

# Polymer Concrete—Structural Applications

## State-of-the-Art Report

Reported by ACI Committee 548

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*Polymer concrete (PC) is used in the construction of structural elements. Applications include wall panels to carry wind and seismic loads; underground vaults that must resist lateral earth pressure; vault and utility box covers that are required to resist vehicle loads; machine tool components subject to a wide range of loadings; and railroad ties to resist static and dynamic rail loads. Structural uses of PC components involve flexure, shear, bearing, and deflections. Creep, fatigue, and service temperature are important aspects of these mechanisms. A need for defining and understanding polymer concrete's structural properties and behavior therefore exists. Standards and codes governing design with polymer concrete have not yet been developed. There is a need for more research on structural behavior before design criteria can be completed.*

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**Keywords:** beams (supports); drainage; floors; insulating concretes; portland cements; **pipes (tubes)**; plastics, polymers, and resins; **polymer concrete**; railroad ties; **structural design**; tools; walls

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Polymer concrete (PC) is used for structural applications where strength, stiffness, durability, and ease in molding provide an advantage over alternate materials. An additional attraction is that many types of reinforcement can be used with PC. This report presents the state of the art in structural uses of PC. The information herein is separated into six major sections. Chapter 1 outlines the historic development of PC used in structures. Chapter 2 presents a general description of PC and some of its properties. Chapter 3 deals with the design implications for structural elements fabricated from PC. Chapter 4 describes structures that have been completed using PC. A glossary of technical terms relating to PC is provided in Chapter 5, and Chapter 6 lists references that contain additional information and background for PC structures.

**CHAPTER 1—HISTORIC DEVELOPMENT**

The use of polymers in concrete was developed in the United States under three general classifications, polymer-impregnated concrete (PIC), polymer modified concrete (PMC), and polymer concrete (PC). Polymer-impregnated concrete is a hydrated portland cement concrete impregnated with a monomer and subsequently polymerized in situ. Large-scale research on PIC commenced in the United States in 1966. Polymer modified concrete is a premixed material in which either a monomer or polymer is added to a fresh

concrete mixture in a liquid, powdery, or dispersed phase, and subsequently allowed to cure, and if needed, polymerize in place. PMC is covered by other documents prepared by ACI (ACI 548.3R) and others.<sup>1</sup> PIC has not been used in commercial applications and is virtually nonexistent in the United States today. PC was first used commercially in the 1950s in the United States in the production of synthetic marble, followed by the manufacture of architectural facing panels in the late 1950s. By the mid 1970s, PC was used as a repair material for Portland cement concrete structures, mainly on highways and bridges. The U.S. Federal Highway Administration, the Bureau of Reclamation, and the Department of Energy all sponsored materials research during the 1970s and the 1980s that included PC. In the United States in the 1980s, chemical companies developed an increasing interest in specific materials and material properties required to produce PC. As a result, many enhancements in the polymers used in PC were developed, and resins tailor-made for PC production began to be offered. This development continues, and material improvements are often achieved by manufacturers.

Information and technical papers concerning PC and its applications were published as the result of the First International Congress on Polymers in Concrete (ICPIC) held in England in 1975. Subsequent congresses were held in Austin, Texas, U.S.A. (1978), Koriyama, Japan (1981), Darmstadt, Germany (1984), Brighton, England (1987), and People's Republic of China (1990). The Seventh International Congress on Polymers in Concrete was held in Russia in September 1992. All published proceedings include papers on several structural aspects of PC. Fatigue, impact, abrasion, and flammability are discussed. Uses of PC in structures in the United States, Russia, India, Japan, Poland, Germany, England and South Africa are described.

The American Concrete Institute (ACI) formed Committee 548, Polymers in Concrete, in 1971. Committee 548 has published proceedings of symposia held with American Concrete Institute conventions. The committee has also published *Polymers in Concrete—State-of-the-Art Report* (ACI 548R) and *Guide for the Use of Polymers in Concrete* (ACI 548.1R). Several test methods specific to PC were developed and published by the Polymer Concrete Committee of the Society of the Plastics Industry, Inc. (See Table 4).

