and orientation of the flakes. Because the flakes are rectangular with the long direction parallel to the grain, they are called strands. Generally, they are $\frac{1}{2}$ to $\frac{3}{4}$-in. (1–2 cm) wide by up to several centimeters long and 1.6 mm thick or less. The strands are laid up in layers with the strand orientation alternating between the long and short direction of the board, much like plywood. It is because of the strand orientation and the strand shape that OSB is considered to have much better structural properties than any of the other reconstituted wood products. It is used in all types of structural sheathing applications, such as roof deck, structural flooring, and structural wall sheathings. A recent application is the manufacture of I-beamlike structures from the sections of OSB, used as replacements for solid wood structural members. These products have the advantage of being more dimensionally stable and uniform, yielding a better building structure.

The 1989 OSB/waferboard sales in the United States were about \$669 million and increased to 451×10^6 m^2 (4.85 billion ft^2 on a $\frac{3}{8}$-in. basis) from 18.2×10^6 m^2 in 1980. These products represent about 20% of the structural panel market; softwood plywood represents the other 80%.

1.2.2.2. Particle Boards. Particle board technology was developed in the late 1930s; the first commercial plant began in Germany in 1941. Today particle board products are about 80% of the total wood panel products used in Europe for furniture and construction applications. In the United States particle board did not become a commercial product until the late 1940s, in large part because of the plentiful supply of wood in the United States. A significant feature of particle board is that it uses wood residues like sawdust, edging, and trimming from lumber mills. These wood residues are therefore small in size compared to the waferboard/OSB wood particles.

Particle boards are classified into three general categories depending on the density of the board. High density (H) panels are those with a density greater than 849 kg/m^3, medium density (M) panels have density between 609 and 849 kg/m^3, and low density (L) panels have a density below 609 kg/m^3. These three categories are further subdivided by the type of resin that bonds the particles together. Urea–formaldehyde (UF) (see Amino resins and plastics) bonded panels are called Type I and are for interior application. Phenol–formaldehyde (phenolic) (see Phenolic resins) bonded panels are called Type II and are used for protected exterior and sheathing applications. Typical applications for the various types of panels are given in Table 3.

Eighty percent of the markets for particle board are furniture, doors, cabinets, and countertops; floor underlayment is the next significant application with 13%. The total market in 1989 was approximately \$930 million.

1.2.2.3. Wood Fiberboards.. The wood particles used to make wood fiberboards are, in fact, individual wood fibers from raw materials including waste woods and other cellulosic materials such as bagasse (sugar

Table 3. Particle Board Grade[a] and Applications

Application	Type[b]	Density	Grade[c]
floor underlayment	I	medium	1
shelving	I	medium	(1–3)
countertops	I	medium	(2, 3)
kitchen cabinets	I	medium	(1, 2)
door core	I	low	1
stair treads	I	medium	3
moldings	I	medium	3
wall sheathing	II	medium	1
siding	II	medium	1
combined subfloor underlayment	II	medium	3
high density industrial products	I	high	(1–3)
high density exterior industrial products	II	high	(1–3)

[a] Ref. 1.
[b] Type I = UF resin bonded; Type II = phenolic resin bonded.
[c] The higher the number, the better the physical properties.

cane). The fibers are glued together into a sheet. There are three general types of wood fiberboards, which differ by density. The low density boards have a density below 529 kg/m^3, the medium density boards have densities between 529 and 801 kg/m^3, and the high density boards have a density greater than 801 kg/m^3. The physical properties are influenced by both the adhesive used and the density.

Low density wood fiberboards are usually manufactured at a density of about 448 kg/m^3 in a wet process similar to papermaking. The natural binding properties of wood fibers are used and adhesives are not usually added. Starch (qv) and asphalt (qv) are used if a binder is needed for additional strength. This type of product is used in residential sheathing where the manufacturer puts an asphalt coating on the board to protect it from the weather during construction. It is also used as roof insulation or utility board under commercial low slope roofing. Roof insulation boards come either with asphalt, a maximum of 4% incorporated into the board to size the board and help control moisture pick-up, or without asphalt, for use with roofing membranes that are not compatible with asphalt. Finally, low density wood fiberboard is used in residential ceiling tile and panels for aesthetic rather than acoustic properties; they have noise reduction coefficients (NRC) less than 0.5 and are not considered acoustically sound absorbing.

Medium density wood fiberboards (MDF) are semistructural products used mainly in furniture applications (95% of the market). The total shipment of MDF in 1989 was approximately $302 million.

High density wood fiberboards are also known as hardboards. The tempered hardboard manufacturing process was developed by W. H. Mason, founder of the Masonite Corp., in 1924. As a result, hardboards are sometimes referred to as Masonite. There are two types of hardboard, standard and tempered. Standard hardboard has the fibers felted; today this is done by a dry process, but in the past a wet felting process was common. The felted fibers are then pressed to a density between 961 and 104 kg/m^3. The strength comes from the consolidation of the fibers under heat and pressure. Tempered hardboard has heat-curing resins impregnated into the standard hardboard before curing. As a result, tempered hardboard is stronger and more moisture-resistant.

Hardboard is available in either $\frac{1}{8}$ or $\frac{1}{4}$ in. (0.32 or 0.63 cm) thicknesses. It is available as peg board with holes punched in it. A significant but declining use has been in interior paneling and exterior siding, and it competes in many applications with thinner OSB and plywood. The U.S. market for hardboard was approximately $669 million or 455×10^6 m^2 (4.9 billion ft^2, $\frac{1}{8}$ in. basis) in 1989.

1.2.2.4. Manufacturing Process Overview. Reconstituted wood products have similar manufacturing processes. The first step is to make the particles that will compose the finished product. Wafers and strands are cut from logs, particle board particles are ground from mill scraps, and wood fiberboard fibers are ground and then treated with steam or other methods to break down the natural lignin adhesives holding the fiber together so that they can be separated into individual fibers. The next step is to mix the wood particles with the resin of choice by a spray and/or tumbling process. Urea–formaldehyde (UF) resins commonly were used in the past. However, because of the lack of moisture resistance and the potential for the resins to hydrolyze in the presence of moisture and decompose into urea and formaldehyde, they are not used as much now. Governmental regulations are under development that eliminate the use of UF resin in wood products. This would limit the exposure of the public to formaldehyde, a listed carcinogen, formed by the decomposition of UF resin. Today most wood products use phenol–formaldehyde (phenolic) resins, but urethane-based resins are becoming more common.

