BUILDING MATERIALS, PLASTIC

Plastics are playing an increasingly important role in the building materials market. From 1980 to 1990 the growth in total plastics volume consumed for building and construction applications averaged 6% annually, nearly two times the average gross national product (GNP) growth over the same period. Whereas plastics were first employed for decorative and nonstructural purposes, today they are used increasingly in functional and structural applications.

Throughout the 1990s, plastics consumption in building materials is forecast to grow at 4–5% average annual rate. Contributing to this growth will be advances in do-it-yourself and professional remodeling products employing plastics, overall growth in the renovation and home remodeling markets, plus the increased penetration of plastics at the expense of traditional materials in building products because of their superior strength in weight performance, corrosion resistance, environmental stability, lower cost, insulation properties, and ability to fabricate complex designs into a single part, ie, low labor assembly intensity. On the other hand, the overall growth of plastics in building materials will be somewhat limited by concerns over their flammability and smoke toxicity, public perception of their negative environmental impact, resistance by the conservative construction industry in adopting new materials, and competitive actions by producers of traditional building materials, such as wood, concrete, glass, and metal seeking to defend their market positions.

1. Polymers and Properties

The physical properties of plastics that are important in building materials are the glass-transition or melt temperature, ease of processing, as indicated by the temperatures and pressures needed for molding, heat deflection temperature, uv stability, tensile and impact strength, oxidative degradation, creep set, fatigue, and elongation. Density, thermal conductivity, and fire resistance are important for foams. The most important plastics building materials are described below, and their physical properties are summarized in Table 1.

1.1. Low and Linear Low Density Polyethylene

Low density polyethylene (LDPE), 0.91–0.94 g/cm^3, is a thermoplastic that melts at ca 115°C. It is insoluble at room temperature but dissolves in various solvents when molten. During polymerization, side reactions cause chain branching. The degree and kind of branching can be controlled to a considerable extent and the properties of the polymer correspondingly modified. Branching decreases crystallinity and density and increases the molecular weight distribution. A decrease in crystallinity decreases hardness, stiffness, melt temperature, and chemical resistance; it increases toughness, flexibility, and permeability. An increase in molecular weight distribution facilitates processing but reduces strength, toughness, and resistance to environmental stress-cracking. The average molecular weight also affects these properties. Increasing molecular weight increases the strength, toughness, and melt temperature but decreases the ease of processing and the melt index.

Table 1. Physical Properties of Selected Plastic Building Material[a]

Properties of plastic[b]	LDPE	LLDPE	HDPE	PP	PVC (flexible)	PS	ABS	Polyacrylic (glazing)	Polycarbonate (glazing)	Epoxy (mineral filled)	Acetal homopolymer
melting point, °C	96–115	122–124	130–137	160–175							175–181
glass-transition temp T_g, °C					75–105	74–105	110–125	90–105	140–150		
injection molding temperature, °C	150–232	177–260	176–274	204–288	160–196	177–260	193–260	163–260	270–295		193–243
injection molding pressure, MPa[c]	34–103	34–103	83–103	69–138	7–14	34–138	55–172	34–138	55–140		69–136
tensile strength, MPa[c]	8–31	13–26	22–31	31–41	7–24	35–52	22–55	46–76	65	48–90	67
elongation, %	100–650	100–965	10–1200	500–600	200–400	1–5	2–25	2–10	110	1–3	25–75
Izod impact strength, J/m[d]	no break	no break	21–213	21–64	varies widely	18–24	74–640	16–32	750	16–24	64–123
heat-deflection temperature, °C	40–44		80–91	107–121		66–96	96–118	80–107	138		

[a]Ref. 1.
[b]LDPE = low density polyethylene; LLDPE = linear low density polyethylene; HDPE = high density polyethylene; PP = polypropylene; PVC = polyvinyl chloride; PS = polystyrene; ABS = polyacrylonitrile – butadiene – styrene.
[c]To convert MPa to psi, multiply by 145.
[d]To convert J/m to ft-lbf/in., divide by 53.38 (see ASTM D256).

Linear low density polyethylene (LLDPE), 0.91–0.94 g/cm^3, is a copolymer of ethylene with an alpha-olefin such as 1-butene, 1-hexene, 1-octene, and 4-methyl 1-pentene. Polymerization to LLDPE is frequently carried out in the gas phase, eg, Union Carbide UNIPOL and British Petroleum gas-phase technologies, employing a catalyst. Linear low density polyethylenes provide additional melt strength, toughness, and tensile strength relative to low density polyethylene (see Olefin polymers). Toughness and flexibility are desired for film; high strength for piping. The relation of branching to crystallinity, molecular weight, and molecular weight distribution are important in achieving the desired properties in the product.

The principal use of LDPE and LLDPE in building products is as a film water barrier under below-grade floors; as a wall vapor barrier, though PVC is typically preferred; and as temporary enclosure film during construction. The film is made either by extruding a thin-walled tube, which may be slit or wound up directly, or by extrusion through a slot die and cast directly on to a cold roll, cooled, then wound up. The former method is more widely used. A much smaller use for low density polyethylene is in piping.

1.2. High Density Polyethylene

High density polyethylene (HDPE), 0.94–0.97 g/cm^3, is a thermoplastic prepared commercially by two catalytic methods. In one, coordination catalysts are prepared from an aluminum alkyl and titanium tetrachloride in heptane. The other method uses metal oxide catalysts supported on a carrier (see Catalysis).

HDPE melts at about 135°C, is over 90% crystalline, and is quite linear, with more than 100 ethylene units per side chain. It is harder and more rigid than low density polyethylene and has a higher melting point, tensile strength, and heat-deflection temperature. The molecular weight distribution can be varied considerably with consequent changes in properties. Typically, polymers of high density polyethylene are more difficult to process than those of low density polyethylene.

Additives are used extensively in compounding this resin. Antioxidants (qv), uv stabilizers, especially carbon black (qv), and fillers (qv) such as glass fibers, silica, or clay provide properties desirable for various purposes.

High density polyethylene is widely used for pipes and drains, especially in large-diameter corrugated forms. The corrugations provide stronger walls at less thickness, which reduces the materials cost of the pipe.

1.3. Polypropylene

Polypropylene [9003-07-0] and high density polyethylene are both thermoplastics prepared with a coordination catalyst in the same type of equipment. The crystallinity of polypropylene gives it high tensile strength, stiffness, and hardness that are retained at high temperatures. It also is free from environmental stress-cracking. However, the hydrogen atoms bonded to tertiary carbons are susceptible to degradation by oxygen, uv light, and heat. Polypropylene, like high density polyethylene, can be stabilized by antioxidants and uv absorbers (see Olefin polymers).

Polypropylene can be fabricated by almost any process used for plastics (see Plastics processing). The extrusion of pipe and injection molding of fittings present no unusual problem. However, there is no way to bond the fittings to the pipe except by remelting the polymer, which is impractical on most construction sites. The resin can be reinforced by glass fibers, mineral fillers, or other types of fillers and can be pigmented readily.

1.4. Poly(vinyl chloride)

Poly(vinyl chloride) (PVC) [9002-86-2] is a thermoplastic for building products. It is prepared by either the bulk or the suspension polymerization process. In each process residual monomer is removed because it is carcinogenic. Oxygen must be avoided throughout the process (see Vinyl polymers).

The polymer is only slightly crystalline, mainly syndiotactic, but with so low a degree of order that only small crystallites are formed. It is fundamentally unstable to heat and light and loses hydrogen chloride by an autocatalytic reaction. Zinc and iron salts also strongly catalyze the decomposition. Many stabilizers, especially combinations of acid acceptors and antioxidants, produce satisfactory results except at high temperatures. The high density, a result of the high chlorine content, is offset by the low cost; thus the cost:volume ratio is quite attractive.

Vinyl chloride polymers are produced in two main types, homopolymers and copolymers, usually with vinyl acetate. Both types can be plasticized by a wide variety of plasticizers (qv), usually esters. Rigid or unplasticized PVC is used extensively for pipe. The plasticized material is used largely in floor coverings. The homopolymer itself is inherently fire-resistant, but addition of plasticizers, unless they are especially fire-resistant, considerably reduces this characteristic (see Flame retardants).

Rigid, unplasticized PVC is stronger, with a higher tensile strength, than the polyolefins including polystyrene and ABS resins. It is not as strong as oxygenated polymers, eg, polyacrylics, polycarbonates, acetal resins (qv), and epoxy resins (qv), though it is similarly intermediate in elongation. Because of its instability to heat, rigid vinyl must be processed quickly, at low temperatures and correspondingly high pressures. PVC is the plastic used most widely in building products; nearly 60% of all PVC is used for this purpose.

1.5. Polystyrene

Polystyrene [9003-53-6] is a thermoplastic prepared by the polymerization of styrene, primarily the suspension or bulk processes. Polystyrene is a linear polymer that is atactic, amorphous, inert to acids and alkalies, but attacked by aromatic solvents and chlorinated hydrocarbons such as dry cleaning fluids. It is clear but yellows and crazes on outdoor exposure when attacked by uv light. It is brittle and does not accept plasticizers, though rubber can be compounded with it to raise the impact strength, ie, high impact polystyrene (HIPS). Its principal use in building products is as a foamed plastic (see Foamed plastics). The foams are used for interior trim, door and window frames, cabinetry, and, in the low density expanded form, for insulation (see Styrene plastics).

1.6. ABS Resins

Acrylonitrile–butadiene–styrene [9003-56-9] resins are thermoplastics that have a wide variety of composition, preparation conditions, and properties. Compositions generally run about 20–30% acrylonitrile, 20–30% butadiene, and 40–60% styrene. The resins are typically tough and rigid, easy to extrude or mold, and have good thermal and abrasion resistance. They can be alloyed and blended with other resins, especially poly(vinyl chloride) or polycarbonate [24936-68-3], and can be shaped by almost any plastic-fabrication process: injection molding, extrusion, or thermoforming. They are used in automotive, marine, and communications applications. In building products, they are used for pipes, ducts, and structural foam. High impact grades used in piping have an Izod strength of over 400 J/m (>7.5 ft $-$ lb/in.) (see Acrylonitrile polymers).

The structural foams are made by means of a blowing agent or by mixing a gas into the hot melt, then injecting it into a mold where the gas expands to form a cellular product. The foams are used for large parts in which light weight and rigidity are desired. Extrusion and free expansion are also used.

1.7. Polymethacrylates

Poly(methyl methacrylate) [9011-14-7] is a thermoplastic. It is the acrylic resin most used in building products, frequently as a blend or copolymer with other materials to improve its properties. The monomer is polymerized either by bulk or suspension processes. For glazing material, its greatest use, only the bulk process is used. Sheets are prepared either by casting between glass plates or by extrusion of pellets through a slit die.

This second method is less expensive and more commonly used. Peroxide or azo initiators are used for the polymerization (see Methacrylic polymers).

The polymer is clear and colorless and remains so on outdoor exposure; thus it often is used for glazing and lighting. Because the resin is softer than glass, various coatings are applied to improve its abrasion resistance. It is strong, tough and, when used as glazing, does not shatter if broken. These qualities render it suitable for vandal-resistant window panes and outdoor light globes. It also is used in plumbing fixtures, simulated-marble compositions, lavatory bowls, vanity tops, countertops, and bathtub–shower units.

1.8. Polycarbonates

Polycarbonates (qv) are partly crystalline thermoplastics with some disorder in the crystalline part and considerable order in the amorphous part. This disorder conveys high impact strength which, combined with its good transparency and outdoor exposure resistance, makes polycarbonates useful for vandal-resistant glazing and outdoor lighting. It is easily processed by extrusion and injection molding. Various uv and flame-retardant agents are often added.

1.9. Epoxy Resins

Epoxy resins (qv) or polyether resins are thermosets used as the binder for terrazzo flooring. The epoxy resin often is made from epichlorohydrin and bisphenol A. An excess of epichlorohydrin is used to assure that the intermediate product contains terminal epoxide groups. This resin, usually a viscous liquid, is mixed with fillers, pigments, and a curing agent. The mix is then applied to the substrate, and cure is obtained in a few hours. The product is strong, tough, and resistant to chemicals and abrasion. It is used for industrial and other floors subject to hard water. The use of epoxy resins for this purpose is only a small fraction of its total use.

1.10. Acetal Resins

Polyacetals are either homopolymer [9002-81-7] or copolymer [95327-43-8] thermoplastics (see Acetal resins). Both are based on formaldehyde [50-00-0] through acetals or trioxane and are highly crystalline, strong, and rigid with high melting points. They are made in a variety of grades with different melt indexes and are processed easily by extrusion or injection molding. They can be reinforced with glass or fluorocarbon fibers and can be pigmented. Both have high resistance to creep and abrasion and low coefficients of friction. They are used as engineering resins and in building products for plumbing fittings such as ball cocks, faucets, pumps, and valves, which are subject to steady wear and must retain close dimensional tolerances. Polyacetals are flammable; however, because of the high oxygen content, they burn cleanly and produce no smoke (2–5).