Today, a major part of PC application is in the form of precast elements. At first, the only precast elements were architectural building panels. Beginning in the 1970s, other structural products began to appear on the market, including floor drains, utility trenches, underground utility vaults and covers, high-voltage insulators, and highway median barrier shells. These products were followed by the introduction of manhole structures and machine tool bases. Research into the behavior of PC structures is continuing at the University of Texas (Austin), Brookhaven National Laboratory, the University of Houston, the Federal Highway Administration, and various state highway departments.

It is anticipated that many new PC materials and innovative uses for these materials will be on the market by the

turn of the century. Research is being conducted on such uses as ballistics panels, electric transmission poles, sandwich panels, building blocks, utility trenches, utility covers, and insulation panels.<sup>2</sup>

## CHAPTER 2—MATERIALS AND PROPERTIES

### 2.1—Materials for structural polymer concrete

The general term, polymer concrete, used in this report includes polymer mortars, polymer grouts, and polymer concretes. Polymer mortars and grouts include materials with aggregate sizes smaller than  $\frac{1}{4}$  in. (6 mm). Differences between mortars and grouts depend on the intended use and affect the fabricator's formulation of the material.

**2.1.1 Polymers**—Thermosetting polymers are used as the binding matrix for structural PC applications. Frequently used polymers include those made from such monomers as methacrylates, epoxy, furan, styrene, trimethylpropane trimethacrylate, unsaturated polyesters (UP), and vinyl ester. The monomers of these polymers, or a mixture of monomers and polymers in liquid form, are mixed with an aggregate system to produce the mixture. Polymerization promoters and initiators are also included in the mix proportioning to cross-link or complete the polymerization (hardening) of the monomers. There are several properties of the monomers or polymers typically used to define the characteristics of the uncured PC. Polymer concretes and mortars are usually classified based on the properties of the uncured binder, the cured binder, and the cured PC or mortar. For most applications, the properties of the cured binder will dominate material selection.

The viscosity of the individual or mixed components may be specified to control the coating of the aggregates. Binder resins with low viscosity are more suitable for highly-filled mixtures. A gel time range may be specified to insure that there is adequate time to place the fresh PC and that the curing will be completed within the time allotted before demolding. Additional properties of the uncured binders, such as specific gravity, shelf life, component content, and flash point, are sometimes specified.<sup>3</sup>

Mixing procedures vary with the polymers selected. The combination of monomers, polymers, initiators, promoters, and chemical additives constitutes the binder system. Some binder systems may be formulated as two components where one component contains the monomers, polymers, promoters, and additives and the second contains the curing agent or initiator. Another common way to prepare the binder system is to premix the promoters and additives with part of the monomers and polymers (usually one-half) and to premix the initiators with the remaining portion. For a specific binder system, the ingredient manufacturer or a chemist should be consulted to select the most appropriate way to mix the required chemicals. Particular care must be taken to avoid mixing promoters directly with initiators because the mixture can react explosively. Refer to Paragraph 2.6 for safety requirements.

**2.1.2 Aggregates**—Aggregates such as silica sand, granite, river gravel, basalt, fly ash, calcium carbonate, and silica

flour are generally acceptable for PC. Individual fly ashes should be tested before use since some may adversely affect the polymerization reaction. Most aggregates meeting the *Standard Specification for Concrete Aggregates*, ASTM C 33, will provide adequate performance in PC. In addition, aggregates must be selected for chemical resistance if that is a factor in the application.<sup>4</sup> Aggregates are usually specified to be dry (less than 0.2 percent free moisture) and free from dirt, clay, asphalt, and organic materials. Rounded river gravel up to  $\frac{3}{4}$  in. (20 mm) has been used for some overlays and is also suitable for precasting larger sections. The larger smooth aggregate provides a more workable mixture, and less resin can be used.