After the wood particles are coated with resin, the particles are uniformly distributed into a board by an air laid process. The art of the process is in controlling and getting a uniform distribution of the wood particles by blowing them out onto a collection chain. After forming the board shape it is moved to hot presses where the wood particles are consolidated and the resin cured. From the hot presses the boards move to trim saws where the boards are cut square to their final size. In some cases, the boards are sanded to final thickness and surface smoothness.

2. Bituminous Products

Bitumen describes a black or dark brown masticlike material that is thermoplastic in nature and softens upon heating. The sources of bitumen are petroleum or coal deposits. The natural product is commonly called gilsonite or pitch, a mineral formed by an old weathered petroleum flow at the surface of the earth that has left behind the larger molecules from the petroleum. A principal source in the past has been Lake Trinidad, a 445,000 m^2 deposit on the island of Trinidad. Bitumen from petroleum or crude oil is called asphalt (qv). It is the material left behind after all the valuable compounds, eg, gasolines, have been distilled out of the crude oil. The amount and quality of asphalt is dependent on the source of the crude oil used in the refining process. Some crude oils have a higher content of asphaltic bitumen left after the distillation process. Bitumen from coal is coal-tar pitch. It remains after the valuable coal oils and tars have been distilled out of the coal tars produced by distractive distillation. Most industrial applications for bitumen products use asphalt or coal-tar pitch because the supply is more uniform and plentiful.

As a construction material, bitumens have principal applications in paving and waterproofing. About 75% of all bitumens are used in paving, and about 20% are used in waterproofing. Of the waterproofing usage, 75% is in roofing applications. Construction applications for natural bitumens are nonexistent and coal-tar application are less than 20% with asphalt being the more important material. The use of coal tar is declining because of its listing as a human carcinogen by the U.S. Government.

Asphalt is not an exact chemical composition but rather a mixture of organic compounds whose nature is dependent on many items (see Asphalt).

2.1. Paving

The principal use of coal tar in paving is as a seal coat to bitumen paving. Asphalt for paving comes in several forms determined by the intended application, ie, straight asphalts called asphalt cements (AC), asphalt emulsions, cutback asphalts, and road oils.

Asphalt cement represents well over 50% of the total amount of asphalt used in paving. It comes in a range of viscosities from $25\ \mathrm{Pa{\cdot}s}$ (250 P) to $400\ \mathrm{Pa{\cdot}s}$ (4000 P), measured at 60°C. The ASTM D3381 classification system lists the number following the AC as the viscosity of the grade in $\mathrm{Pa{\cdot}s}$ divided by 10, eg, AC 20, a common grade, would have a viscosity of $200\ \mathrm{Pa{\cdot}s}$ (2000 P) at 60°C. ASTM D3381 also lists other physical properties for the various grades. The main application of asphalt cement is as a binder in asphaltic concrete paving, commonly called blacktop. Over 90% of the paved roads in the United States are asphaltic concrete. Asphaltic concrete is a mixture of sand, size-grade rock (2–4 cm) (maximum $1\frac{1}{2}$ in., more typically $\frac{3}{4}$ in.), and asphalt cement. The mixture is heated so that the aggregate is fully coated with asphalt cement and then applied as a uniform layer to the prepared road bed and consolidated under pressure before it cools and sets.

Asphalt cutbacks are asphalts dissolved in a solvent. The choice of solvent and its rate of evaporation determines how quickly the cutback sets up. Cutbacks are used as road sealers and coatings and may be mixed with aggregate and sand for cold patches used to repair minor road damage. The cold patch is put into the hole, consolidated, and allowed to cure; it does not have to be kept hot prior to use. Asphalt cutback is also used as dampproofing by applying a continuous film of asphalt to foundations to retard the flow of vapor water. Current and future limitations on volatile organic compounds (VOCs) found in most organic solvents are responsible for the decreased use of cutback asphalts. It is estimated that all asphalt cutbacks, including those used in roofing, represent about 3–5% of the total asphalt market.

Asphalt emulsions are dispersions of asphalt in water that are stabilized into micelles with either an anionic or cationic surfactant. To manufacture an emulsion, hot asphalt is mixed with water and surfactant in a colloid mill that produces very small particles of asphalt on the order of 3 μm. These small particles of asphalt are prevented from agglomerating into larger particles by a coating of water that is held in place by the surfactant. If the asphalt particles agglomerate, they could settle out of the emulsion. The decision on whether a cationic or anionic surfactant is used depends on the application. Cationic stabilized emulsions are broken, ie, have the asphalt settle out, by contact with metal or silicate materials as well as by evaporation of the water. Since most rocks are silicate-based materials, cationic emulsions are commonly used for subbase stabilization and other similar applications. In contrast, anionic emulsions only set or break by water evaporation; thus an anionic emulsion would be used to make a cold patch compound.

Road oils are very fluid asphalts that are used to keep the dust down on dirt roads. They are only a small part of the asphalt paving market.

2.2. Roofing

Asphalts are used for waterproofing in roofing and as below-grade water barriers applied to foundations. Roofing represents the largest waterproofing application of asphalt, and is commonly classified into low slope roofing and steep slope roofing. The dividing line between steep and low slope is a 2 in. (5 cm) rise per foot (30 cm) of run, also referred to as a 2 in 12 slope. This dividing line generally means the difference between membrane roofing systems versus shingles. However, membrane roofing systems can be used on slope of up to 6 in 12, but shingles are never used under 2 in 12 and generally not used under 4 in 12.

Asphalts in the roofing industry are used as coatings for shingle and roll goods (60%), as mopping asphalts in membrane roofing (20%), as saturants for shingle and roll goods (15%), and as roof coatings (5%). With the exception of saturants and polymer-modified asphalts, the asphalts used in roofing are air-blown or oxidized to increase the softening temperature and penetration so that they will not flow off the roof in hot weather.

The roofing market size is generally reported by building type rather than by roofing material type, ie, residential and commercial. The total roofing market in 1990 was $11.6 billion commercial and $5.1 billion residential for a total of $16.7 billion including labor. Labor is included because in most cases the finished product is produced on site. Of the total, 59% was asphalt roofing with 81% of that based in the residential market and 19% in the commercial markets.