1.11. Amino Resins

Amino resins (qv) include both urea- and melamine–formaldehyde condensation products. They are thermosets prepared similarly by the reaction of the amino groups in urea [57-13-6] or melamine [108-78-1] with formaldehyde to form the corresponding methylol derivatives, which are soluble in water or ethanol. To form plywood, particle board, and other wood products for adhesive or bonding purposes, a liquid resin is mixed with some acid catalyst and sprayed on the boards or granules, then cured and cross-linked under heat and pressure.

The decorative plastic laminates widely used for countertops and cabinets are based on melamine–formaldehyde resin (see Laminates). Several layers of phenolic-saturated kraft paper are placed in a press and a sheet of α-cellulose paper printed with the desired design and impregnated with melamine–formaldehyde resin is placed over them. Then a clear α-cellulose sheet, similarly impregnated with the resin, is placed on top to form a clear, protective surface over the decorative sheet. The assembly is cured under heat and pressure

up to 138°C and 10 MPa (1450 psi). A similar process is used to make wall paneling, but because the surfaces need not be as resistant to abrasion and wear, laminates for wall panels are cured under lower pressure, about 2 MPa (290 psi).

Amino resins are lighter in color and have better tensile strength and hardness than phenolic resins; their impact strength and heat and water resistance are less than those of phenolics. The melamine–formaldehyde resins are harder and have better heat and moisture resistance than the urea resins, but they are also more expensive. The physical properties of the melamine–formaldehyde laminates are listed in Table 1.

1.12. Phenolic Resins

Phenolic resins [9003-35-4] (qv) are thermosets prepared by the reaction of phenol with formaldehyde, through either the base-catalyzed one-stage or the acid-catalyzed two-stage process. The liquid intermediate may be used as an adhesive and bonding resin for plywood, particle board, fiberboard, insulation, and cores for laminates. The physical properties for typical phenolic laminates made with wood are listed in Table 1.

1.13. Polyester Resins

Reinforced polyester resins are thermosets based on unsaturated polyesters from glycols and dibasic acids, either or both of which contain reactive double bonds. The ratio of saturated to unsaturated components controls the degree of cross-linking and thus the rigidity of the product (see Polyesters, unsaturated). Typically, the glycols and acids are esterified until a viscous liquid results, to which an inhibitor is added to prevent premature gelation. Addition of the monomer, usually styrene, reduces the viscosity to an easily workable level.

When the resin is to be used, fillers, eg, glass fibers, asbestos, or cotton, are mixed with it. The amount and kind of filler affect the strength, flexibility, and cost of the product. Alumina trihydrate acts as a fire-retardant when needed. Thixotropic agents control the viscosity and prevent the mix from draining from sloping surfaces. Pigments are used to provide color, usually white, and uv absorbers provide outdoor stability. To reduce smoke generation in burning resin and to improve outdoor stability, styrene can be replaced by methyl methacrylate. A peroxide catalyst and a combination of a cobalt soap and a tertiary amine are added as initiators (qv). The reaction is exothermic, and gelation is usually rapid.

For spas, shower stalls, bath tubs, etc, a gel coat containing no fiber reinforcement is applied first to the mold. It forms a smooth, strong, impervious, durable chemical, weather, and wear-resistant surface. The bulk of the resin, which may be reinforced with glass fiber, is applied by hand lay-up or by spray gun. The article is then cured at or near ambient conditions.

The physical properties of the reinforced polyester product made from chopped glass are listed in Table 1. The chemical resistance varies according to the composition but is generally good. Its principal uses in building products are for sanitary ware, eg, tub-shower units, and for panels, especially translucent or cement-filled types for roofing and walls of commercial or industrial buildings.

1.14. Polyurethane

Polyurethanes (pu) are predominantly thermosets. The preparation processes for polyurethane foams have several steps (see Urethane polymers) and many variations that lead to products of widely differing properties. Polyurethane foams can have quite low thermal conductivity values, among the lowest of all types of thermal insulation, and have replaced polystyrene and glass fiber as insulation in refrigeration. The sprayed-on foam can be applied to walls, roofs, tanks, and pipes, and between walls or surfacing materials directly. The slabs can be used as insulation in the usual ways.

1.15. PolyIsocyanurates

Polyisocyanurates are thermosets prepared by condensation of 4,4′-methylenebis (phenyl isocyanate) [101-68-8] with an acidic, basic, or organometallic catalyst, or a combination of them, to form a six-membered ring (see Cyanuric and isocyanuric acids). This structure is considerably more heat- and fire-resistant than urethanes, which dissociate at 100–130°C; the isocyanurates are stable to 350–500°C, probably because there is no hydrogen atom on the ring. Polyisocyanurate foams are rather brittle; therefore, they are modified with an active hydrogen compound to increase flexibility and resilience. The preparation of polyisocyanurate foams is similar to that of polyurethanes. Building panels for walls and roof decks are made by pouring the mixed components into a closed mold in which the liquid foams. A solid skin forms against the surface of the mold, which produces a skin integral with the matrix foam. The density of the foam decreases from surface to center.

2. Applications

The use of plastics in the U.S. building and construction sector increased at a rate of nearly 6% per year from 3,077,000 t in 1980 to 5,389,000 t in 1990 as shown in Table 2 (by resin class) and Table 3 (by market application). This advance is almost two times the overall U.S. GNP growth for the same period and is a testimony of plastics' increasing popularity as materials within the building and construction sector.

Table 2. Market Consumption by Polymer, 10³ t[a]

Polymer	1980	1981	1982	1983	1984	1985	1986	1987	1988	1989	1990	ACGR,[b] %
acrylics												
glazing and skylights	29.9	30.8	34.0	37.2	39.0	38.1	52.6	58.1	59.9	62.1	63.5	
lighting fixtures	9.1	10.0	13.2	15.0	15.0	15.0	14.5	17.7	20.0	21.3	20.4	
panels and siding	5.0	5.0	5.9	6.8	6.8	7.7	7.7	10.4	11.8	13.1	12.7	
plumbing	10.0	10.9	11.8	14.1	14.1	15.4	14.5	17.2	18.1	19.0	19.5	
Total	*54.0*	*56.7*	*64.9*	*73.0*	*74.8*	*76.2*	*89.4*	*103.4*	*109.8*	*115.6*	*116.1*	7.96
ABS												
pipe, fittings, conduit	110.2	99.8	59.9	79.8	82.1	56.7	70.3	74.8	69.9	70.3	63.5	−5.37
acetal												
plumbing	8.2	9.1	9.1	10.9	11.8	13.2	5.9	6.4	6.8	4.5	2.3	−11.90
butyrate												
panels and siding	1.8	1.8	1.8	1.8	1.8	1.8	1.8	2.3	2.3	2.3	2.3	2.40
cellulosics												
lighting fixtures	1.8	1.8	1.8	1.8	1.8	1.8	1.8	2.3	2.3	2.3	2.3	2.40
epoxy												
flooring[c]	8.2	8.2	6.8	8.2	6.8	8.2	7.7	9.5	11.3	11.3	11.8	
pipe, fittings conduit (coatings)	4.1	5.0	5.0	5.0	5.0	5.0	5.0	5.4	6.4	6.8	6.8	
Total	*12.2*	*13.2*	*11.8*	*13.2*	*11.8*	*13.2*	*12.7*	*15.0*	*17.7*	*18.1*	*18.6*	4.27
HDPE												
pipe, fittings, conduit	209.1	243.1	214.1	257.2	293.0	283.0	229.1	259.5	243.6	220.4	248.1	1.72
LDPE												
pipe, fittings, conduit	9.1	11.8	34.9	35.8	35.8	43.1	44.0	45.8	54.4	61.2	68.9	
vapor barriers	69.9	68.0	62.1	67.1	66.2	68.5	69.4	70.3	77.1	81.6	82.5	
Total	*78.9*	*79.8*	*97.1*	*103.0*	*102.1*	*111.6*	*113.4*	*116.1*	*131.5*	*142.9*	*151.4*	6.73
phenolic												
decorative laminates	20.0	15.0	14.1	16.8	16.8	14.5	18.1	21.8	31.3	40.3	31.7	
insulation	127.9	135.2	150.1	165.1	160.1	166.5	190.5	197.3	228.2	187.8	180.0	
resin-bonded woods	210.0	200.0	430.0	580.2	600.1	580.6	576.1	817.8	834.2	763.7	785.5	
Total	*357.9*	*350.2*	*594.2*	*762.1*	*777.0*	*761.6*	*784.7*	*1036.9*	*1093.7*	*991.8*	*997.2*	10.79

Table 2. *Continued*

Polymer	1980	1981	1982	1983	1984	1985	1986	1987	1988	1989	1990	ACGR,[b] %
polycarbonate												
glazing and skylights	30.8	32.2	29.9	34.0	37.2	40.8	44.5	45.4	46.7	49.0	48.5	
lighting fixtures	4.1	4.1	3.2	4.1	4.1	4.1	4.5	4.5	5.0	5.4	5.4	
Total	*34.9*	*36.3*	*33.1*	*38.1*	*41.3*	*44.9*	*49.0*	*49.9*	*51.7*	*54.4*	*53.9*	4.43
polyester, reinforced[d]												
glazing and skylights	15.0	18.1	15.9	18.1	20.0	18.6	18.1	17.7	19.1	22.7	21.8	
panels and siding	64.9	69.9	59.9	79.8	84.8	55.3	55.8	52.2	53.1	56.7	54.4	
pipe, fittings, and conduit	99.8	104.8	94.8	110.2	117.9	61.7	62.1	63.0	64.9	71.7	68.0	
plumbing	59.9	64.9	59.0	72.1	74.8	45.8	46.3	45.4	50.8	52.1	51.2	
Total	*239.5*	*257.6*	*229.5*	*280.3*	*297.6*	*181.4*	*182.3*	*178.3*	*187.8*	*203.2*	*195.4*	−2.01
polyester, thermoplastic (PBT)												
plumbing	3.2	1.8	3.2	3.2	5.0	2.7	3.2	3.2	3.2	3.1	3.2	0.00
polyethylene												
profile extrusion[e]	1.8	3.2	1.8	3.2	3.2	2.7	3.6	4.5	5.0	5.4	6.8	14.12
polypropylene												
pipe, fittings, and conduit	10.9	9.1	10.0	10.0	9.1	11.3	15.4	16.8	13.6	15.9	14.5	2.91
polystyrene												
insulation (foam)	79.8	81.2	87.1	93.0	108.9	79.4	75.3	78.5	108.0	109.8	105.2	
lighting fixtures	6.8	14.1	10.9	13.2	13.2	16.3	18.1	17.7	20.9	19.9	20.4	
pipe, fittings, and conduit	3.2	5.0	4.1	5.0	5.0	8.2	9.5	9.1	10.9	13.6	13.1	
plumbing	1.8	5.0	3.2	4.1	4.1	7.3	8.6	9.1	10.4	9.5	9.1	
profile extrusions	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	10.9	11.3	
wall coverings	4.1	9.1	6.8	8.2	8.2	9.5	10.0	11.3	12.2	12.2	12.7	
Total	*95.7*	*114.3*	*112.0*	*123.4*	*139.3*	*120.7*	*121.6*	*125.6*	*162.4*	*176.0*	*171.8*	6.02
polyurethane												
flooring (rug underlay-foam)[c]	49.9	52.2	44.9	54.9	54.9	53.5	59.0	61.2	145.2	145.1	158.7	
insulation (foam)	120.2	140.2	130.2	140.2	152.0	190.5	204.1	235.9	235.0	204.1	217.7	
Total	*170.1*	*192.3*	*175.1*	*195.0*	*206.8*	*244.0*	*263.1*	*297.1*	*380.1*	*349.2*	*376.4*	8.27
PVC												
flooring[c]	113.9	128.8	110.2	137.9	141.1	135.2	138.8	160.1	167.8	177.3	189.1	
lighting fixtures	6.8	8.2	6.8	8.2	9.1	8.2	13.6	15.9	16.3	13.6	13.1	
panels and siding	92.1	93.0	98.9	120.2	170.1	194.1	248.6	296.2	319.3	358.2	404.0	
pipe, fittings, and conduit	938.0	973.9	890.9	1106.8	1191.1	1376.7	1500.0	1580.8	1558.6	1439.9	1637.1	
profile extrusions[e]	53.1	52.2	73.0	92.1	112.0	128.8	139.7	160.1	149.7	152.3	159.1	
vapor barriers[f]	14.1	15.9	15.0	27.2	28.1	21.3	20.9	20.9	22.2	24.5	26.3	
wall coverings	22.2	20.0	16.8	19.1	19.1	16.3	17.2	29.9	31.3	31.3	35.3	
Total	*1240.1*	*1291.8*	*1211.6*	*1511.4*	*1670.6*	*1880.6*	*2078.8*	*2263.9*	*2265.3*	*2197.1*	*2464.0*	7.11
poly(phenylene oxide)												
plumbing	0.0	3.2	3.2	5.0	4.1	2.7	2.3	2.3	2.3	2.3	2.3	−3.52
urea and melamine												
decorative laminates	11.8	15.9	10.9	16.8	20.0	20.0	20.4	23.6	18.6	30.8	18.1	
resin-bonded woods	435.0	463.1	346.1	435.0	459.0	446.3	458.1	511.7	512.6	439.9	481.1	
Total	*446.8*	*479.0*	*357.0*	*451.8*	*479.0*	*466.3*	*478.5*	*535.2*	*531.2*	*470.7*	*499.2*	1.12
Total	*3077.2*	*3244.1*	*3191.0*	*3924.1*	*4212.1*	*4276.5*	*4506.9*	*5093.4*	*5279.9*	*5045.5*	*5389.3*	5.76

[a]Ref. 6.
[b]Annual average compound growth rate (1980–1990).