Concern for the preservation of the environment and the conservation of natural resources has focused attention on the need to recycle waste materials such as plastics, glass, and incinerator ash to produce useful products for the public and private sectors. Waste glass is a major portion of all municipal waste, accounting for about 10.5 percent or 13.5 million tons (12.2 million Mg) in 1975. This glass fraction of municipal solid waste is an inert aggregate that may be used in PC composites. Examples of glass-polymer composites include sanitary pipe, culvert pipe, septic tanks, cesspools, and building blocks or brick. Municipal park benches and tables and other decorative products normally made of portland cement concrete can also be made of glass polymer composites.<sup>5</sup>

**2.1.3 Reinforcement**—There are many types of reinforcement available for PC: bars and rods made from steel or fiberglass; fabrics made from steel wire, fiberglass, or polymers; and fibers made from steel, glass, carbon, or polymers. Ductile materials such as steel with high tensile strength and stiffness are generally preferred to provide the ductile behavior and high flexural strength for the component. Fiberglass cloth or mats are frequently used as reinforcement due to the ease of its placement in molds and its durability, strength, and chemical resistance.<sup>5</sup>

The addition of various types of fibers can result in increases in the splitting tensile strength and ductility of PC. Increases in splitting tensile strength of 9 percent for 1-in.- (25-mm)-long AR (alkali resistant) glass fibers (2 wt. percent) and from 10 to 50 percent for various steel fibers (2 to 7 wt. percent) have been reported.<sup>6</sup>

**2.1.4 Additives**—Additives, such as air release agents, wetting agents, flexibilizers, shrinkage reducers, UV inhibitors, fire-resisting agents, and bond enhancers are added to PC polymers to improve one or more properties. Each of these additives is designed and selected to match the particular polymer being used. Air release and wetting agents are used in polymer systems to remove air encapsulated during mixing and to decrease the polymer content when a low-polymer-ratio PC is required. Flexibilizers are added to reduce the modulus of elasticity and increase toughness. Shrinkage reducers compensate for polymerization shrinkage. PC is naturally resistant to ultraviolet (UV) degradation due to the opacity of the aggregates, as evidenced by up to 25 years of field exposure of some building panels and utility structures. However, UV inhibitors are sometimes used to protect the surface of polished finishes. Fire-resistive agents

are used to decrease the surface flammability of systems with higher polymer contents. Bond enhancing agents (such as silanes and titanates) provide a chemical bond between the aggregate and the polymer, typically increasing strength properties by 10 percent and decreasing effects of water degradation for some systems.<sup>7</sup>

## 2.2—Polymer concrete types

Since the polymer forms the continuous phase, behavior of the composite is significantly affected by the choice of polymers.<sup>8</sup> For that reason, PC can be categorized by binder type.

**2.2.1 Epoxy polymer concrete**—Epoxy resins used for PC are typically two-component systems. One component is the epoxy resin and the second component is the hardener or curing agent. Most epoxy resins are condensation products of Bisphenol A and Epichlorohydrin. Because of their structure, epoxy resins form strong bonds with portland cement concrete, steel, and most construction materials.

Epoxy resin cure times and strengths can vary dramatically. Epoxies tend to be slow-setting and continue to gain strength for weeks; however, they can be formulated to cure rapidly. They are resistant to most chemicals and can be formulated to cure under many moisture and temperature conditions. They have low curing shrinkage, good adhesion properties, high tensile strengths, and excellent abrasion resistance. Epoxy resins tend to have high viscosity and putty-like mortar consistency that may be sticky to finish.

The two-component systems are normally mixed at a resin-to-hardener ratio of either 1:1 or 2 (resin):1 (hardener) by volume. Varying the specified ratio of the two components can significantly decrease mechanical and chemical properties. Batching should be done in complete units or by using accurate volumetric or weight measures. Acceptable tolerance of the mixing ratio is plus or minus 5 percent, although variations of less than 2 percent are recommended. The individual components should be thoroughly mixed before combining them with the aggregate or filler system. Equipment available for automatic metering of resins insures that proper mix ratios are obtained.

Epoxy PCs can be user prepared with the many formulations of epoxy resins that are available. The selection of the material for a particular application should be based on specific manufacturer's product information and field performance data. Epoxy resins are available for use in a variety of application temperature conditions. The ratio of the two components should never be adjusted to change the curing time. Epoxy resins are considered allergenic; safe handling practices must be exercised.<sup>9</sup> See Paragraph 2.6 for additional safety information.

Koblischek<sup>10</sup> reported properties for an epoxy PC being used in the manufacture of machine tool bases. The compressive strength was 17,400 psi (120 MPa), the tensile strength was 1500 psi (10 MPa), and the bending tensile strength was 3200 psi (22 MPa). He also reported a compressive modulus of elasticity of  $5.8 \times 10^6$  psi (40 GPa) and a tensile modulus of  $4.1 \times 10^6$  psi (28 GPa) for the same epoxy PC.