2.2.1. Asphalt Shingles

Asphalt shingles are one of the least expensive roofing options. They represent about 65% of the residential roofing market on a dollar basis, and represent well over 65% on an area basis. The two basic types of asphalt shingles are fiber-glass mat reinforced and organic-felt reinforced. Fiber-glass mat reinforced shingles represent about 85% of the market.

Manufacturing processes are different for each type of reinforcement. Organic felt reinforced shingles have been around since the turn of the century. They start with a blotterlike paper called the felt, which is manufactured from cellulosic materials. Large rolls of the felt are passed through a saturator, ie, a large tank filled with a very soft or low softening point asphalt called saturant. The felt is passed through the saturant numerous times so that the felt picks up about 120% its original weight in saturant and weighs about 0.6 kg/m^2. The saturated felt is then run through a roofing line where both sides are coated with a filled asphalt coating. The filled asphalt coating is a hard or high softening point air-blown asphalt blended with 50% or more of a fine filler, commonly ground limestone, that keeps the coating from flowing off the roof and provides a fire rating on fire rated shingles. The top surface has granules of color-coated crushed rock about 3 mm in diameter pressed into it to protect the asphalt from the weather and provide the aesthetics of the shingle. The back coating is treated with sand or other release-type agents to keep the shingles from sticking in the bundles. Lastly an asphaltic adhesive is applied in a strip to seal the tabs of the shingles down on the roof in order to resist wind damage to the finished roof.

Fiber-glass mat reinforced shingles are produced from fine (about 16 μm diameter) glass fibers uniformly dispersed and bonded together with a thermosetting resin. Typically the mat weighs $\sim$0.1 kg/m^2. The fiber-glass mat is then run through a coating line where both sides are coated with a filled asphalt coating. The top surface has granules pressed into it, and the back coating is treated with sand or other release-type agents. Lastly an asphaltic adhesive is applied in a strip to seal the tabs of the shingles down on the roof.

The finished shingles, either fiber glass or organic-based, weigh between 9.8 and 16.6 kg/m^2 (200–340 lbs/100 sq ft). Standard three-tab shingles are lighter in weight than laminated (two-layer) shingles.

2.2.2. Membrane Roofing

Many of the same types of materials used in membrane roofing are also used in waterproofing applications, because usually a membrane is needed to maintain the waterproofness of the foundation. They are used mainly on large commercial buildings.

Three types of asphalt-based roofing materials are used in the membrane roofing market: built-up roofing (BUR), modified bitumen membranes, and mopping asphalt. BUR represents about 33% of the membrane roofing market and modified bitumen has about 16% of the total market.

2.2.2.1. Built-Up Roofing. BUR has been used since the late 1800s with a variety of reinforcements. Fiber glass mat and organic felt are the reinforcements used today in the United States; fiber-glass mat is used in most of the material produced. BUR roofing systems use several types of felts or reinforcements between layers of asphalt, to build up the roof. Asphalt is used to provide waterproofing and to glue the layers together; the reinforcement is used to span imperfection in the substrate, and strengthen and stabilize the asphalt against flow and movement. The most common type of felt used to construct roofs is called a ply felt. Additionally, a coated base sheet, or ply sheet coated with filled coating on each side, is used when the roof must be nailed to the substrate rather than adhered. Some roofs may use a cap sheet, or a heavily coated sheet with granules on the top side, for anesthetic reasons.

Typical application of a BUR would be to mop or apply asphalt to a substrate to approximately 1.1 kg/m^2 (23 lbs/100 ft^2), or the thickness of a dime. A ply sheet would then be unrolled into the hot asphalt. Additional ply are then mopped in, with each layer offset so that the roof has three or four plies of felt over the entire roof. The amount of offset is calculated by the formula, $\text{offset} = 34\ \text{in.}$ (86.4 cm)/number of plies. Manufacturers of plies print laying lines on the felts at the correct locations to assist in laying up the roof with the correct offset.

Ply sheet manufacture depends on the type of reinforcement used and is similar to the manufacture of asphalt shingle. Fiber-glass mat reinforced ply sheets represent about 95% of the ply sheet produced in the United States. Fiber-glass mats are coated with a hard unfilled coating asphalt, applied thinly so that only the fiber-glass fibers are coated and the sheet retains its porosity to allow gases to escape during the roof application and the interply asphalt to flow together between layers for a stronger roof construction. The ply sheets are produced 3 ft (91 cm) wide in rolls that cover 500 ft^2 (46.5 m^2) with laying lines applied to the top side of the sheets.

Organic ply sheets are manufactured from 3 ft (91 cm) wide organic felts, saturated with soft asphalt, that cover 400 ft^2 (37 m^2). Laying lines are applied to the top side of the ply sheets, and the felts are perforated about 2 to 4 in. (5 to 10 cm) on center to permit the gases to escape during the roof construction process.

2.2.2.2. Modified Bitumen Membranes. These membranes were developed in Europe during the late 1950s and have been used in the United States since the late 1970s. There are two basic types of modified asphalts and two types of reinforcement used in the membranes. The two polymeric modifiers used are atactic polypropylene (APP) and styrene–butadiene–styrene (SBS). APP is a thermoplastic polymer, whereas SBS is an elastomer (see Elastomers, thermoplastic elastomers). These modified asphalts have very different physical properties that affect the reinforcements used.

Atactic polypropylene (APP) is a by-product of the crystalline or high density polypropylene manufacturing process (see Olefin polymers). Its use as a modifier for asphalt was developed in Italy. The addition of APP to asphalt gives a uniform matrix that increases the flexibility of the asphalt at both high and low temperature and improves water penetration resistance as well as ultraviolet resistance. The addition of between 20 and 35% APP increases the softening point of the asphalt mixture to about 149°C, which is high enough to prevent slippage on the rooftop. This higher temperature does not allow fusion between the APP coating and the mopping asphalt to take place or a bond to develop between the mopping asphalt and the membrane. For this reason, APP membranes are generally installed using a gas-fired torch to melt the thick back coating of APP-modified asphalt; thus it is used as the mopping or interply asphalt. This application technique is valuable when it is difficult to get hot asphalt to the rooftop. Even though the ultraviolet resistance is improved over nonpolymer modified asphalt, most manufacturers recommend that APP membranes have a coating or other protective surface applied to protect the bitumen from ultraviolet radiation damage. Most APP membranes use a nonwoven polyester mat as the reinforcement in the membrane. This increases the flexibility of the sheet. Also, APP membrane systems generally include a basesheet or other underlayment sheet, making them a minimum of a two-ply system, which provides a second layer of protection against leaks.