[c]Excluding bonding or adhesive materials.
[d]Including reinforcements (1980–1984).
[e]Including windows, rainwater systems, etc.
[f]Including swimming pool liners.

Table 4 lists plastics consumed in building and construction vs total U.S. plastics consumption for 1990. There was more PVC consumed in the building and construction sector than any other resin type.

Table 3. Market Consumption by Application, 10^3 t[a]

| | | | | | | | | | | | 1990 | | |
| | | | | | | | | | | | | Total,[b] | ACGR,[c] |
Application	1980	1981	1982	1983	1984	1985	1986	1987	1988	1989	Total	%	%
decorative laminates													
phenolic	20.0	15.0	14.1	16.8	16.8	14.5	18.1	21.8	31.3	40.3	31.7		
urea and melamine	11.8	15.9	10.9	16.8	20.0	20.0	20.4	23.6	18.6	30.8	18.1		
Total	*31.8*	*30.8*	*24.9*	*33.6*	*36.7*	*34.5*	*38.6*	*45.4*	*49.9*	*71.1*	*49.8*	0.9	4.60
flooring[d]													
epoxy	8.2	8.2	6.8	8.2	6.8	8.2	7.7	9.5	11.3	11.3	11.8		
PVC	113.9	128.8	110.2	137.9	141.1	135.2	138.8	160.1	167.8	177.3	189.1		
urethane foam (rug underlay)	49.9	52.2	44.9	54.9	54.9	53.5	59.0	61.2	145.2	145.1	158.7		
Total	*171.9*	*189.1*	*161.9*	*200.9*	*202.8*	*196.9*	*205.5*	*230.9*	*324.3*	*333.7*	*359.6*	6.7	7.66
glazing and skylights													
acrylic	29.9	30.8	34.0	37.2	39.0	38.1	52.6	58.1	59.9	62.1	63.5		
reinforced polyester[e]	15.0	18.1	15.9	18.1	20.0	18.6	18.1	17.7	19.1	22.7	21.8		
polycarbonate	30.8	32.2	29.9	34.0	37.2	40.8	44.5	45.4	46.7	49.0	48.5		
Total	*75.8*	*81.2*	*79.8*	*89.4*	*96.2*	*97.5*	*115.2*	*121.1*	*125.6*	*133.8*	*133.8*	2.5	5.85
insulation													
phenolic (binder)	127.9	135.2	150.1	165.1	160.1	166.5	190.5	197.3	228.2	187.8	180.0		
polystyrene foam	79.8	81.2	87.1	93.0	108.9	79.4	75.3	78.5	108.0	109.8	105.2		
PU foam (rigid)	120.2	140.2	130.2	140.2	152.0	190.5	204.1	235.9	235.0	204.1	217.7		
Total	*328.0*	*356.5*	*367.4*	*398.3*	*420.9*	*436.4*	*469.9*	*511.7*	*571.1*	*501.7*	*502.9*	9.3	4.37
lighting fixtures													
acrylic	9.1	10.0	13.2	15.0	15.0	15.0	14.5	17.7	20.0	21.3	20.4		
cellulosics	1.8	1.8	1.8	1.8	1.8	1.8	1.8	2.3	2.3	2.3	2.3		
polycarbonate	4.1	4.1	3.2	4.1	4.1	4.1	4.5	4.5	5.0	5.4	5.4		
polystyrene	6.8	14.1	10.9	13.2	13.2	16.3	18.1	17.7	20.9	19.9	20.4		
PVC	6.8	8.2	6.8	8.2	9.1	8.2	13.6	15.9	16.3	13.6	13.1		
Total	*28.6*	*38.1*	*35.8*	*42.2*	*43.1*	*45.4*	*52.6*	*58.1*	*64.4*	*62.5*	*61.6*	1.1	7.98
panels and siding													
acrylic	5.0	5.0	5.9	6.8	6.8	7.7	7.7	10.4	11.8	13.1	12.7		
butyrate	1.8	1.8	1.8	1.8	1.8	1.8	1.8	2.3	2.3	2.3	2.3		
PVC	92.1	93.0	98.9	120.2	170.1	194.1	248.6	296.2	319.3	358.2	404.0		
reinforced polyester[e]	64.9	69.9	59.9	79.8	84.8	55.3	55.8	52.2	53.1	56.7	54.4		
Total	*163.7*	*169.6*	*166.5*	*208.7*	*263.5*	*259.0*	*313.9*	*361.1*	*386.5*	*430.3*	*473.4*	8.8	11.20
pipe, fittings, conduit													
ABS	110.2	99.8	59.9	79.8	82.1	56.7	70.3	74.8	69.9	70.3	63.5		
epoxy (coatings)	4.1	5.0	5.0	5.0	5.0	5.0	5.0	5.4	6.4	6.8	6.8		
HDPE	209.1	243.1	214.1	257.2	293.0	283.0	229.1	259.5	243.6	220.4	248.1		
LDPE	9.1	11.8	34.9	35.8	35.8	43.1	44.0	45.8	54.4	61.2	68.9		
polypropylene	10.9	9.1	10.0	10.0	9.1	11.3	15.4	16.8	13.6	15.9	14.5		
polystyrene	3.2	5.0	4.1	5.0	5.0	8.2	9.5	9.1	10.9	13.6	13.1		
PVC	938.0	973.9	890.9	1106.8	1191.1	1376.7	1500.0	1580.8	1558.6	1439.9	1637.1		

Table 3. *Continued*

Application	1980	1981	1982	1983	1984	1985	1986	1987	1988	1989	1990 Total	Total,[b] %	ACGR,[c] %
reinforced polyester[e]	99.8	104.8	94.8	110.2	117.9	61.7	62.1	63.0	64.9	71.7	68.0		
Total	*1384.4*	*1452.4*	*1313.6*	*1609.8*	*1739.1*	*1845.7*	*1935.5*	*2055.2*	*2022.1*	*1899.8*	*2120.0*	39.3	4.35
profile extrusions[f]													
PVC (including foam)	53.1	52.2	73.0	92.1	112.0	128.8	139.7	160.1	149.7	152.3	159.1		
polyethylene	1.8	3.2	1.8	3.2	3.2	2.7	3.6	4.5	5.0	5.4	6.8		
profile extrusions	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	10.9	11.3		
Total	*54.9*	*55.3*	*74.8*	*95.3*	*115.2*	*131.5*	*143.3*	*164.7*	*154.7*	*168.6*	*177.2*	3.3	12.43
plumbing													
acetal	8.2	9.1	9.1	10.9	11.8	13.2	5.9	6.4	6.8	4.5	2.3		
acrylic	10.0	10.9	11.8	14.1	14.1	15.4	14.5	17.2	18.1	19.0	19.5		
polyester, thermoplastic (PBT)	3.2	1.8	3.2	3.2	5.0	2.7	3.2	3.2	3.2	3.1	3.2		
PPO alloys	0.0	3.2	3.2	5.0	4.1	2.7	2.3	2.3	2.3	2.3	2.3		
polystyrene	1.8	5.0	3.2	4.1	4.1	7.3	8.6	9.1	10.4	9.5	9.1		
reinforced polyester[e]	59.9	64.9	59.0	72.1	74.8	45.8	46.3	45.4	50.8	52.1	51.2		
Total	*83.0*	*94.8*	*89.4*	*109.3*	*113.9*	*87.1*	*80.7*	*83.5*	*91.6*	*90.5*	*87.6*	1.6	0.54
bonded woods													
phenolic	210.0	200.0	430.0	580.2	600.1	580.6	576.1	817.8	834.2	763.7	785.5		
urea and melamine	435.0	463.1	346.1	435.0	459.0	446.3	458.1	511.7	512.6	439.9	481.1		
Total	*645.0*	*663.2*	*776.1*	*1015.2*	*1059.1*	*1026.9*	*1034.2*	*1329.5*	*1346.7*	*1203.6*	*1266.6*	23.5	6.98
vapor-barriers													
LDPE	69.9	68.0	62.1	67.1	66.2	68.5	69.4	70.3	77.1	81.6	82.5		
PVC[g]	14.1	15.9	15.0	27.2	28.1	21.3	20.9	20.9	22.2	24.5	26.3		
Total	*83.9*	*83.9*	*77.1*	*94.3*	*94.3*	*89.8*	*90.3*	*91.2*	*99.3*	*106.1*	*108.8*	2.0	2.63
wall coverings													
polystyrene	4.1	9.1	6.8	8.2	8.2	9.5	10.0	11.3	12.2	12.2	12.7		
PVC	22.2	20.0	16.8	19.1	19.1	16.3	17.2	29.9	31.3	31.3	35.3		
Total	*26.3*	*29.0*	*23.6*	*27.2*	*27.2*	*25.9*	*27.2*	*41.3*	*43.5*	*43.5*	*48.0*	0.9	6.20
Total	*3077.2*	*3244.1*	*3191.1*	*3924.1*	*4212.1*	*4276.5*	*4506.9*	*5093.4*	*5279.9*	*5045.5*	*5389.3*	100	5.76

[a]Ref. 6.
[b]Total 1990 plastics consumption,%.
[c]Annual average compound growth rate (1980–1990).
[d]Excluding bonding or adhesive materials.
[e]Including reinforcements (1980–1984).
[f]Including windows, rainwater systems, etc.
[g]Including swimming pool liners.

Phenolics are consumed at roughly half the volume of PVC, and all other plastics are consumed in low volume quantities, mostly in single application niches, unlike workhorse resins such as PVC, phenolic, urea–melamine, and polyurethane. More expensive engineering resins have a very limited role in the building materials sector except where specific value-added properties for a premium are justified. Except for the potential role of recycled engineering plastics in certain applications, the competitive nature of this market and the emphasis placed on end use economics indicates that commodity plastics will continue to dominate in consumption. The application content of each resin type is noted in Table 2. Comparative prices can be seen in Table 5. The most dynamic growth among important sector resins has been seen with phenolic, acrylic, polyurethane, LLDPE/LDPE, PVC, and polystyrene.

Table 4. Sales Volume of Selected Polymers, 1990, 10^3 t[a]

Resin	Total U.S. consumption	Use in building and construction	Total consumption, %
PVC	4216.3	2464.0	58%
phenolic	1282.0	997.2	78%
urea and melamine	652.6	499.2	76%
polyurethane	1480.7	376.4	25%
HDPE	3857.1	248.1	6%
polyester, reinforced	721.0	195.4	27%
polystyrene	2329.7	171.8	7%
LLDPE/LDPE	5385.9	151.4	3%
acrylic	340.5	116.1	34%
ABS	549.7	63.5	12%
polycarbonate	281.2	53.9	19%
epoxy	210.4	18.6	9%
polypropylene	3688.0	14.5	0.4%
other polyethylene	na	6.8	na
polyester, thermoplastic[b]	89.8	3.2	4%
acetal	65.0	2.3	4%
cellulosics	36.3	2.3	6%
butyrate	14.0	2.3	16%
mPPO[c] alloys	90.2	2.3	3%
Total	*25290.4*	*5389.3*	*21%*

[a]Ref. 7.
[b]Poly(butylene terephthalate) (PBT) [24968-12-5] and others.
[c]Modified poly(phenylene oxide).