**2.2.2 Methacrylate polymer concrete**—Methyl methacrylate (MMA) and high molecular weight methacrylate

(HMWM) are the primary monomers used in methacrylate PC. MMA has been used in the PC industry for many years. It has provided a satisfactory level of performance and long-term durability. HMWM is a more recent development, and good long-term performance has yet not been fully demonstrated. Due to its low viscosity, MMA monomer has excellent wetting properties and excellent bond strengths. MMA monomer is a clear, thin, highly volatile liquid with a sharp, pungent odor. Typically, MMA will provide between 30 and 60 min of working time, then cure very rapidly. MMA monomers can, however, be formulated to cure over a wide range of temperatures and is well suited for use in cold weather. MMA PCs also have excellent flow characteristics and are well suited for placement around closely spaced reinforcing or formwork for narrow cross sections. Since MMA is highly volatile, a plastic sheet or other cover should be placed over the completed work to reduce monomer loss due to evaporation before curing.

MMA systems can be user formulated or prepackaged. When the systems are formulated by the user, a promoter and initiator must be added to the monomer to begin the polymerization reaction. The monomer should contain an inhibitor, such as hydroquinone, to extend its shelf life. The polymerization reaction is initiated by adding a promoter, such as dimethyl aniline (DMA) or dimethyl-para-toluidine (DMpT), and an initiator, such as benzoyl peroxide (BPO). A variety of initiators and promoters are available to provide a range of cure times and physical properties. The amount and type of initiator and promoter used will change the setting time of the PC. Unlike epoxies, MMA will tolerate wide variations in the ratio of initiator/promoter to the resin. A cross-linking agent such as trimethylpropane trimethacrylate (TMPTMA) is typically added to the resin.<sup>11</sup>

Koblischek<sup>12</sup> reported properties for a particular MMA PC being used in the manufacture of machine tool bases. The properties reported included a compressive strength of 17,400 psi (120 MPa), a bending tensile strength of 4200 psi (29 MPa), a tensile strength of 1700 psi (11.5 MPa), and a Poisson's ratio of 0.35. Koblischek also reported several measurements of the modulus of elasticity. These measurements included  $3.5 \times 10^6$  psi (24 GPa) in tension and  $4.5 \times 10^6$  to  $5.7 \times 10^6$  psi (31 to 40 GPa) in bending.

**2.2.3 Unsaturated polyester (UP) polymer concrete**—Most commercially-produced precast PC products made in the United States and Europe are made with UP resins. The resins are typically supplied prepromoted with cobalt salts. After mixing with the aggregate system, an initiator is added that, with the promoter, causes a cross-linking reaction between styrene and polyester. Typical initiators are methyl ethyl ketone peroxide (MEKP) or ketone peroxide blends. The resulting thermoset polymer is a strong and durable binder. A variety of UP is used, depending on the application conditions. General purpose products are made with orthophthalic or dicyclopentadiene polyesters. Where improved mechanical strength or chemical resistance is required, an isophthalic or vinyl ester may be selected.

**2.2.4 Furan polymer concrete**—Furan-based PCs have been used extensively in the former Soviet Union and South



Africa. The furan monomer is manufactured from grain by-products and, therefore, the cost is not related to the availability or price of petroleum. Furans are typically cured by the addition of an acid catalyst. Reaction times are controlled by the choice of acid and through the addition of buffers for the acid. Cured furan polymers are black, which limits the color of the finished PC. Until the cure is complete, the acidic catalyst can be very corrosive to metal tools and formwork, further limiting the applications of furan PC. Furan resins also should not be used with alkaline aggregates.

**2.2.5 Lightweight polymer concretes**—Aminabhavi et al,<sup>13</sup> showed that lightweight polymer concretes generally shrink and creep more than portland cement concretes. The ratio of tensile to compressive strength is often lower than that of ordinary concrete. Lightweight PC has a lower coefficient of thermal conductivity than portland cement concretes and, therefore, on exposure to fire it will increase in temperature at a lower rate than portland cement concrete. Thus, the resistance to internal heat gain of structural lightweight PC components is approximately one-third higher than that of components made of portland cement concrete. In extended fire exposures, however, the lightweight PC will begin to lose its strength as the internal temperature of the structural element approaches the glass transition temperature.