Styrene–butadiene–styrene modified bitumen is an elastomeric material mixed into an asphalt between 10 and 15%. By using high energy mixing, the SBS is uniformly dispersed throughout the asphalt to form a network, referred to as phase reversal because the minor component's (SBS) physical properties are displayed by the final mixture. A properly formulated SBS asphalt blend has an elongation of 100% or greater and is flexible down to temperatures below -6°C.

SBS membrane systems are generally installed in hot asphalt but can be installed using a torch like APP products or in some cold application cement systems. Like APP systems, they are generally installed in multiple layers. The underlayment layers are generally standard BUR felts or basesheets. SBS membrane sheets can also be formulated to be self-adhering. These products are no longer used in membrane applications but are used as ice and water dam materials on the eaves under shingle roofs in cold climates.

Both fiber-glass mats and polyester mats are used either individually or combined in SBS membrane sheets. Because of the elastomeric properties of the asphalt, SBS sheets have developed a reputation as being very tough and abuse-resistant. However, they do not have any better ultraviolet resistance than conventional asphalts, so most of the SBS sheets come with a factory-applied surfacing of granules.

2.2.2.3. Mopping Asphalt. When it was discovered in the late 1800s that oxidizing asphalt gave improved properties of tenacity, less brittleness, and less changes with temperature, the asphalt roofing industry was off and running. Mopping asphalts are air-blown or oxidized asphalts classified in ASTM D312 by softening point and penetration into the four types described below.

Type I asphalt is the softest type of mopping asphalt with softening points between 68°C and with penetration at 25°C between 18 and 50 mm/10. It is for roof slopes of less the $\frac{1}{4}$ in. per ft (0.25 per 12). It is also called dead level asphalt and is not commonly used today because of the porosity of the fiber-glass ply felts and the industry recommendation that roof slope a minimum of $\frac{1}{4}$ in. per ft.

Type II asphalt is the second most common type of asphalt used because it offers the best compromise between softness and weatherability and lack of flow at rooftop temperatures. It has softening points between 71 and 79°C with penetration at 25°C between 18 and 40 mm/10. It is for roof slopes less than 1 per 12 and is also called flat asphalt. If Type II asphalt is used on the roof, it cannot be used on flashings.

Type III asphalt is the most common type of asphalt used. It has softening points between 85 and 93°C with penetration at 25°C between 15 and 35 mm/10. It is for roof slopes between $\frac{1}{4}$ (0.63 cm) and 3 in. (7.6 cm) per ft (30.5 cm), ie, 0.25–3 per 12 and is also called steep asphalt or 190 asphalt, in reference to its nominal softening point (190°F = 88°C). Type III asphalt can be used on flashings, except in the hottest climates.

Type IV asphalt is not common except in very hot climates. It has softening points between 96 and 107°C with penetration at 25°C between 12 and 25 mm/10. It is for roof slopes greater than 1 per 12, and is also called special steep asphalt. Type IV asphalt is used on flashings and in hot climates to keep the roofing system from sliding off the roof in hot weather.

2.2.3. Coal Tar

In roofing, coal tar is used as mopping bitumen in between 15 and 20% of the BUR roofs installed. Coal-tar pitch and asphalt are considered incompatible and should not be mixed. If mixed, an oily exudate is formed that plasticizes the bitumen, and the mixture remains soft and does not weather well. For this reason, if coal tar is used in BUR systems the felts must be coal-tar saturated. There has been some success using asphalt-coated fiber-glass mat felts with coal-tar pitch. However, this has only been done for a limited number of years so the actual compatibility is not fully known.

3. Gypsum Products

Gypsum [13397-24-5], $CaSO_4{\cdot}2H_2O$, is a naturally occurring mineral found mainly in the western United States and eastern Canada (see Calcium compounds, calcium sulfate). The purer deposits require only minimal beneficiation to get a product pure enough for commercial applications. Other deposits require cleaning to remove clay and other impurities.

The principal use of gypsum in construction is as a wall finishing material. The manufacturing process requires that the gypsum be partially dehydrated to the hemihydrate [10034-76-1], $CaSO_4{\cdot}\frac{1}{2}\,H_2O$, commonly known as plaster of paris. When mixed with water the hemihydrate dissolves and the gypsum precipitates out as the interlocking crystals that make gypsum a hard monolithic material. The reaction is rapid, exothermic, and autocatalyzed by gypsum itself. For some applications the reaction is slowed by the addition of protein materials to the hemihydrate–water mixture.

In the United States, over 90% of the gypsum products sold are as gypsum board. Gypsum board is used as an interior wall surfacing in both residential and nonresidential construction and is referred to as drywall to differentiate it from the older wet plaster walls. The board is composed of a core of gypsum attached to a facing of heavy paper and is attached to the framing members using either nails or screws made especially for installing drywall. The joints between the board are cosmeticly treated with a reinforcing tape and joint compound composed of mineral fillers and a thermosetting resin emulsion; some flow control and viscosity modifiers may be added to help get an easy, smooth-applying system. The reinforcing tape, either a 5-cm wide paper or fiber mesh, is embedded into the joint compound, allowed to dry, and then topped with a second or third coat of joint compound to obtain a smooth surface. To help in the taping process most board is produced with a tapered edge on the long edges.

The standard sized sheets are four ft (1.22 m) wide and from 8 to 16 ft long. Sheets are available in thicknesses from $\frac{1}{4}$ up to 1 in. (0.63 to 2.5 cm), but the most common thicknesses are $\frac{1}{2}$ and $\frac{5}{8}$ in. (1.3 and 1.6 cm). There are special products for bathrooms, such as moisture-resistant board (3% of market) and sheathing applications (2% of market), but the vast majority of the product sold is either standard board (60% of market) or the fire-rated Type X board (29% of market). Type X (1.6 cm thick) is the basis of most of the one-hour fire walls in buildings built since the 1960s.