Table 5. Prices of Plastics Used for Building and Construction, \$ / kg[a]

Plastic	1983	1985	1987	1989
ABS, medium impact	1.90	1.94	1.63	1.98
acrylic, impact	2.23	2.23	2.03	2.38
cellulose acetate	2.84	2.84	2.84	2.84
epoxy, general purpose	2.53	2.56	2.56	2.56
phenolic	1.01	1.01	0.95	1.22
polyacetal, copolymer	3.26	3.44	3.44	2.76
polycarbonate, extrusion-grade	3.55	3.73	3.59	3.20
unsaturated polyester, general purpose	1.10	1.04	1.43	1.37
HDPE, pipe-grade	0.95	0.82	0.95	1.19
LDPE, liner-grade	0.88	0.79	0.82	0.90
PP, general purpose homo, extrusion-grade	0.84	0.77	1.01	0.90
PS, general purpose crystal-grade	0.86	0.71	1.21	1.17
PS, expandable beads	1.41	1.23	1.46	1.57
PU—polymeric MDI	1.79	1.61	1.61	1.72
PU—80/20% TDI	1.98	1.61	2.09	2.09
PVC, pipe-grade	0.71	0.57	0.84	0.77
melamine	1.52	1.54	1.54	1.61
urea–formaldehyde	1.08	1.10	1.10	1.10
PBT, glass-filled	3.53	3.75	3.46	3.31
nylon-6, unfilled	3.51	3.51	3.02	2.69
nylon-6,6, unfilled	3.99	4.28	3.90	3.02
mPPO, extrusion-grade	2.89	2.89	3.09	3.31

[a]Ref. 8.

Over 60% of the total plastics volume for building materials is consumed for pipes, fittings, conduit, and wood bonding applications. Other important applications include insulation, panels and siding, and flooring (additional 25%). Ten-year growth has been greatest in profile extrusions, panels and siding, flooring, lighting fixtures, and wood bonding applications. Table 3 provides the percentage of total 1990 plastics consumption for each application (9–11).

2.1. Solar Heating

Plastics are used in both active and passive solar-heating systems. They are used more frequently in passive systems because of their lower operating temperature, but many components of active systems are also made of plastics. Components under development include carbon-filled polypropylene pipes and poly(phenylene oxide) (PPO) plates and pipes. As covers, polycarbonate, polyacrylate, cellulose acetate–butyrate, and glass-fiber-reinforced polyester all transmit solar heat well and are resistant to uv light. Additional protection from uv radiation is provided by films of poly(vinyl fluoride), acrylate, or a new fluorocarbon film that is stable to sunlight. For frames to hold the assembly, high density polyethylene, ABS, polycarbonate, or rigid structural polyurethane foam can be used. Insulation behind the absorber plates can be of foamed plastic, especially foamed polyisocyanurate, which has good heat resistance. Phenolic-bonded glass fiber may vaporize and fog the inside of the cover but is necessary for high temperature use. Polyurethane foam also can be used. Several designs for single-piece solar collectors that incorporate a collector consisting of carbon black-loaded, cross-linkable polyethylene have also been introduced.

Focusing collectors are usually cast acrylic Fresnel lenses, or mirrors of aluminized polyester film in frames of aluminum. These reflectors are either enclosed in a bubble of poly(vinyl fluoride) film, or under polycarbonate glazing, which may be covered with a fluorocarbon film to reduce the reflectivity. The absorbers for active systems are copper or aluminum since the temperatures are too high (325–370°C) for plastics. The frames, however, can be molded ABS, high density polyethylene or polyurethane, either solid or structural foam. Polybutylene or chlorinated PVC can be used for piping hot water, and tanks can be made of either reinforced polyester or blow- or rotational-molded, high density polyethylene (12–15).

2.2. Thermal Insulation

Foamed plastics (qv) are used as thermal insulation for all types of construction because of their low heat- and moisture-transmission values. Polystyrene is used either as foamed board or expandable beads. The foam may be faced with a structural surfacing material, eg, a kraft liner-board, to form a panel for insulating mobile homes. These foams can duplicate the appearance of wood and be used as trim. Foams can also be used as backing, for example, on aluminum siding, to provide heat and sound insulation. Foamed beads can be incorporated in concrete to reduce its density and provide some thermal insulation.

Poly(vinyl chloride) foams may be rigid or flexible; the rigid foams are used to replace wood for interior trim and some door frames where the insulating properties are advantageous. They are dry-blended with a chemical blowing agent, fed to an extruder at 180–200°C, and passed through a profile die, which provides up to 8 cm of land length. The die temperature should be cooler than the stock temperature to produce a good surface. The melt expands upon leaving the die; then it is sized and cooled.

Polyurethane foams for building purposes are normally of the rigid kind used for roof and wall insulation. Polyols containing halogen or phosphorus are used to increase the fire resistance of the foam.

Polyisocyanurate foams are superior to others in fire-resistance. The initial step in their preparation is the trimerization of MDI to form a ring quite stable to heat. This polymer is mixed with blowing agents, as for polyurethanes, and expanded to obtain a low density closed-cell foam, stable up to 150°C. The process may be used for continuous buns or laminates. The product has dimensional stability and is much more fire-resistant than polyurethane foams. In some fabrication, the foam is poured at a rate of 4.5–9.0 kg/min between facings

Table 6. R-Values vs Insulation Thickness for Selected Plastics[a]

Insulation material	K-Factor[d]	R-Value[b] for thickness in cm				Relative cost[c]
		7	5.3	3.5	1.8	
phenolic, aged	1.73	12.2	9.1	6.1	3.0	4
polyurethane or polyisocyanurate, aged	2.60	18.3	13.7	9.1	4.6	3
extruded polystyrene	2.88	20.3	15.2	10.2	5.1	2
expanded polystyrene	3.46	24.4	18.3	12.2	6.1	1
glass fiber	4.03	28.4	21.3	14.2	7.1	
foamed glass	5.04	35.6	26.7	17.8	8.9	
mineral wool	5.04	35.6	26.7	17.8	8.9	
perlite	5.62	39.6	29.7	19.8	9.9	
vermiculite	6.91	48.8	36.6	24.4	12.2	

[a]Ref. 16.

[b]R-Values are directly proportional to thickness shown. To convert R-value in $\mathrm{m^2 \cdot K/W}$ to $\mathrm{h \cdot ft^2 \cdot {}^\circ F/Btu}$, multiply by 5.7.

[c]$1 = \mathrm{best}; 4 = \mathrm{worst}.$

[d]K-Factor data for phenolic supplied by Manville; source for all other K-factors is The Dow Chemical Company. Units of K-factor are $(\mathrm{W \cdot cm})/\mathrm{hm^2 \cdot K}$ (= 1.4 Btu·in./h·sq ft°F). R-Value per cm of thickness is the K-factor. K- and R-factors can vary with age and use conditions. Values shown are averages obtained from lab samples.

held vertically in a jig and then allowed to expand. The board can be removed from the jig after about one minute per 2.5 cm of board thickness. Because the pressure developed is not more than 0.14 MPa (20 psi), lightly built jigs can be used. The facings may differ in shape and material. Boards of 2.5–23 cm thickness and from 1.2×2.4 m to 4.5×12 m have been made. The foam has uniform density from bottom to top and from side to side. It is used in wall and ceiling systems with a great variety of assembly and installation procedures. The wide choice of thickness, facing material, and foam density renders it suitable for many different construction designs. It is somewhat more expensive than polyurethane foam products.

The need to conserve energy and keep heat inside homes (insulate) is a driving force behind the growing use of insulative materials. U.S. homes have made drastic improvements in energy efficiency since the first energy shocks of the early 1970s. Between 1972 and 1986 energy use per household fell 34%. Thermal insulation products compete on a cost/performance basis, where performance includes such factors as thickness, density, and thermal insulation rating (R-value). Several plastic foams compete for the thermal insulation market in the U.S. building and construction industry. They include polyisocyanurate boardstocks, sprayed-up polyurethane foams, extruded polystyrene board, board made from molded blocks of expandable polystyrene (EPS), and phenolic foam. Although other foams exist, they are either too expensive or lack the insulative properties required to be competitive. Table 6 compares the thickness (cm) of insulation required to achieve the R-values shown.

Based on performance (thermal insulation), polyisocyanurate, polyurethane, and phenolic foams have the lowest thermal conductivities, mainly because of the blowing agent used in their respective processes (CFC-11). Preventing the loss of CFC (chlorofluorocarbon) through such techniques as adding impermeable skins, eg, metal foils, is critical to maintaining the long-term insulation value of such foams as polyisocyanurate and polyurethane but also raises the cost. Although the relative cost of expanded polystyrene is the lowest among the key plastic foams and phenolic is the highest, sheet thickness, building codes, temperature resistance (both environmental and via the application of roofing tars), and the overriding concern of long-term insulation performance, help determine the actual choice of materials. All candidates have their place in various building and construction applications, eg, roofing and wall insulation.

Environmental considerations have dramatically affected the future prognosis of thermal insulation materials based on their heavy reliance on chemical blowing agents such as CFC-11 and pentane for insulation performance. CFC-11, along with other fully halogenated chlorofluorocarbons, has been linked with ozone

depletion and the potential of global warming. Pentane has been linked to environmental pressure to reduce volatile organic emissions (VOC), also believed to contribute to ozone depletion. Under the Montreal Protocol, the primary industrial nations of the world have agreed to control the use and production of CFCs. The protocol requires signatory nations to reduce 1986 CFC consumption by 20% in 1993, and 50% in 1998. Because of the distribution of CFC use in the United States, the primary impact to the plastics industry of the Montreal Protocol will be felt in the rigid foam (insulation) segment, where CFC use has significantly contributed to product performance. Developmental efforts aimed at phasing out CFC consumption have centered on such alternatives as hydrochlorofluorocarbons (HCFCs), eg, HCFC-123, HCFC-1416, hydrofluorocarbons (HFCs), and use of blends including HCFCs or HFCs plus carbon dioxide generated by the addition of water, which reacts with isocyanates. Unfortunately, toxicity and ozone-depletion concerns remain for the proposed alternatives and these alternatives only approximate the performance standards set down by the original CFC-based formula. The concern to the polymer/plastics/fabricating industries, despite huge current and continuing investments in new technologies, is the threat that thermal insulation products could move to nonplastic forms of insulation (12, 13, 17–31).

2.3. Roofing

Roofing membranes are used on residential and nonresidential buildings. In 1989, nonresidential buildings represented 70% of the roofing market dollar volume. Within each segment, reroofing represents greater than 70% of the activity compared to new constructions. In general, residential roofing systems do not employ polymers; they use materials such as asphalt shingles, concrete, clay tiles, and treated wood. Nonresidential roofing systems include single-ply, built-up, modified bitumen, and metal. Polymeric materials used in the single-ply segment of nonresidential roofing systems include PVC and PVC alloys, chlorosulfonated polyethylene (CSPE), chlorinated polyethylene (CPE), and ethylene–propylene diene rubber (EPDM). Built-up roofs dominate (32% for 1989) among nonresidential material systems.

Among other polymers used in this market, EPDM (30%) leads followed by PVC/PVC alloys (5%), and CSPE/CPE (3%). Modified bitumen (20%) and metal (10%) have the remainder of the market. Single-ply material systems including PVC/PVC alloys, EPDM, and CSPE/CPE are gaining share, with PVC expected to grow at about 5–6%/yr over the next five years.

PVC/PVC alloys have advantages in seaming (heat seaming and radio frequency welding), flexibility, repairability, permeability, and winter installation; disadvantages include cost, reputation for prior failures, cold-cracking related to plasticizer migration, and incompatibility with asphalt/coal-tar. CSPE/CPE have advantages in chemical resistance, compatibility with asphalt/coal-tar, ability to withstand high temperatures, and durability; disadvantages include cost, curing after exposure, repairability, susceptibility to algae, and chalking/thinning. Being an elastomer, EPDM has advantages in cost and elongation; disadvantages include seaming and emissions from solvent-based adhesives. Modified bitumen has advantages in seaming with torching, compatibility with asphalt/coal-tar, repairability, and similarity to built-up roofing (labor advantage); disadvantages include durability, safety component relating to the torching operation, seaming with mopped-on asphalt, and narrow widths. Built-up roofs have the simple advantage of low cost and the disadvantage of poor durability.

Development efforts in alloying offer PVC and PVC alloys the opportunity to capture shares from the higher performing chlorinated and chlorosulfonated polyethylenes (CPE/CSPE). Alloys including PVC copolymer, nitrile–butadiene rubber, ethylene interpolymer, and tripolymers already have an estimated 35% of the PVC/PVC alloy segment with plasticized PVC homopolymer controlling the remaining 65%. Developmental thrusts to date have included the incorporation of elastomeric modifiers in vinyl systems so low temperature flexibility could be attained without total reliance on plasticizers. In the early 1980s PVC roof membranes that relied entirely on plasticizers for flexibility failed when environmental conditions, including contact with the ballast, caused the plasticizers to migrate and leach out of the membrane, and the resulting unreinforced

membrane experienced cold-cracking, embrittlement, and loss of properties. Additional development centered around the use of higher molecular weight plasticizer less susceptible to migration. Developments of this type have allowed PVC to restore its reputation and stage a comeback in this market.

Calendered PVC has approximately 55% of the PVC/PVC alloy segment, PVC dispersion coatings using a reinforcement are 40%, and PVC extrusion with width limitations is about 5%. Almost all PVC membranes are reinforced or supported with thicknesses from 1.2–2.4 mm (47–91) mils. Converters typically purchase rollstock in 5–6 ft widths (1.5–1.8 m). Colors and designs are not common; most manufacturers offer a solid white, gray, or tan sheet.