### 2.3—Mechanical properties

The mechanical properties of PC fall between typical values used for portland cement concrete and structural metals. Flexural strength, tensile strength, shear, and flexural modulus are similar to the corresponding properties of wood. Different polymers used in PC production will impart different properties to the finished material, but when the mixing proportions, materials, and procedures are held constant, the resulting PC has very consistent properties. Less than 2 percent variation in the properties of test specimens taken from several mixes is common.<sup>14</sup>

Vipulanandan and Paul<sup>15</sup> have published results of extensive research into the effects of curing conditions, temperatures, aggregate sizes, and strain rates on the mechanical properties of epoxy and UP PCS. The report concludes that the behavior of these systems is significantly influenced by the curing method, temperature, strain rate, and testing temperature. The authors have developed relationships for these systems to test temperature and strain rates. They concluded that there was no direct relationship between the aggregate gradation and the strength of the PC within the range of aggregate sizes studied. Test results suggest that the ACI 318 code relationships for calculating the compressive modulus and the tensile strength using the compressive strength do not apply to PC. Similar relationships published for use with high strength concrete also do not apply. A constitutive model capable of modeling both strain-softening and strain-hardening has been developed for the stress-strain relationships of epoxy PC and UP PC. The predictions compare well with experimental data.

**2.3.1 Compressive strength**—PC possesses different properties under axial compression and axial tension. Under normal

conditions of short-term application of static loads, the ratio of compressive to tensile strength ranges from 6 to 10. As load duration is increased, the limiting tensile strength decreases due to the viscoelastic nature of the binder and creep effects. The effects of load duration on compressive strengths are less pronounced.<sup>16</sup> Fig. 1 shows a typical stress-strain curve for polyester PCs and MMA PCs in compression.<sup>17</sup> The curve labeled PE-PC is for a PC with an isophthalic polyester. The curve labeled PE-FLEX is for a PC with an isophthalic polyester with a flexible resin added.<sup>18</sup>

PCs have demonstrated compressive strengths of 9000 psi to 26,000 psi (60 to 180 MPa), depending on the polymer binder being used and the aggregate size, type, and gradation. Most commercial PCs have compressive strengths of 12,000 to 15,000 psi (80 to 100 MPa).

**2.3.2 Flexural strength**—Flexural strengths are influenced considerably by the choice of polymers. Generally highly cross-linked polymers produce a higher flexural strength. They also tend to have a more brittle failure mode and a higher modulus of elasticity. An unreinforced PC may have flexural strengths of 2000 to 4000 psi (14 to 28 MPa) or higher. Unreinforced flexural members should not be used as primary structural elements due to the potentially brittle nature of the failure. Ultimate flexural strengths for unreinforced sections should be based on flexural tests of the formulation to be used, from which the modulus of rupture may be determined.

Static flexural properties of PC can be determined using the same test method used for portland cement concrete (ASTM C 293 or C 78). The method specified for nonmetallic, corrosion-resistant materials (ASTM C 580) has also been used and is more suitable for PC mortars and grouts.

PC made with flexible polymers exhibits more ductile behavior than those made with rigid polymers. The ductility index may be as high as 2.0 for flexible PCs and energy absorption for PC beams is higher than for portland cement concrete control beams. Effective stiffness for PC beams are lower than for concrete control beams. The strain distribution along the depth in the compression zone of flexural beams is

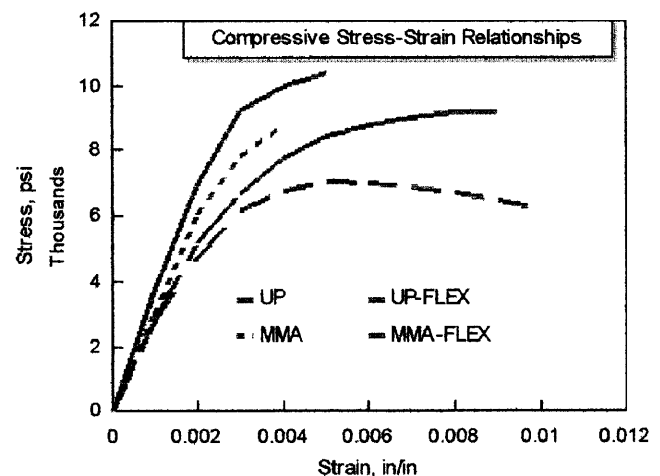


Figure 1

linear. Hsu<sup>19</sup> showed a conservative value of 0.008 in./in. (m/m) can be assumed for the maximum compressive strain at the extreme fiber.