The total market for gypsum product in 1989 was approximately $2.47 billion. Of this amount, 70% was sold by the three largest producers.

3.1. Gypsum Board Manufacture

The manufacture process begins with the mining of the gypsum rock from open-pit mines. After mining, the rock is crushed and cleaned to an 85% purity level or better. In a process called calcination, the powdered gypsum is heated to dehydrate the gypsum to the hemihydrate. The calcination process is carried out as either a continuous process, ie, flash calcining, or by the older batch-type process, ie, kettles process. The calcined gypsum or hemihydrate, also called stucco, is ready to be mixed with water, soap foam to reduce the core density, accelerator or retarders to adjust the reaction rate, and other additives used by the manufacturer. Other additives include starch to help with the core facer bond, vermiculite and glass fibers in the Type X product, asphalt–wax emulsions in moisture-resistant products, and pulped waste paper for added strength. These ingredients are all mixed with a high speed mixer and the resultant mix dumped out onto the face paper, which is prefolded so it can wrap around to the back side of the core. The backing paper is brought down and bonded to the folded over edges of the face paper, and the whole assembly is sized for thickness by a roller and doctor bar.

Gypsum board paper is a special three-ply paper manufactured from repulped newspapers. The face paper or cream face has the ply against the core unsized so that the gypsum crystals can grow into it, as this is the principal form of bonding between the core and facers. The middle ply is sized and the outer ply is more heavily sized and treated to control paint absorption. For the completed gypsum board system to work, the joint treatment and paper must absorb paint at the same rate.

The back paper or gray back is also a three-ply paper very similar in construction to the face paper, except it is approximately 4 ft (1.2 m) wide and the outside surface is not treated for paint absorption like the cream face.

To produce tapered edge wallboard, tapered belts are added to the rubber conveyor belt that carries and supports the board while the gypsum core sets up, typically in about four minutes.

After the core sets up, but while it is still wet, the board is cut to rough length, flipped over so that it goes through the oven on the back side, and sent in to dry. The drying step must be done with care otherwise the board will dry too fast, releasing steam faster than it can escape from the facers and blow the facers off the core. In addition, if the board is heated too much the gypsum crystals that have grown into the facer will be calcined, thus destroying the bond.

After exiting the oven, the boards are cut to final length, packaged face to face, and the four-foot edge is taped making a “book.” From there it is ready for shipment to the customers.

4. Portland Cement

Portland cement is the most widely used construction material in the world (see Cement), especially in Third World nations, because of its availability, ease of use, and versatility. Estimated 1989 worldwide production is almost 1.12 billion metric tons. The United States represented 71.2 million metric tons, ie, fourth, behind China (207 million metric tons), the former USSR (140 million metric tons), and Japan (82 million metric tons). Spain is tenth with 27 million tons. The top 10 world producers of Portland cement account for just under 43% of the total production.

Portland cement is classified as a hydraulic cement, ie, it sets or cures in the presence of water. The term Portland comes from its inventor, Joseph Aspdin, who in 1824 obtained a patent for the combination of materials referred to today as Portland cement. He named it after a grayish colored, natural limestone quarried on the Isle of Portland, which his cured mixture resembled. Other types of hydraulic cements based on calcium materials were known for many centuries before this, going back to Roman times. Portland cement is not an exact composition but rather a range of compositions, which obtain the desired final properties. The compounds that make up Portland cements are calcium silicates, calcium aluminates, and calcium aluminoferrites (see).

Portland cement is not useful by itself to the construction industry. Its value is in the resultant concrete in which it is used as a binder. Concrete is a mixture of smaller particles that coalesce into a solid mass, and the typical particles in a Portland cement concrete are aggregates of rock and sand. In general, the larger the aggregate size the stronger the Portland cement concrete. The crush and shear resistance of the aggregate, and the ratio of Portland cement to sand and aggregate are important to the strength of Portland cement concretes, with higher Portland cement levels yielding stronger concrete.

4.1. Portland Cement Manufacture

Portland cement is manufactured by two basic processes, the wet process and the dry process. The dry process uses approximately 25% less energy per ton of Portland cement and is used to produce about 68% of the U.S. Portland cement. Both processes start by mixing selected raw materials, crushed and/or milled to approximately $\frac{3}{4}$ in. (1.9 cm) diameter, in the correct ratios to give the final desired chemical composition.

The choice of selected raw materials is very wide, but they must provide calcium oxide (lime), iron oxide [1309-37-1], silica, and aluminum oxide (alumina). Examples of the calcereous (calcium oxide) sources are calcium carbonate minerals (aragonite [14791-73-2], calcite [13397-26-7], limestone [1317-65-3], or marl), seashells, or shale. Examples of argillaceous (silica and alumina) sources are clays, fly ash, marl, shale, and sand. The iron oxide commonly comes from iron ore, clays, or mill scale. Some raw materials supply more than one ingredient, and the mixture of raw materials is a function of their chemical composition, as determined by cost and availability.

In the wet process, the correct ratios of raw materials are ground up and mixed in a water slurry to a uniform intimate mixture, which is sent to the kiln where the chemical reactions take place to form the Portland cement composition. In contrast the dry process does all the grinding and blending on dry materials. Following the grinding and blending step, both wet and dry processes are very similar. The chemical transformations take place at high temperatures in a rotating kiln, which has large sloped rotating tubes whose length and diameter determine the production rate.

Kilns in the United States range in size from about 50,000 metric tons per year to 1.36 million metric tons per year of production. The ground raw materials are fed into the upper end of the kiln, while the lower end is fired to temperatures of 1425 to 1650°C using either coal, oil, or gas; approximately 85% of the production capacity is coal fired. The ground raw materials are moved countercurrent to the hot exhaust gases by the slope and rotation of the kiln. While moving down the kiln, the raw materials have some components driven off as gases whereas the remaining components are combined to form a material with new chemical and physical properties called clinker. Clinker is a grayish black marblelike pellet approximately 1 cm in diameter. It is collected, cooled, and then ground to a fine powder with a small amount of gypsum to regulate the setting time of the cement. The grinding produces a very fine powder with 90% finer than 75 μm and 80% finer than 50 μm. This is Portland cement.