Important trends in this market include a shortage of labor because of regulations on worker exposure, growth of single-ply roofing that are easier to install and need less equipment, growth of reroofing (stagnant new growth, short lives of traditional materials, spill-over of past failures), lower prices (pressure from EPDM), use of reinforced and thicker sheets (memory of failures), and increasing performance targets (alloy development) (12, 13, 30, 32–38).

2.4. Swimming Pools and Spas

Swimming pools in the United States are both in-ground and above-ground types for residential, commercial, and institutional markets. There is a need for a vapor barrier in the construction of pools for which calendered (flexible) PVC is the primary material used. By their nature, above-ground pools are concrete (63%), fiberglass (3%), or vinyl-lined (34%). A replacement pool market parallels the types of pools mentioned above. Above-ground pools consume about 54% of the PVC used as pool liners, and in-ground types consume the rest. The replacement market is beginning to dominate the consumption of PVC for both types of pools based on the already high and escalating cost of new pools. Vinyl-lined pools are maintained easily, typically cost less than prepackaged alternatives, and are available in a variety of designs. Their disadvantages include limited flexibility in design/shape and the perception that they are cheap. Fiber glass, typically reinforced polyester, is characterized by longer life and ease of cleaning but suffers from limited sizes/shapes, limited colors, availability only near manufacturing sites, and sensitivity to improperly maintained poolwater chemistry. Concrete pools offer design flexibility, more permanent/stronger perception, and status orientation but are more costly than alternatives, require more chemicals, and are more difficult to clean.

In-ground pool liners are typically calendered flexible PVC, 0.5 mm (20 mil) in thickness, that are printed. Above-ground liners are typically calendered flexible PVC, 0.3–0.5 mm in thickness, with some printing and embossing. About 80% of the PVC in this market is calendered with consistent thickness across the roll and high print quality; the rest is extruded. The PVC formulation used in this market has the advantage of uv stability, cold-crack resistance, resistance to algae, low shrinkage, low cost, and flexibility. Decorative aspects including color and exclusive prints are outstanding. Growth for PVC in pool liners is estimated at 3–4%/yr in the early 1990s, with the replacement markets gaining dominance.

Historically, spas and hot tubs were compression molded thermoset composite systems, including reinforced unsaturated polyesters. Since the early 1980s, thermoformed thermoplastic, generally a coextruded sheet of weatherable polymer like acrylonitrile–styrene–acrylate (ASA) on a substrate of ABS, has taken this market from thermoset composites. The thermosets were found to be vulnerable to attack by algae. By employing ASA as an outer surface, the weatherability and chemical resistance to cleaning compounds of the thermoplastics is greatly improved. New low profile surface systems under development include resin mixtures with unsaturated polyester, including dicyclopentadiene, that offer pigmented appearance and aesthetics that rival natural marble. Performance attributes in this area include class A appearance, which is a high quality finish, structural integrity including uniform properties, reasonable cost, acceptable processability, improved fire and smoke resistance, and low VOC emissions.

Important trends in this market include the 30% decrease of the new pool market over the past two years (1989–1990), and the trend toward printed above-ground liners with unique designs (39).

2.5. Electrical Applications

Plastics are used for electrical insulation, conduit and enclosures, lighting fixtures, and mechanical devices. The most widely used plastic for wire and cable insulation is flexible, plasticized PVC, which constitutes well over half the market in insulating wires for buildings, automobiles, appliances, and power and control lines. Polyethylene is also a factor. Higher performance plastics such as nylon and fluoropolymers also play a smaller role in this area.

Electrical conduit includes several metals that account for roughly 65% of the market and PVC, which accounts for the remaining 35%. Conduit is used primarily to protect electrical wiring from mechanical and environmental damage. PVC is nonconductive, nonsparking, and inherently fire-resistant. In addition, it does not corrode, has high impact resistance, and its smooth uniform interior walls make wire pull-through easier, faster, and less prone to damage. Driven by its commanding cost advantage over competing metals (25–55%), it is anticipated that PVCs share of the general conduit market will continue to grow into the 1990s. In control and communication wire there is a trend away from traditional vinyl or other polyolefin-based insulation. Significant savings can be realized by using plenum-rated perfluorinated resin-jacketed wire, which may be run or rerun as needed in drop ceilings or raised floors without conduit.

For switch and motor housings, engineering resins such as thermoplastic poly(phenylene oxide) that has high impact strength, allowing thin walls, is used. With its low moisture absorption, it is a good electric insulator. It is also corrosion-, heat-, and fire-resistant. Polycarbonate is used for switches and outdoor electrical plugs because of its good low temperature impact strength and fire resistance. For lighting fixtures, polycarbonate is useful not only as a sheet glazing material for electrical lighting, based on its transparency, but also for molding housings and outdoor fixtures. Thermoplastic polyesters, eg, PBT, PET, and PCT (poly(cyclohexane-1,4-dimethanol terephthalate)), are playing increasingly important roles in such electrical applications as switches, wiring devices, connectors, and relays. Reinforced polyesters (thermoset) also play a role in power boxes based on their composite structural integrity and dimensional stability. Epoxies play an important role in electrical laminates, eg, printed circuit boards, whereas high heat thermoplastics, eg, polyetherimide (PEI), polyethersulfone (PES), and polysulfone (PSO), are now penetrating this market via injection molding technologies. Overall, the superior performance of engineering thermoplastics will allow them to continue to grow in electronic applications as spaces become more confined and heat requirements increase. However, for the foreseeable future, workhorse resins such as PVC, LDPE, HDPE, ABS, and phenolic will continue to dominate (12, 40–42).

2.6. Glazing

Polyacrylates and polycarbonates are the resins most widely used for glazing. They are light in weight, easily formed, and provide heat and sound insulation. Their chief advantage is their resistance to breakage and their failure to shatter when they break. Coatings of fluoropolymers often are used to improve abrasion resistance, and cross-linked polysilicate, almost as hard as glass, has been used. Some grades of polyacrylates can be cemented with solvents instead of with adhesives that need curing. The surface can be rippled or given a matte finish, or it can act as a sunscreen.

Polycarbonates are dimensionally more stable, have high impact strength and heat resistance, provide thermal insulation, and are fire-resistant. Surface coatings of more abrasion-resistant films can be applied. Polyacrylates have been introduced for glazing where the amber tint and high temperature resistance, over 150°C, are advantageous. Their present cost limits their use to extreme service conditions. Architectural-grade fiber glass reinforced plastic (FRP) can also be used in translucent panel skylight systems. Panel widths of up to five feet (1.5 m) are manufactured as a sandwich consisting of FRP bonded under controlled heat and pressure to a mechanically interlocked aluminum I-beam grid core.

Plastic conductive (metallized) films are also used in conjunction with glass surfaces to create an active window system capable of achieving over 90% the insulating performance of a solid wall. The metallized film surface allows visible light transmission while blocking heat and uv light radiation. Security/safety windows are manufactured by laminating an inner layer film of poly(vinyl butyral) between an inner and outer layer of tempered glass. This construction is frequently used in high security applications such as jewelry store display windows or prisons and is similar to automotive safety glass.

Windows comprise a relatively small amount of the total exterior surface area of a house; however, it is estimated that they account for nearly 25% of a home's total energy costs via thermal losses such as conduction, convection, and radiation. In 1991, California was debating a proposed system for window energy performance ratings based on their high importance as a source of heat loss. This rating, if enacted as legislation, is part of a proposed comprehensive energy code that California is considering. It would require window manufacturers to display the thermal conduction ratings (*R*-values) of their products. Single-pane glass has a relatively low *R*-value of about *R*-1. Double-pane windows rate about *R*-2. The active window systems described above are capable of values as high as *R*-4 to *R*-8 (12, 13, 31, 34, 43–47).

2.7. Siding

The resin most used for siding is poly(vinyl chloride) homopolymer, compounded with modifiers, stabilizers, and pigments. Modifiers are most often acrylic esters, followed by chlorinated polyethylene or ethylene–vinyl acetate, used at 6–8 phr (parts per hundred resin). The modifier increases the impact strength of the rigid PVC.

Heat stabilizers are usually methyl- or butyltin compounds at 1.5–2.5 phr. New alternatives to organotins include mixed metal stabilizers such as barium–zinc or calcium–zinc. Other organotin and barium–cadmium stabilizers are being developed that would permit the use of less TiO_2 in the composition. In light colors TiO_2 is a pigment, but it also functions as a uv screen. If less TiO_2 is used, stabilization must be increased by other means. A barium–cadmium phosphite with an epoxy-plasticizer stabilizing system is said to be so effective that TiO_2 can be eliminated. However, the liquid components reduce the heat distortion temperature and impact strength so that more rigid modifiers may be needed. In further efforts to reduce costs, compounding is done by the extruder, thereby eliminating the pelletizing step by high intensity dry-blend mixing of powders that are fed directly to the extruders. This method also reduces the heat exposure and provides better quality with reduced amounts of stabilizers.

Siding is usually produced by extrusion of the PVC composition through a profile die. It also is prepared by extruding a flat sheet, embossing it, then postforming it in a press. This process is relatively low cost at a high production rate, up to 270 kg/h, but the appearance obtained with extruded profiles is usually preferred. Extruded profiles are conventionally cooled with air, which requires a cooling length of 7.5–10.5 m. In some new processes the profile is held by means of a vacuum against a metal shape, through which water at a controlled temperature is passed. The profile is thus cooled at a controlled rate, in a shorter time, and with less residual internal stress. The profile cooled in this manner shows about 1.5% shrinkage after 30 minutes at 30°C, as compared with 2–5% by conventional cooling. Output rates are 135–160 kg/h. The product also has a higher impact strength. In another process more tolerant of formulation changes, some producers use twin-screw extruders to get high shear, lower temperatures with less power, and little or no backflow. The design of the dies and the control of stresses during cooling are vitally important to obtain a good product.

Another technology trend is the growing use of coextrusion for the production of vinyl siding. Dual, coupled extruders are used in conjunction with a multislot die to allow a two-layer profile to be extruded. The lower, or substrate, layer provides mechanical rigidity but, because it does not face exposure to the environment directly, it can be manufactured using less expensive grades of PVC along with lower levels of expensive additives such as heat and uv stabilizers plus colorants. The top, or capstock, layer of the profile that comprises the surface of the siding is compounded with the higher levels of additives required for color stability, weatherability, eg, resistance to chalking, etc. Careful compounding is necessary to obtain adequate physical properties including

controlled cooling to avoid dimensional changes that lead to oil-canning, which is the uneven stress-relaxation and thermal expansion that cause distortion.

The postextrusion phase of the process is usually the most difficult to accelerate and is the controlling limit on line speed, which often is no more than 4.5–9.0 m/min. The numerous stages include an embosser, vacuum-sizing/calibration, cooling, pulling, punching, cutting, and stacking.

Residual stress in PVC is a factor in heat distortion of siding. When the sun shines on an installed strip of siding, the center of the strip becomes hotter than the edges or the covered portion. The various temperatures have been measured and resulting stresses estimated; to counteract these stresses, residual stresses have been set up in certain areas of the strip during production. Quenching the shaded portion, the butt, and the hanger creates compressive stresses; tensile stresses are produced by cooling the center slowly. When the siding is exposed to hot sunlight, the center shrinks and the shaded portions expand, thereby counteracting the oil-canning caused by thermal expansion. Thus, a good appearance is maintained.

Although PVC has several advantages as a siding and affords good impact resistance and low sound transmission, only in light colors does it offer adequate resistance to outdoor heat and light. Manufacturers who wish to produce PVC siding in dark or earth colors have had to consider the high cost of pigments and the fact that the TiO_2 used in light colors acts both as a pigment and stabilizer. If the TiO_2 is eliminated, more stabilizer must be used; if it is retained, more pigment must be used. One way to overcome this problem is to use coextrusion of a dark colored, thin-walled capstock over a low cost, less pigmented substrate or core. Another process uses a foamed rather than a solid core, and the coextruded film provides a smooth, dark colored skin. The components may also be resins other than PVC. Acrylic films, which are inherently light-stable, have been coextruded over PVC or chlorinated PVC substrates. Both methods raise the cost.

The usual inorganic pigments for dark colors may contain iron or other metal ions that can adversely affect the stability of PVC. Some organic pigments, though more expensive, contain only traces of heavy metals. Because inorganic pigments reflect more ir radiation, less heat is absorbed by the plastic, whereas organic pigments have a high tinting strength and hiding power over TiO_2. Pricing according to color may be necessary. The inherent fire resistance of rigid PVC and its high flash-ignition temperature are definite advantages for its use in construction. However, once burning, PVC can generate toxic gases such as hydrochloric acid, HCl.