**2.3.3 Tensile strength**—Direct tensile testing of PC is rare since PC is not normally used in direct tension applications. Preparing and mounting a specimen in a tensile-testing fixture without introducing stress concentration effects is difficult. A dogbone specimen can be used but care must be taken to eliminate end effects at the jaws of the test fixture. Tensile strengths are normally measured using the splitting tensile test method (ASTM C496). Tensile strengths of 1000 to 2500 psi (10.3 to 17.2 MPa) are typical.

**2.3.4 Modulus of elasticity**—The deformation response of PC depending on the modulus of elasticity and maximum elongation of the binding polymer, with elastic moduli up to  $5 \times 10^6$  psi (35 GPa) for rigid polymers. PCs also exhibit excellent toughness properties. Toughness is related to the material's impact strength and its ability to absorb energy before failure, as measured by the area below the stress-strain curve.

PC can be produced with a wide range of elastic moduli. Moduli of PC are generally dependent on the moduli of the resin binder and the percentage of the resin used. As binder content decreases (approaching 5 percent by volume), the moduli is increasingly influenced by the aggregate and reinforcements. Elastic moduli range from 500,000 psi (4 GPa) for a flexible resin system up to 5,000,000 psi (40 GPa) for a rigid matrix (tensile failure strains of 15 percent to less than 1 percent, respectively). The modulus of elasticity varies with temperature and for each of the major stress states: pure tension, pure compression, and pure flexural.<sup>20,21</sup>

**2.3.5 Poisson's ratio**—Very few measurements of Poisson's ratio for PC have been reported to date. A value of 0.35 was given for an MMA PC used for machine tools.<sup>22</sup>

**2.3.6 Shear strength**—Most shear failures in PC structures are actually diagonal tension failures or perhaps diagonal compression failures as in portland cement concrete. PC, like portland cement concrete, is much weaker in tension than in compression, leading to diagonal tension failures in regions of pure shear. Actual shear strengths of 275 to 3700 psi (2 to 26 MPa) are between the tensile and compressive strength for those PCs tested to date.<sup>23</sup>

**2.3.7 Fatigue strength**—Tests to date<sup>24</sup> have shown that fatigue loading increases both flexural strength and the modulus of elasticity. The applied stress is the most important factor influencing the fatigue life of PC beams. As the applied stress increases, fatigue life decreases. The range between maximum and minimum applied stress also has a significant effect. The wider the stress range, the shorter the fatigue life. Hsu<sup>25</sup> observed higher flexural strength and stiffness in static tests done on beams that did not fail in fatigue. Lastly, PC beams were superior to portland cement concrete beams in fatigue life.

**2.3.8 Creep**—PC exhibits the general creep behavior of the polymer binder. Several studies of creep in PC<sup>26,27</sup> have shown that at some stress level substantially below short-term ultimate strength, PC will creep to failure. As the level of applied stress is increased, creep strain also increases as expected. However, at some level of stress, creep proceeds

rapidly to failure in a short time. The closer the applied stress is to the short-term ultimate strength, the faster that creep to failure results. By connecting the inflection or failure points on a family of creep curves, a creep rupture envelope may be developed. The creep rupture envelope describes the maximum allowable design stresses for the PC at different anticipated load durations. This stress level is about 50 percent of the short-term ultimate strength for most PCs. All stresses used for design should be factored to account for this behavior of PC under long-term loading.