The manufacture of Portland cement is very energy intensive. It has been identified by the Department of Commerce as one of the six most energy intensive industries per ton of product. Portland cement is also very heavy, having a specific gravity of 3.15; thus it is not shipped very far. This accounts for the presence of over 100 plants around the United States. Industry data show that the average shipping distance for Portland cement is approximately 176 km.

4.2. Types of Portland Cement

ASTM C150 Standard Specification for Portland cement defines eight types of Portland cement produced to meet the performance requirements of different applications.

4.2.1. Type I (Normal)

This is the general purpose Portland cement used for all applications where special properties are not needed. Common applications include concretes for paving, building floors, roof decks, reinforced concrete buildings, pipes, tanks, bridges, and other precast concrete products. In 1989 Type I and Type II accounted for over 92% of the Portland cement produced in U.S. plants. Exact data are not available that separate Type I and Type II Portland cement, but it can be assumed that Type I production was much greater than Type II.

4.2.2. Type II (Moderate Sulfate Resistance)

This Portland cement is used where exposure to sulfate attack at concentrations between 150 and 1500 ppm is possible, such as drainage structures where higher than normal sulfate exists in ground water. Type II Portland cement releases about 80 to 85% of the heat of hydration of Type I Portland cement during the first seven days and is used where slightly lower than normal heats of hydration are needed, such as in structures with considerable mass, ie, large piers and retaining walls. This keeps the internal heat on the poured structure down, increasing its final strength. Type II Portland cement is also often used in warm weather construction.

4.2.3. Type III (High Early Strength)

Type III Portland cement provides higher strength earlier (one week) than does Type I (four weeks) Portland cement, but it generally does not achieve the same final strength as Type I. Chemically, Type III is the same as Type I except it is ground finer. Type III is used where it is necessary to remove the forms quickly or in cold weather where it is desirable to have less time under controlled temperature conditions. It releases about 150% of the heat of hydration of Type I Portland cement during the first seven days. Production of Type III Portland cement in the United States in 1989 was approximately 3.7% of the total Portland cement production.

4.2.4. Type IV (Low Heat of Hydration)

Type IV is used where the rate and amount of heat generated from hydration have to be minimized, ie, large dams. Compared to Type I, Type IV Portland cement has only about 40 to 60% of the heat of hydration during the first seven days and cures at a slower rate. In large structures such as dams where the heat of hydration cannot be readily released from the core of the structure, the concrete may cure at an elevated temperature, and thermal stresses can build up in the structure because of nonuniform cooling that weakens the structure. U.S. production of Type IV Portland cement is less than 1%.

4.2.5. Type V (High Sulfate Resistance)

Type V Portland cement is used in concrete exposed to severe sulfate attack of 1,500 to 10,000 ppm. Low concentrations of tricalcium aluminate [12042-78-3] give Type V its sulfate resistance. The sulfate resistance is improved with air entrainment and low water to cement ratios in the wet concrete. U.S. production of Type V Portland cement in 1989 was 0.9% of the total Portland cement production.

Type IS	Portland cement and blast furnace slag cement
Type IP or P	Portland cement and pozzolan cement
Type I(PM)	pozzolan and modified Portland cement
Type S	slag cement
Type I(SM)	slag and modified Portland cement

4.2.6. Air Entraining Portland Cement

Types IA, IIA, and IIIA Portland cements are similar to the standard counterparts, but they are air entraining. During the grinding process, small amounts of air entraining agents are coground with the clinker and form tiny, well-distributed, completely separated, air bubbles during the concrete mixing process at a rate of 6% or more by volume. The air bubbles impart improved freeze–thaw resistance and improved slump or flow at the same water content. Air entrainment can also be obtained with the use of admixes designed to entrain air when standard Portland cements are used.

4.2.7. Other Types of Portland Cements

White Portland cement is standard Type I or III Portland cement with raw materials selected and controlled to have negligible amounts of iron and manganese oxides, which impart the gray color. The white Portland cement is used in decorative and architectural applications like precast curtain walls, terrazzo surfaces, stucco, tile grout, and decorative concrete.

Blended hydraulic cements are used to conserve energy. They are intimate and uniform blends of fine materials such as Portland cement, ground blast furnace slag, fly ash, and other pozzolans, ie, fine, reactive silica sources. ASTM C595 lists five classes or types.

Masonry cements are hydraulic cements designed to have improved workability for use in mortar for masonry construction. The standards are given in ASTM C91.

Expansive cements are hydraulic cements designed to expand rather than shrink on curing, as do standard Portland cements. They are defined in ASTM C845 and are used to control and reduce shrinkage cracks in large poured-in place structures.

Plastic cements are hydraulic cements that have plasticizing agents added to Portland cement during the grinding operation to make them flow better. The primary use for plastic cements is in plasters and stucco.

4.3. Portland Cement Chemistry

The chemistry of Portland cement is not completely understood. During the burning or kiln process, the calcium oxide [1305-78-8] combines with the acidic compounds in the clinker to form four principal compounds that make up approximately 90% of Portland cement by weight. These materials are tricalcium silicate [12168-85-3], $3CaO–SiO_2$; dicalcium silicate [10034-77-2], $2CaO–SiO_2$; tricalcium aluminate [12042-78-3], $3CaO–Al_2O_3$; and tetracalcium aluminoferrite [12612-16-7], $4CaO–Al_2O_3–Fe_2O_3$. When these four materials are mixed with water they hydrate and form other materials that are the infrastructure of the hardened Portland cement paste in concrete. Tri- and dicalcium silicates, which make up about 75% of the Portland cement, react with the water to form calcium hydroxide [1305-62-0] and calcium silicate hydrate, $3CaO{\cdot}2SiO_2{\cdot}3H_2O$, also known as tobermorite gel. In the hydrated Portland cement, tobermorite gel is about 50% by weight and calcium hydroxide, $Ca(OH)_2$, is 25%. It is the tobermorite gel that gives the cured cement its strength and other properties. The hydration of tricalcium aluminate also involves reactions with the calcium hydroxide released by the calcium silicate hydration to form tetracalcium aluminate hydrate, $3CaO{\cdot}Al_2O_3{\cdot}Ca(OH)_2{\cdot}12H_2O$. Lastly, the calcium aluminoferrite hydrates to form calcium aluminoferrite hydrate, $6CaO{\cdot}Al_2O_3{\cdot}Fe_2O_3{\cdot}12H_2O$.