Another PVC siding is an extruded product of an internally ribbed, dual-wall profile. A conventional screw extruder, with a vacuum sizer cooled with water and air, forms a product about 20 cm wide with 160 mm walls and 80 mm ribs on 25 cm centers. The total thickness is about 0.64 cm. The ribs provide rigidity and strength and the dual-wall construction adds thermal insulation. No backing or core is used.

A recently introduced polycarbonate-based blend offers a low coefficient of thermal expansion. This new thermoplastic is designed for large sheet applications such as doors or siding. Its high dimensional stability will eliminate warping from exposure to varying temperatures.

Outdoor building products such as guttering, siding, and roofing have seen sharp increases with the recent remodeling boom. Vinyl siding will continue to grow at nearly 5% per year at the expense of brick and aluminum siding and as a substitute for painting. Residential use will comprise 90% of the total market with the do-it-yourself market becoming more important. Vinyl siding accounted for 80% of all siding replacement work in the late 1980s but was used on less than 10% of new single-family homes in the same year. Vinyl siding is growing in popularity because of increased consumer acceptance, its attractive appearance, and low maintenance features. A 30% share of the new home market is anticipated for vinyl siding by 1995 (11, 12, 33, 34, 48–59).

2.8. Shutters and Exterior Trim

These have been made largely from thermoformed rigid cellular PVC. Foaming the PVC and reducing its density from 1.4 to 0.4–0.5 g/cm^3 reduces the cost considerably though the composition itself is somewhat more expensive. Thermoforming may produce either cut-sheet or roll-sheet. The former uses stock up to 1.25

cm thick, the latter is limited to no more than 0.625 cm thickness. An extruder line may feed directly to a roll-sheet thermoformer line. Metal or wood reinforcements may be provided for structural support. Shutter and other exterior trim can also be extruded by conventional single-screw machines. Dies may be designed to allow the extrudate to expand to give a balanced flow to the sizing die, which holds and cools the extrudate to the desired dimensions, and allows for some residual shrinkage during final cooling. For large profiles from PVC foam, the Celuka process can be used, whereby the hot and sizing dies are the same size, which causes an inward expansion in the hollow core. This product has a thicker skin and a more variable cell structure than normal extrudate. All the problems and solutions that apply to siding, including capstock coextrusion for dark colors, apply to these products as well. Shutters have also been made from high impact polystyrene foam coated with an acrylic ester and from ABS capped with acrylic ester to provide protection from uv light and improve outdoor weatherability (32, 33, 40, 58, 60).

2.9. Door and Window Frames and Sashes

The first successful application of rigid PVC for windows was as a cladding over a wood core to avoid the need for painting and repainting the sash and the exterior of the frame. Since then, extruded profiles of rigid PVC have been developed to allow door and window frames and sashes that do not rot, corrode, or need paint and that provide good insulation and low air infiltration. One window system extrudes profiles 1.8-mm thick with a series of closed channels for rigidity, thermal insulation, and low cost. The extrudate is cooled with a vacuum calibrator, then cooled further by forced air, sawn, cut, and the corners mitered. The pieces are put in holding jigs and holes are drilled for screws. Corners are secured with metal braces to resist the spring-loaded sash weight and to hold the screws. Joints are sealed with silicone polymers, then polycarbonate or metal hardware is attached, and double-pane glass installed. A 0.9×1.2 m window weighs about 11 kg and uses perhaps 8 kg of PVC. With a single-screw extruder, an output of over 100 kg/h of lineals is considered very good in view of the close tolerances that must be maintained to obtain a tight seal and smooth operation. Double-hung, side-slide, and picture windows can be made of extruded PVC.

All the difficulties in achieving dark colors for PVC siding apply also to door and window frames and sashes. Coextrusion of a PVC core capped with a vinyl or acrylic film from an adjacent extruder can be used. In addition, PVC-acrylic alloys can be used for dark colors. The modifiers, stabilizers, and pigments incorporated in siding are used in these products as well. To date, building codes restrict their use in new construction, so that their installation is primarily as replacements.

Because of the extraordinary outdoor weatherability of ASA, it is being molded and extruded in various door and window frame applications. Likewise, in commercial construction, thermoplastic elastomers are finding increasing use in window-wall constructions. Poly(vinyl chloride) strips have been used as thermal breaks in aluminum windows, and aluminum doors and frames have been clad with PVC. A dual-wall, internally-ribbed construction, like that used for siding, has been used for door and window frames and sashes in mild climates.

Foams have limited use for these purposes. Rigid cellular PVC is good as a thermal barrier but not for structural parts. Doors and frames of structural molded foam, eg, foamed high impact polystyrene, can be made by injection molding, with recesses for hinges, striker plates, and miter corners. Solid polystyrene and structural foam-molded polyurethane have been molded for door frames.

Recently, storm doors have been constructed of advanced thermoplastic composites. Stampable, glass-mat reinforced polypropylene sheet is used to create a high strength outer skin. These compression molded skins are welded together using a friction or ultrasonic process then injection molded with a polyurethane foam core to produce an insulated structure. New technology for window frames incorporate the pultrusion of frame channels to produce a thermoset composite channel that can be filled with fiber glass for further insulation enhancement (12, 31, 33, 34, 48, 49, 54–56, 60–67).

2.10. Wall and Ceiling Panels

Most panels incorporating plastics use foamed plastic cores with various surfacing materials for inside and outside facings. These facings may be an integral part of the panel or applied separately. The foam may be of polystyrene, polyurethane [26778-67-6], polyisocyanurate, phenolic, or urea–formaldehyde [9011-05-6]. For some panels, expanded polystyrene beads are foamed in a large aluminum mold, with an accumulator feeding an injector of twenty or more nozzles. The foam has good moisture resistance and dimensional stability. Inserts and reinforcing materials, eg, glass fiber, steel rods, or wire mesh, have been used for greater strength. Door and window frames and conduits for services can be inserted during molding. After the foam is prepared, it is faced with a surfacing material for either interior or exterior exposures. Exterior facing may be wood, aluminum, vinyl, or plaster. Wall panels are used extensively for mobile homes. One panel uses polystyrene foam sheathing over the studs, covered by wood, aluminum, or vinyl siding. Polyurethane or urea–formaldehyde foam may be used between the studding. Gypsum board is used for the interior surface.

Roofing panels have been made from polyisocyanurate foams, both foam- and felt-reinforced with glass fiber. Phenolic resins are used especially for decorative laminates for paneling. The substrate may be fiberboard or a core of expanded polystyrene beads. In one case the beads are coated with phenolic resin, then expanded in a mold to form a structural foam panel.

In another application expanded polystyrene foam panels, 1.2×2.4 m, are faced with a wire mesh and mounted in a metal channel bolted to a concrete slab. These panels are then sprayed on both sides with plaster, which is anchored to the wire mesh and forms the interior and exterior surfaces. Roof and interior partitions provide low cost housing for mild climates.

Several companies have begun the mass production of foamed polyurethane wall panels as a modular product. Using a fully integrated computer-aided design (CAD) and manufacturing process, they are able to customize these panels by cutting them into tailored shapes including the insertion of doors and windows. This off-site manufacture of building components also aids the energy efficiency of finished, assembled structures by allowing a tight fit of modules to very close tolerances.

Even when plastics are not a preferred material for the structural element of paneling, they are often incorporated as a surface coating or sheet to enhance aesthetics. Some lay-in ceiling panels for commercial and institutional applications consist of gypsum board covered with a poly(vinyl chloride) surface sheet to add a textured appearance. Many more are based on gypsum board or mineral wall with a fiber glass or PVC surface.

An additional polystyrene panel application for one-piece structural building applications with high R-values is compatible with conventional wood framing. The panels may be used for load bearing walls up to three stories. Made from lumber facings and solid expanded polystyrene EPS insulation, the panels have the strength of a continuous column. A core of rigid EPS insulation 8.8 cm to 29 cm thick is adhesively welded between oriented strand board facings to form a structural panel that will not twist, warp, or be subject to racking.

Finally, a new aluminum fire-resistant paneling consists of a composite design that includes a solid thermoplastic compound core covered with a high density polyethylene adhesive film and an aluminum skin. The product is easily formable. It has sound deadening abilities, and an optional poly(vinylidene fluoride) resin coating provides damage resistance.

As a structural element to support paneling and wall mounts, there is growing interest in the use of plastic lumber produced using the recycled scrap or waste of polyethylene (HDPE), polypropylene, and PET materials from various packaging and other high turnover applications (12, 17, 18, 21, 23, 24, 32, 34, 44, 62, 68–71).

2.11. Plastic Flooring

Plastic flooring is marketed either as tile or sheet flooring. Tile is supplied as pieces usually 30.5×30.5 cm with a thickness of 0.16–0.32 cm and is usually homogeneous in composition. Sheet flooring, on the other hand, is produced in roll form 1.8, 2.7, 3.7 and 4.6 m wide (2- and 4-m in Europe), and generally consists of a plastic upper component on a fibrous backing.

Tile is based mainly on vinyl chloride and vinyl acetate copolymers. Some polypropylene tile systems have recently been introduced. A petroleum resin is usually employed as an extender and processing aid; conventional vinyl plasticizers and stabilizers also are incorporated. Reinforcing fibers and limestone constitute the remainder of the tile composition; the fibers contribute hot strength for processing and dimensional stability in the finished tile, limestone supplies bulk at an economical cost. Stable pigments are also incorporated. Since tile is installed on and below grade level, it is important that the finished product be resistant to the effects of moisture and alkali.

Tile is manufactured in several ways. In each method, a continuous sheet is formed; gauge refinement and planishing are carried out in subsequent calendering steps. Stresses that could lead to poor dimensional stability are avoided. The efforts to prevent stresses are governed by formulation, stock and roll temperatures, conveyor speeds, etc. After the final calendering, a resin–polymer–wax finish is applied to the surface of the sheet which is then buffed before it moves to the punch press. Frame scrap and tile rejected because of defects are returned to the mixers and recycled.

Several techniques are used to introduce decorative elements into tile. Random straight-graining effects are obtained by introducing pigmented, filled vinyl chips and granules, ie, mottle, into the tile composition at the appropriate point in the formation process. These flow to produce distinctive streaks as the sheet is formed. Less directional designs are produced by introducing grained vinyl chips, which form a continuous surface over a plain tile base. Random and registered designs are produced on a variety of tile bases by embossing and valley printing. Tile decorated by rotogravure printing is protected by a clear wear layer of plasticized PVC.

No-wax tile has long been important in the residential market. Such products have a high gloss surface coating that resists abrasion and soiling. When properly designed and maintained, no-wax tile retains its shiny appearance for an extended period of time without application of floor polish.

Resilient sheet flooring, though based on plasticized PVC, is manufactured from a variety of compositions by several processes. Generally, the type of decoration achieved depends on the process and composition. Since compositions are specific to processes, resilient sheet flooring can be classified by process alone. Rotogravure printing is used for the largest volume of sheet flooring. This type of flooring, often called rotovinyl, is manufactured almost exclusively from PVC plastisols and organosols. These liquid dispersions of homopolymer and plasticizer, when properly stabilized, can be applied as coatings that fuse into clear, tough films at temperatures of 180–200°C. Blowing agents can be incorporated to produce foams. Both clear coatings and foams are used in rotovinyl flooring. The typical structure consists of a fibrous inorganic or fiber glass backing, a vinyl foam layer decorated with a rotogravure-printed design, and a clear vinyl surface layer. Many products of this type are embossed in register with portions of the design. Thickness varies from one product to another. Wear layers are 0.1–0.65 mm, depending on intended use, but the most common wear layer gauge is 0.25 mm. Rotovinyl flooring is produced in widths of 1.8, 2.7, 3.7, and 4.6 m. The fibrous backing is coated with a foamable plastisol containing a blowing agent. Clear plastisol is applied and the entire structure is heated enough to fuse the plastisols and cause expansion of the foamable gels. In this final step, embossing occurs by either chemical or mechanical means. The most widely used chemical technique involves a foaming inhibitor introduced in the appropriate inks.

In Europe, rotogravure flooring is made with a solid or foamed vinyl back; polyurethane froth also is used. A glass mat with urea–formaldehyde resin binder is incorporated for dimensional stability. Most U.S. rotovinyls are defined as no-wax floors, though only a few have a shiny polyurethane surface coating of 25–50 μm that aids in gloss retention and maintenance. Other rotogravure-decorated flooring contains opaque, translucent,

or transparent vinyl chips embedded in the clear plastisol wear layer for added decoration. In Europe, rotary screen printers are used with vinyl plastisols to produce sheet flooring similar to that described as cushioned rotovinyl.

Stencil flooring is made 1.8 m wide on a similar fibrous inorganic fiber glass mat backing. It consists of granules of a mixture of PVC homopolymer and copolymer formulated with plasticizers, stabilizers, filler, and pigments to achieve the proper consistency for this process. These granules are deposited on the backing through automated stencils, each of which delivers a portion of the total design. The sheet moves intermittently, allowing time for the simultaneous deposition of granules from as many as 10 stationary stencils. The completed pattern is consolidated and embossed with heat and pressure in flatbed presses coordinated with the stencil line movement. This process is capable of a wide variety of designs that can extend through the thickness (ca 1 mm) of the deposited vinyl. A film of polyurethane is frequently applied to stencil sheet flooring to impart no-wax characteristics. A vinyl-backed product of this type has been introduced, combining rotogravure decoration with the stencil design and polyurethane surface.

Another 1.8-m wide sheet floor is made by a continuous process, called roll-press, on a similar felt backing by deposition of filled and pigmented vinyl granules or chips with subsequent consolidation in the nip between a steel pressure roll and a back-up roll. Most products of this type employ shaped or variegated vinyl chips oriented edge-to-edge in a monolayer, with clear vinyl filling the spaces between them. The chips are formulated from homopolymers of PVC with as much as 65% limestone. Dry-blend, used as mortar between the chips, is made from suspension polymers of PVC in mixers that allow the absorption of plasticizers and other liquid components at relatively low temperatures so that free-flowing dry powders result. Wear layer thicknesses vary between 0.8 and 1.3 mm (30 and 50 mils). Some of these products are coated with polyurethane for gloss retention and easier maintenance (72–74).

2.12. Pipe

Plastic pipe can be made for pressure uses such as potable water supply, gas pipelines, and pressurized sewers, or for nonpressure uses such as other sewers, drains-waste-vent (DWV), and other drainage. For some time, high density polyethylene was used most widely, with ABS preferred for DWV. In the last decade, use of PVC in piping has grown and now represents over 75% of the material used for pipe, fittings, and conduit. Over 40% of the North American consumption of PVC is used for this market with demand anticipated to reach 2 million metric tons by 1994. Pipe for potable water may be made from PVC or polybutylene. However, negative publicity regarding polybutylene piping when used in conjunction with polyacetal fittings has hurt the market prospects for this system. High molecular weight, high density polyethylene (HDPE) is used for pressurized sewer lines, up to 0.7 MPa (100 psi). A resin of molecular weight 75,000–90,000 is preferred; it is compounded with tin stabilizers and a mixture of lubricants, and blended in a high speed mixer to obtain a uniform dry blend. Multiple-screw extruders, 8–13 cm in diameter, mix and push the compound through a die designed to give a streamline, not turbulent, flow at a rate of 500–1600 kg/h. Impact modifiers of acrylic or ABS resins are added to reduce breakage and provide better performance under pressure.

Chlorinated PVC (CPVC) is preferred in some cases, especially in mobile and site-constructed homes, for hot water pipe because it is stable to 88°C at 0.7 MPa (100 psi). Polybutylene is also good for hot water lines and has the advantage of flexibility. Chlorinated PVC can be solvent-welded, whereas polybutylene must be mechanically clamped or heat-welded. In some cases, fittings of chlorinated PVC or polyacetal can be connected to polybutylene. High density polyethylene is extruded through single-screw extruders, which are lower in cost and have a higher output rate. ABS resin can be used for pressurized applications, such as gas and water lines, where adverse conditions are met. For extreme pressure conditions, PVC pipe may be filament-wound or overwrapped with glass-fiber tape and impregnated with a polyester or an epoxy resin to provide the much greater bursting strength required for municipal water pipe when relatively thin-walled PVC pipe is used.

For nonpressure conditions, a greater variety of resins and production processes is available. One of the largest uses is for DWV piping; the principal resins are ABS and PVC modified with ABS to improve its impact resistance. The pipe may be cut or sawed and is solvent-welded readily with an ABS cement. Foamed ABS pipe has a lighter weight and lower cost and it has a closed-cell structure with a solid skin. Two extruders are used, one for the surfaces and one for the core, which may be of a different and possibly lower cost resin. Both the skin thickness and the core density can be accurately controlled. The pipe is more rigid and lower in cost than solid ABS pipe of the same diameter, but it also has lower tensile strength. PVC and HDPE also can be foam-extruded for the same purposes, with similar advantages and limitations. These pipes can be used for sewers and drains.

Overall, improvements in processing technology and material properties will propel the continued growth of plastic pipe. Further penetrations into markets such as sewer mains and chemical process piping will come from making pipe with greater strength and better tolerance to temperature extremes, pressure, and corrosion. Cost considerations are a primary factor when choosing materials for piping. Building contractors save up to 30 cents on every dollar by using PVC pipe because of material, installation, and labor cost advantages. CPVC plumbing pipe systems cost up to 25% less than copper in new hot and cold water installations. When PVC is compared to cast-iron soil pipe in drain, waste, and vent pipe installations, savings vary from 10 to 25%. Because of the cost advantages and long life, PVC commands over three-fourths of the plastic pipe market and is expected to maintain its position well into the next century. Barriers to growth include the fact that PVC is not approved in some municipal codes for use in pressure situations. With no single national code authority, fragmentation has occurred as a result of regional, state, and local codes that reflect different geographical requirements. In many situations, the type of pipe required will be specified by a professional engineer, who has more experience with iron and concrete.

Ductile iron pipe makers realize their best returns in the greater than 10-cm (4-in.) pipe market, and in fittings, flanges, and valves where PVC is not widely used. Since fittings made of PVC are generally not accepted in the engineering community, ductile iron makers enjoy the advantage of being able to supply a full product line. The concrete sewer pipe market is more vulnerable to penetration by PVC pipe. Advances in ribbed, foam core, channel core and truss pipe enable PVC to compete in larger-diameter markets. Unlike the pressure pipe market where PVC is generally not price competitive above 30 cm, this new sewer pipe technology pushes PVC up into the 45–75 cm range.

While concrete pipe will have trouble being cost competitive, its poor corrosion-resistant properties can be overcome with the use of PVC liners, putting it in a position to compete against PVC pipe on its superior crush resistance. The more recent news in PVC and HDPE pipe manufacturing is geared toward materials saving, as the price of resin has risen dramatically. PVC foam-core pipe reduces material consumption up to 40% and tooling is currently applicable to DWV pipe from 1–20-cm (0.5 to 8-in.) diameters. Small-diameter, aluminum-reinforced, cross-linked HDPE pipe consists of an aluminum tube sandwiched between inner and outer layers of cross-linked HDPE. Current availability is for diameters of 1–20 cm. This pipe is impermeable to gas, immune to corrosion, and is easier to blend and install than either all-aluminum or all-HDPE pipe. It is rated to 1 MPA (150 psi) at temperatures over 90°C, making it applicable for closed indoor heating systems. Two new types of corrugated pipe with smooth inner bores, each produced by a proprietary system, have now met all specifications for sewer pipe and are said to provide material savings of up to 50% over conventional PVC pipe (40, 75, 76).

2.13. Plumbing and Bathroom Fixtures

Plastics for fittings such as faucet handles, shower heads, and plumbing parts must have high strength and resistance to creep, abrasion, and dimensional change, especially when exposed to moisture. ABS resin is widely used for these purposes, and for soap dispensers, water filters, and other accessories. The article can be chrome-plated or color can be molded in. Polyacetal can also be used for these articles as well as for valves,

couplings, and pumps where its natural self-lubricity is an advantage. Polycarbonate may be injection-molded to form handles and other parts, which can be connected by a press fit instead of by threaded lock-nuts, as required for metal.

Sanitary ware, including tubs, showers, combined units, basins, and toilet tank, may be made of thermoformed ABS or acrylic sheet, molded glass-fiber-reinforced polyester, or cast acrylic resins. The glass-polyester type dominates the tub/shower market. It is possible to install the units as a two-component system, assembled in place. Gel coats may be of thermoformed decorative acrylic skins. To reduce the smoke generated by fire, methyl methacrylate can be substituted for the styrene in the polyester and alumina trihydrate used as a fire-retardant filler. Marble chips and dust can be included in the formulation to give a cultured-marble product for vanities, tubs, and panels. Thermoformed acrylic is usually given a glass–polyester backing which is sprayed on, or the acrylic and backing are press-molded together. A thermosetting acrylic filled with marble chips and dust is cast in an aluminum mold, cured to achieve cross-linking, then postcured to obtain a cultured marble basin, tub/shower unit, or paneling. It may be a polished or matte finish with a great variety of colors and patterns.

By a casting process using about one-third acrylic resin, usually methyl methacrylate, and two-thirds ATH, integrated counter top/bowl units and sheet can be fabricated. These marblelike products are very durable, both retaining their initial appearance and having a renewable surface.

The do-it-yourself market has been largely fueled by plumbing product sales. Consumers have been spending more on bath and kitchen remodeling, where it is viewed as an investment. The overall growth in the market is because of rising consumer incomes, replacements, additions, alterations, and growth in niche markets such as designer and plastic fixtures and fittings. Plastic fixtures, unlike porcelain, are easy to mold in any color, and can be made an integral part of a well-designed kitchen or bath. The use of plastics in plumbing expanded from 20% to 32% between 1977 and 1989 with plastic and glass-fiber-reinforced plumbing fixtures accounting for nearly 50% of plumbing fixtures in 1990 (5, 12, 17, 40, 77–83).

3. Toxicity

3.1. Indoor Air Quality

Indoor air quality has become a greater concern since the energy crisis of the early 1970s as buildings have become more energy efficient and airtight. A number of real and potential health hazards regarding air quality have been debated including radon, tobacco smoke, asbestos, formaldehyde, volatile organic compounds (VOCs), and combustion by-products from stoves and furnaces. With regard to plastics, urea–formaldehyde insulating foams have received the greatest publicity. In the early to mid-1980s, they were studied for their formaldehyde release, ie, outgassing. The U.S. EPA has set an acceptable level of formaldehyde within indoor air at 0.1 ppm. Another potential source of formaldehyde release in buildings is from the binder systems, such as phenol–formaldehyde and urea–formaldehyde, used in pressed wood products such as particle board (84, 85).

3.2. Smoke Toxicity of Burning Plastics

Smoke, not flames, is the primary cause of death in most fires. However, past efforts to determine which building product components, eg, wood, fabric, plastic, etc, generate the most harmful or toxic smoke emissions have proven inconclusive. The National Institute of Building Sciences (NIBS) lists seven factors that contribute to the overall risk/danger of materials' combustion toxicity: (*1*) ease of ignition; (*2*) flame spread; (*3*) fire endurance or how rapidly fire penetrates a barrier; (*4*) rate of heat rise; (*5*) ease of fire extinction; (*6*) smoke evolution; and (*7*) toxic-gas generation. NIBS has noted that combustion toxicity is not just a building materials issue but also a building products design issue. At present, several state, eg, New York, and local governments have

enacted legislation requiring the testing and filing of smoke toxicity data for all building construction products used within their jurisdiction. However, because these tests, such as the Pittsburgh Test developed at the University of Pittsburgh, measure an arbitrary value of toxicity, typically on mice under short-term laboratory conditions excluding long-term chronic health effects or teratological factors, no effort has been successful at linking these test data to a meaningful set of building code regulations. NIBS is currently working to develop a nationally recognized standard for measuring combustion toxicity that it will present to ASTM. Finally, several companies are developing proprietary wall coverings that trigger ionization-type smoke detectors early in the thermal cycle of a fire. This pre-alert capability will further enhance the safety of buildings from the risk of fire (84, 86, 87).

3.3. Additive Toxicity

Plastic building products almost always incorporate additives such as colorants, plasticizers, uv light stabilizers, and flame retardants. Several families of these various additives are under increasing regulatory scrutiny for their potential risks with regard to smoke toxicity and their effects upon worker health in compounding/processing plants. In Europe, there is currently an effort by Germany to have the EEC regulate the use of poly(brominated diphenyl oxide) (PBDPO) flame retardants because of their suspected risks when inhaled by workers. Antimony oxide, an effective synergist with other flame retardants, is also under review in several locations though no regulatory actions are pending. Additionally, chlorinated flame retardants are being reviewed for their likelihood to generate hydrochloric (HCl) gas upon combustion. Most heavy-metal colorants, eg, those based on cadmium, lead, and cobalt, are also being reviewed for safety; in many cases, alternative colorants are available (88, 89).

4. Engineering and Recycled Plastics

The plastic building materials industry is facing rapid change and the accelerated use of engineering and recycled plastics is one catalyst for this change. Engineering thermoplastics have better mechanical properties than commodity plastics. For instance, polypropylene sheet melts at temperatures under $100°C$, whereas temperatures in excess of $150°C$ are required to melt most engineering thermoplastics. Thermoplastics can be combined with fibers, fillers, and traditional building materials like concrete or wood, creating composite materials with special performance features such as durability, fireproofing, and stress resistance. Plastic products account for less than 10% of the materials used to make a typical U.S. home today. Despite this limited market penetration, building and construction uses are the second largest market (behind packaging) for plastic resin. Resin demand for building and construction is expected to double by the year 2000, to about 14 million metric tons.