The properties of cured Portland cement are affected by these four constituents of the manufactured Portland cement. Tricalcium silicate hydrates and hardens rapidly, giving rise to the initial set and early strength. Increased concentrations of tricalcium silicate causes an increase in the early strength of Portland cement concretes. Dicalcium silicate hydrates and hardens more slowly, giving the cured concrete its strength increase beyond one week.

Tricalcium aluminate is the principal exothermic reactor in Portland cement giving rise to the heat release during the first couple of days and contributing some to the early strength. Gypsum added during grinding slows down the hydration reaction of tricalcium aluminate, thus controlling the overall reaction rates.

$$3CaO{\cdot}Al_2O_3 + 10H_2O \ + \ \underset{\text{gypsum}}{CaSO_4{\cdot}2H_2O} \longrightarrow 3CaO{\cdot}Al_2O_3{\cdot}CaSO_4{\cdot}12H_2O$$

Low tricalcium aluminate improves sulfate resistance.

Tetracalcium aluminoferrite acts as a processing aid by reducing the clinkering temperature. It hydrates rapidly but does little for any performance property of the cured concrete. It does, however, cause most of the color effects in the cured concrete.

4.4. Applications

The primary market for Portland cement is in building construction, which historically takes approximately 65% of all Portland cement sold. Forty-five percent of the construction market goes for residential construction and 38% goes for commercial construction. These markets use Portland cement for concrete foundations and structural and precast products. Precast products generally have some form of reinforcement in them, either steel reinforcing rods or more generally pretension steel cables that are tensioned prior to pouring the concrete. After the concrete cures, the tension is released and the cables attempt to contract, thus putting the concrete under compression. Portland cement concretes perform very well in compression but poorly in tension. With the addition of steel reinforcing the concrete has good performance in both compression and tension. A newer twist on this concept is post-tensioning where the cable is tensioned and maintained under tension after the concrete sets.

For special high strength applications, ie, up to 69 MPa (10,000 psi), special formulations of Portland cement concretes have been developed. These are based on the use of chemical and mineral admixtures. The typical mineral admixtures are fumed silica and other pozzolanics. The chemical admixtures are generally chemicals termed superplasticizers that allow very low water to cement ratios, ie, between 0.4 and 0.25, and reduce the amount of water needed to provide plasticity or flow to the concrete. Public works applications take just under 32% of the total Portland cement market; streets and highways represent 68% of this usage, and water and waste account for 23%.

5. Bricks

Bricks are the oldest manufactured building material in use. Sun-dried bricks were manufactured as early as 6000 BC, and fired bricks were used during the Middle Ages. Today's bricks differ very little except in the efficiency of manufacture; they are still made from clay or shale, a clay-based sedimentary rock that is kiln-fired.

5.1. Manufacturing Process

There are three processes used to make bricks. All three start with clay that has been milled and screened to remove coarse materials and impurities. The clay used must have enough plasticity when mixed with water to allow molding and have enough wet and dry tensile strength to maintain the brick shape after forming. Water is added to the prepared clay in an amount appropriate for the brickmaking process that will be used. The clay and water mixture is then kneaded with rotating knifes to form a plastic mass, which is then molded into a brick shape by one of the three processes.

The stiff-mud process is the most common method in use. In this process, the clay–water mixture is extruded into a long ribbon of the correct cross-section size. The water content is typically 12 to 15% by weight. Very often before extruding, the clay water mixture is subjected to a vacuum of 50–97 kPa (375 to 725 mm Hg). This step removes air holes and bubbles, thus increasing the strength of the finished brick and the workability of the clay–water mixture. The ribbon is cut to individual brick lengths by rotating wire knifes and the raw bricks stacked for drying and burning, ie, firing.

The soft-mud process is used to make handmade brick. More water is added to the clay to make a thinner paste, typically about 20 to 30% by weight of water. The resulting slurry is packed into molds that have a sand or water coating on them that acts as a release agent. The wet brick shapes are removed from the molds when they have set up enough to handle and are then stacked for drying and burning.

The dry-press process is used to make good quality face brick, ie, brick used on exposed walls. Very little water is added to the clay, less than 10% by weight. This is only enough water to make the clay damp. The damp clay is then pressed into molds under pressures of 3.4 to 10.3 MPa (500 to 1500 psi). The damp brick shapes are removed from the molds when they have set up enough to handle and are stacked for drying and burning.

Following the forming process, the bricks are dried in drying rooms where hot air (38 to 204°C) is circulated. The bricks must be dried slowly to prevent large amounts of shrinkage and cracking. Drying times depend on the condition and the moisture content on the brick shapes, but normally range from 24 to 48 h.

After drying, the bricks are put into a kiln where the temperature is raised slowly to between 870 and 1316°C or higher depending on the temperature needed to fuse the clay. With the clay particles partially melted and fused together, the brick is a ceramic material with excellent strength and fire resistance.

There are two basic types of kilns used, the tunnel kiln and the periodic kiln. The tunnel kiln has the highest production rate and uses cars to carry the dried brick through the firing or burning process. Tunnel kilns can produce from 40 to 80 million bricks a year each. The periodic kiln is a batch-type kiln that is loaded, run through the cycles, and then emptied. Because of the firing process, brick manufacture requires much energy, which represents approximately 35% of the total manufacturing cost.

There are six stages of firing. Water-smoking is the evaporation of free water, done at temperatures up to 204°C. Dehydration removes the chemically combined water from the clay structure at temperatures between 149 and 982°C. During oxidation the iron oxide is oxidized to ferrous oxide, which gives a red color. It is done between 538 and 982°C. Vitrification fuses the clay particles together at temperatures between 871 and 1316°C. Flashing runs the kiln with a reducing atmosphere at a temperature below the vitrification temperature to produce color variation. Reduced iron oxides are purple in color. Cooling brings the hot brick down to near ambient temperature slowly, over 48 to 72 h, to keep the bricks from cracking and changing color.

Bricks are available with several types of textures: roughened, smooth, or glazed with a glasslike glaze coating applied to its face. In the United States 94% of the production is face brick used for the outer surface of a wall. The bulk of the remainder is backing or common brick used behind face brick.