The Dow Chemical Company, General Electric (GE), Monsanto, and many other companies have focused their efforts on opportunities for plastic in the building and construction industry. The Dow Chemical Company offers a wide range of products, including Styrofoam extruded polystyrene foam board insulation and a series of construction-related engineering resins designed for OEM, converter, and fabricator applications. Its polycarbonate blends resist warping and have high dimensional stability and a low coefficient of thermal expansion for use in exterior large-sheet applications, such as doors and siding. Exterior products thermoformed from The Dow Chemical Company resins can be stained or painted like wood after being subjected to a new surface treatment technology.

GE has invested $10 million to build a 300-square meter residence in Pittsfield, Massachusetts, that will use over 20,000 kilograms of resin, accounting for 30% of all the building materials used in this structure. Resins are used in the roof, windows, siding, plumbing, foundation, and electrical system. In the design for the radiant interior wall, laminated panels do three fundamental jobs: divide space; allow for service distribution

such as water, electricity, and control networks; and provide heating and cooling. The core of the panel is extruded low density poly(phenylene oxide) foam; skins are of glass-reinforced thermoplastic. Through the core runs a vertical channel that houses water and gas pipe and wiring and also serves as supply and return duct for air.

Other innovative applications for plastics have recently been introduced into the construction market. For example, reinforced-thermoplastic urethane joints and reinforced-vinyl ester structural rods are being incorporated into lightweight scaffolding. The new components prevent rust and resist chemical attack. The joints are injection molded of rigid thermoplastic urethane. The material is said to have the impact strength needed to withstand the force of joints being dropped to the ground when the scaffolding is being dismantled. A composite reinforcement material, aimed at replacing steel rod reinforcements in concrete, is made from aramid (aromatic polyamide) and carbon fibers (qv) that have been braided together and then impregnated with a resin to form stiff rods. Braiding adds to the overall mechanical strength of the composite and also creates surfaces that form tight bonds with concrete. This material is only one-sixth the weight of iron reinforcement materials, but its strength is said to be five to six times as great. Ultrahigh molecular weight polyethylene (UHMWPE) molds are replacing wood-slat molds for brickmaking. These UHMWPE molds have a longer life, boost productivity, and reduce maintenance costs without sacrificing the character of the bricks. Fiber glass studs and nuts have developed a specialty market in structures that must be nonconductive or chemical- and corrosion-resistant. Pultruded glass-reinforced vinyl ester fasteners are used in structures that house underwater cameras in the assembly of geodesic panels that form a radome and are used in the construction of chemical plants.

Recycled plastic products have just recently been introduced in the construction market, primarily for exterior use. Eventually, recycled plastics may represent one-half of the thermoplastics in a commercially-made home. Milk and detergent bottles, scrap generated by extruders and molders, and scrap from the manufacture of engineering plastics are being combined and processed into lumber. Various resins, including high density polyethylene and styrene-based engineering plastics, are processed in a specially designed extruder and the lumber is used for landscaping, retaining walls, sign posts, and fencing. Recycled plastic from fast-food containers and soda bottles is being made into insulation, which its producer claims is safe from both toxicological and environmental standpoints (10, 31, 90).

5. Emerging Developments

A very high price and performance family of polymers called liquid crystal polymers (LCPs) exhibit extremely high mechanical and thermal properties. As their ease of processing and price improve, they may find application in thin-wall, high strength parts such as nails, bolts, and fasteners where metal parts cannot be used for reasons of conductivity, electromagnetic characteristics, or corrosion.

Thermoset polyurethane as a binder material for gravel systems is also under development. Applications could include roofing systems that require a high degree of uv light and abrasion resistance.

Certain state highway authorities are studying the use of fiber-reinforced polymers, typically thermosets such as epoxy or unsaturated polyester, for bridge construction. On an even more futuristic scale, fiber optics that employ polymeric jacketing and, in some cases, optically active polymeric cores, may someday be employed in place of wires for home security systems, climate control, etc (10, 91).

BIBLIOGRAPHY

"Plastic Building Products" in *ECT* 3rd ed., Vol. 18, pp. 87–110, by L. H. Dunlap, Consultant, and R. Desch, Armstrong World Industry.

Cited Publications

1. R. Juran, ed., *Modern Plastics Encyclopedia*, Vol. **66**, McGraw-Hill Book Co., Inc., New York, 1990, 4–138.
2. F. W. Billmeyer, *Textbook of Polymer Science*, 2nd ed., John Wiley & Sons, Inc., New York, 1971, Chapt. 8–10.
3. H. S. Kaufman and J. U. Falcetta, *Introduction to Polymer Science and Technology*, John Wiley & Sons, Inc., New York, 1977, Chapt. 2.
4. *Modern Plastics Encyclopedia*, Vol. **56**, No. 10A, McGraw-Hill Book Co., Inc., New York, 1979–1980, 4–111, 132, 147, 292–300, 498–521, 528, 626.
5. N. C. Baldwin, paper presented at the *33rd Annual Technical Conference of Society of Plastic Engineers,* Vol. 21, Atlanta, Ga., 1975, p. 30.
6. *Mod. Plast.* **57**–**68** (Jan. issues 1980–1991).
7. *Mod. Plast.* **68** (Jan. 1991).
8. *Plast. Technol.* **37** (Dec. current market price estimates, 1991).
9. *Chem. Mark. Rep.* **239**, 3, 46 (May 8, 1989).
10. *Plast. World* **45**, 30–38 (Sept. 1987).
11. *Mod. Plast.* **64**, 112 (Jan. 1987).
12. J. A. Helgesen and co-workers, *Plast. Eng.* **34**(7), 22 (1978).
13. D. V. Rosato, *Plast. World* **36**(8), 60 (1978).
14. R. Martino, *Mod. Plast.* **53**(5), 52 (1976).
15. *Plast. Des. Forum* **4**(5), 63 (1979).
16. *Mod. Plast.*, 42–44 (Feb. 1990).
17. R. Martino, *Mod. Plast.* **53**(2), 48 (1976).
18. A. S. Wood, *Mod. Plast.* **53**(4), 50 (1976).
19. R. Martino, *Mod. Plast.* **54**(4), 46 (1977).
20. *Mod. Plast.* **54**(7), 14 (1977).
21. R. Martino, *Mod. Plast.* **54**(10), 44 (1977).
22. *Mod. Plast.* **55**(12), 46 (1978).
23. *Mod. Plast.* **56**(3), 46 (1979).
24. *Mod. Plast.* **56**(10), 16 (1979).
25. R. S. Hallas, *Plast. Eng.* **31**(2), 36 (1975).
26. R. A. Kolakowski, H. G. Nadeau, and H. E. Reynolds, Jr., *35th Annual Technical Conference of Society of Plastic Engineers,* Vol. 23, Montreal, Canada, 1977, p. 171.
27. *Mod. Plast.* **67**, 42–44 (Feb. 1990).
28. *Plast. News* **2**, 22 (Oct. 1990).
29. *Consult. Spec. Eng.*, 16 (Aug. 1989).
30. *Roof. Siding Insul.*, 20–26 (July 1987).
31. "Special Report: Plastics Seek Boost in Construction," *Plast. News* (Jan. 14, 1991).
32. R. Martino, *Mod. Plast.* **54**(1), 38 (1977).
33. R. Martino, *Mod. Plast.* **56**(6), 54 (1979).
34. B. Miller, *Plast. World* **33**(10), 46 (1975).
35. *Chem. Week* **128**, 13 (Apr. 29, 1981).
36. *Rubber World* **79**, 12 (Apr. 1990).
37. *Roof. Siding Insul.*, 28–30 (Dec. 1990).
38. *Roof. Siding Insul.*, 40–49 (May 1988).
39. *Mod. Plast.*, 93 (Jan. 1990).
40. R. Martino, *Mod. Plast.* **53**(8), 34 (1976).

41. L. C. Ambler, *PVC Pipe as a Pipe Substitute for Traditional Piping Products*, Certain Teed Corp., Nov. 30, 1988.
42. *National Home Center News*, 21 (June 4, 1990).
43. *Mod. Plast.* **52**(5), 52 (1975).
44. *Mod. Plast.* **52**(10), 66 (1975).
45. *Custom Building*, 27–30 (Dec. 1987).
46. *Mod. Plast.*, 46–491 (Feb. 1987).
47. *Am. Glass Rev.*, 9 (June 1989).
48. R. Martino, *Mod. Plast.* **53**(6), 34 (1976).
49. L. F. Foro, *Plast. Des. Process.* **19**(2), 29 (1979).
50. M. Hartung, *Plast. Technol.* **25**(2), 67 (1979).
51. J. S. Summers and R. J. Brown, *Plast. Eng.* **35**(4), 34 (1979).
52. A. Stoloff, *Plast. Eng.* **35**(7), 29 (1979).
53. J. Changfoot, A. G. Dickson, F. Noel, and W. P. Start, paper presented at *34th Annual Technical Conference of the Society of Plastic Engineers,* Atlantic City, N.J., 1976, p. 42; J. W. Summers, p. 333.
54. J. T. Lutz, Jr., paper presented at the *35th Annual Technical Conference of the Society of Plastic Engineers,* Montreal, Canada, 1977, p. 146; R. C. Durham, Jr., p. 151; J. D. Isner and J. W. Summers, p. 237; J. W. Summers, p. 240.
55. K. M. Tamski, paper presented at the *36th Annual Conference of the Society of Plastic Engineers,* Washington, D.C., 1978, p. 20; R. C. Durham, Jr., p. 23; L. F. Fow, Jr., p. 29; T. W. Williams and J. W. Summers, p. 754; J. W. Summers, J. D. Isner, and E. B. Rabinovich, p. 757.
56. L. F. Fow, Jr., paper presented at the *Society Plastic Engineers Regional Technical Conference, Vinyl Plastics Division and Ontario Section,* Toronto, Canada, 1978, p. 17; L. C. Weaver, p. 45; D. S. Car, B. Baum, and R. D. Deanin, p. 57; W. J. Reid, p. 70; J. H. Orem and J. K. Sears, p. 94.
57. *Plast. News* **2**, 3 (Sept. 10, 1990).
58. *Chem. Mark. Rep.*, 19 (Aug. 20, 1990).
59. *Custom Builder*, 15–22 (Nov. 1987).
60. T. J. Krauss and R. J. Straight, Jr., *Plast. World* **36**(7), 58 (1978).
61. R. Martino, *Mod. Plast.* **52**(6), 38 (1975).
62. *Mod. Plast.* **53**(1), 37 (1976).
63. R. Martino, *Mod. Plast.* **55**(5), 42 (1978).
64. R. R. McBride, *Mod. Plast.* **56**(6), 16 (1979).
65. R. C. Durham, Jr., *Plast. Eng.* **33**(6), 21 (1977).
66. *Plast. News*, 6 (Aug. 6, 1990).
67. *Mod. Plast.*, **65**, 30, 34 (Nov. 1988).
68. *Mod. Plast.* **54**(9), 76 (1977).
69. *Mod. Plast.* **56**(9), 18 (1979).
70. *Plast. Des. Process.* **18**(1), 51 (1978).
71. R. R. Divis, *Plast. Eng.* **32**(2), 19 (1975).
72. *Flooring* **38**, 6 (Aug. 1990).
73. *Flooring* **38**, 27 (May 1990).
74. *National Home Center News*, 54 (Apr. 23, 1990).
75. *Consult. Specifying Eng.*, 16 (May 1990).
76. *Mod. Plast.*, **64**, 42–42 (Feb. 1987).
77. A. S. Wood, *Mod. Plast.* **52**(3), 40 (1975).
78. *Plast. Technol.* **21**(4), 9 (1975).
79. *Do-It-Yourself Retailing* **17**, 77, 78 (Jan. 1991).
80. *Nat. Home Center News*, 46 (June 18, 1990).
81. *Plast. World* **48**, 71 (Feb. 1990).
82. *Building Supply Home Centers*, 80, 81 (Sept. 1989).
83. *Building Supply Home Centers*, 37 (Apr. 1988).
84. *Research Studies*, Frost and Sullivan, Inc., New York, 1990, 1–3.
85. L. M. Hunter, *The Healthy Home*, Rodale Press, Emmaus, Pa., 1989, pp. 3, 17, 46, 101–115.
86. "Fire Hazards of Construction Plastics," *Indust. Health Hazards Update,* (Aug. 1990).

87. *Plast. Des. Forum* **67**, 63–70 (Apr. 1987).
88. *Mod. Plast.* **67**, 40–44 (May 1990).
89. *Mod. Plast.*, Additives special report (Sept. 1990).
90. *Wall Street Trans.*, 97, 694+ (July 2, 1990).
91. *D & B Rep.*, 34–37 (Feb. 1988).

JAMES A. FINNEGAN
BRIAN P. GERSH
JULIE B. LANG
RONALD LEVY
Arthur D. Little, Inc.

Related Articles

Building materials, survey; Laminated materials, plastic; Foamed plastics; Olefin polymers; Styrene plastics; Polyesters, unsaturated; Acrylonitrile polymers