The brick industry in the United States is comprised of approximately 120 companies that operate 236 plants across the country. Their sales in 1989 were $1.2 billion, with 64% in residential construction, 31% in commercial construction, and 5% for nonbuilding usage. Brick was used on 31% of new commercial buildings and 17% of new homes built.

6. Glass

Glass (qv) was not used until the early 1800s as a construction material. Prior to the 1930s the only use of glass for construction was in windows. In the mid-1930s, fibrous glass was developed, which is widely used as an insulation material.

The term glass has two meanings, ie, the material and a state of matter. The glassy or vitreous condition is where the atoms of the material have a random orientation. This amorphous or noncrystalline nature leads to physical properties typical of the product called glass, including unpredictable breaks, no sharp melting temperature, and no heat of fusion.

The products called glass are in the glassy state and are made mainly from silica [7631-86-9] (silicon oxide [10097-28-6], SiO_2). Sodium oxide [1312-59-3], Na_2O, and calcium oxide [1305-78-8], CaO, are commonly added up to 30% or more in combination. Sodium oxide is added to reduce the viscosity or melting temperature of the silica, whereas calcium oxide gives the glass durability against water attack. Glasses can contain a wide range of oxides depending on the application and properties needed of the glass. Examples of other oxides include the oxides of boron, aluminum, potassium, magnesium, lead, barium, zinc, and lithium.

Sand is the common silica source, but the sand must have only minor impurities in order to make good quality, clear glass. A common source for sodium oxide is sodium carbonate [497-19-8], Na_2CO_3, from soda ash. Upon heating in the glass furnace it forms the oxide. Calcium oxide comes from limestone, which when burnt becomes lime [1305-78-8], CaO. Alumina [1344-28-1] commonly comes from feldspar [68476-25-5], which is an alumina silicate rock. Boron oxide [1303-86-2] is obtained from borax, sodium tetraborate [1330-43-4], $Na_2B_4O_7{\cdot}10H_2O$. Other oxides generally are not used in large amounts or at all in glass construction materials.

Uses of glass in construction products fit into three categories: flat glass (window glass); fibrous glass; and specialty glass products. Each is made by different processes and has different applications.

6.1. Flat Glass

Flat glass is widely used in applications other than construction, such as automotive glass, etc, but approximately 57% of the flat glass is used in construction applications, mainly as windows. This represents about $2.2 billion worth of material in 1989 for the United States.

The float glass manufacturing process was developed by Pilkington Brothers Ltd. of England in 1959. It starts with a large continuous tank furnace in which finely ground glass raw materials are added at one end and molten glass is removed at the other end. Typically the tank is heated with natural gas to melt the glass. The glass must be retained in the tank after it melts for a period of time to allow the materials to fully intermingle and form good quality glass. The molten glass is then fed onto a tank of molten tin called a float bath. The temperature of the molten tin is carefully controlled so that any imperfections in the bottom surface of the glass can be melted out. Since the melting temperature of tin is lower than that of glass, the glass starts to solidify on the tin, incorporating the smooth surface of the molten tin on its underside and a smooth surface on the air side. The glass sheet is then annealed, ie, heated below its melting temperature, with controlled cooling to relieve stresses. The glass is then cut into smaller pieces.

6.2. Fibrous Glass

Fibrous glass is manufactured in two different forms, very fine intermingled fibers called insulation fibrous glass for insulation and fine but coarser fibers called continuous or textile fibers for reinforcement and other textile applications. Both products have construction related applications.

6.2.1. Insulation Fibrous Glass

Most insulation fibrous glass is manufactured by a rotary process. The glass is melted in either continuous tank furnaces or electric furnaces. The molten glass is directed to a rapidly spinning disk with a multitude of fine holes in its rim, which operates very much like a cotton candy machine in that the molten glass is extruded out of the hole by centrifugal force. The fine fibers are further attenuated or drawn finer by jets of air or flame. Fibers typically have average diameters of 3 to 6 μm. The fibers are immediately coated with either a binder or a dedusting agent and collected into the familiar insulation batt. Most insulation fibrous glass is coated with a phenol–formaldehydebased resin that is cured in an oven. The density of the final product depends on the amount of compression done on the blanket in the curing oven and the needs of the application for which the product is manufactured. Densities of less than 0.0624 kg/m^3 to over 0.624 kg/m^3 can easily be made. Besides wall insulation batts, fibrous glass is used to insulate and make air ducts and insulate pipes and equipment. Fibrous glass is not only used to insulate against heat flow but is also commonly used for sound absorption and control applications.

Fibrous glass insulation products require energy in their manufacture. However, it has been estimated that they save approximately 20 J per year for each joule used in production. In the United States in 1980, approximately $1.9 billion of insulation fibrous glass was sold, which is over 1.4 billion kg.

6.2.2. Continuous Filament Fibrous Glass

This glass is manufactured by drawing molten glass out of a bushing, which is manufactured from platinum or platinum alloys and contains many holes. The diameter of the continuous filament fibrous glass is dependent on the rate that the glass is pulled from the holes of the bushing. Immediately after coming out of the bushing the fibers are coated with either a chemical coating called a size, or water to protect the glass surface from damage. Continuous filament fibrous glass is commonly manufactured in fiber diameters between 10 and 16 μm.

The largest market, approximately 30% in 1989, for continuous filament fibrous glass in the United States construction markets is as fiber-glass mat used to make roofing materials. This is manufactured on a wet forming machine similar to equipment used to make paper or polymer nonwovens. Other uses of fiber glass mat include backing for vinyl flooring and wallpaper. The other market for continuous filament fibrous glass products in the construction market is as fiberglass reinforced polymer materials like bathtubs and shower stalls (see Reinforced plastics).

6.3. Specialty Glass Products

Foam glassinsulation and glass building blocks are two specialty glass products with construction applications.

Foam glass was invented in 1942 and is a closed cell glass material blown with hydrogen sulfide gas. It is used in industrial and roof insulation applications where its extremely low moisture permeability is valuable.

Glass building blocks are manufactured by molding both sides of the block, then fusing the two sides together to form the block. They are used to let light into buildings while still having some insulation value because of the dead air space inside the block.

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THEODORE MICHELSEN
Schuller International

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