Creep in PC is approximately two to three times the creep of portland cement concrete. However, the specific creep for both is about the same. Fig. 2 shows the specific creep strain for a specific polyester PC, for example, and Fig. 3 shows the effect of ambient temperature on specific creep for the same PC.<sup>28</sup> The static strength of PC was not significantly affected by the long-term creep loading within the creep rupture envelope. The PC creep strain is high, and the PC sustained strength is low compared to portland cement concrete. For stress levels of 0.5 (and higher), creep strain in furan-based PCs is extremely high and the specimens will creep to failure in as little as two months.<sup>29</sup> When design loads will be applied continuously for 10 days or more, appropriate reductions for creep effects should be applied. A design stress of 50 percent of ultimate, or less, should be used in strength design for these cases.

PC creep behavior is also influenced by ambient temperature and resin content. Creep increases with increased ambient temperature. PC should not be used in environments where the temperature approaches the heat-distortion temperature of the resin.

Creep is important in PC design calculations of long-term deflections and deformations. Performing creep tests using the specific mix design and temperatures to be used is necessary. Creep strains generally increase with increased polymer loading; for that reason, a well-graded aggregate system should be selected to reduce the amount of polymer, if creep is to be minimized. The resin or monomer, aggregate type, and gradation all effect the creep behavior of the PC.<sup>30</sup>

**2.3.9 Impact and abrasion resistance**—Neelamegam et al.<sup>30</sup> studied the behavior of various glass-fiber reinforced PC mortars when subjected to impact and abrasion. The PC was made with an isophthalic polyester resin and fine river sand. Glass fiber contents were varied from 0 to 4 percent by mass. Results showed that glass-fiber addition significantly increased impact resistance with fiber contents of more than 2 percent. Fiber length also affected on the improvement, with longer fibers providing higher impact resistance values. Abrasion resistance also increased with addition of 2 to 3 percent of the longer fibers. Fiber lengths were between  $\frac{1}{4}$  and 1 in. (6 and 25 mm).

**2.3.10 Reinforcement development length**—Fowler<sup>32</sup> studied development lengths for steel reinforcing bars in PC and found that the ACI 318 code provisions would be conservative for PC. Development lengths have been found for only Grade 60 steel and for one strength of PC. The ACI 318 code requirements for development length should be used unless

development lengths are found from tests for the actual PC and bar size and strength to be used in a given application.

Some polymers bond better to preformed fiberglass bars or steel reinforcement than others. Tests show MMA PC has a higher bond strength to steel reinforcing bars than does portland cement concrete. Epoxies also bond well to reinforcing, while UP PC does not bond well. Furan-based PCs may not work well with steel reinforcing because of the acidic catalysts used. Glass-fiber reinforcement is frequently used in PC both as preformed bars and as fibers. Bond to glass fibers is dependent upon the coating or sizing applied to the fiber by the manufacturer. The bond to fiberglass bars depends on the polymer used to make the bar and the polymer used in the PC. Where development length is an important criterion in design, tests with the specific PC and reinforcement to be used are recommended.<sup>33</sup>

#### 2.4—Chemical and physical characteristics

Several physical and chemical characteristics of PC affect its performance in structural applications. Each of these characteristics should be considered as it applies to a particular structure. The primary mechanism of aging is the splitting of the complex molecules of the polymer. This is a very slow process.<sup>34</sup> The phenomenon has not yet been fully studied, but the effect of aging does not seem significant over the expected life of a structure. Building curtain wall panels and underground utility enclosures have been in service for up to 30 years in the United States and have not shown any decrease in serviceability based on visual evaluations of these structures.

**2.4.1 Ultraviolet light and temperature resistance**—Aging of polymers is significantly affected by exposure to ultraviolet rays and high temperature. PCs should, therefore, be selected based on their resistance to aging when they will be exposed to these conditions. Because high filler loading increases the opacity of a PC, degradation caused by ultraviolet rays is reduced. Thus, behavior of the binding polymer alone may not be a good indicator of ultraviolet light resistance.

**2.4.2 Moisture absorption**—The moisture absorption of PC is low, generally 1 percent or less by weight. All of the liquid components of the fresh mix polymerize to a solid during curing, so no interstitial capillary pores are created. Most moisture absorbed will be in discrete pores at or near the surface created by air entrained during the mixing and placing processes. Some research has shown that strengths of particular polymers are reduced by exposure to water, presumably because of deterioration of the aggregate-polymer bond.<sup>35</sup> Some commonly used polymers are affected much more than others by water exposure. This phenomenon is particularly noted in distilled water exposures and depends on the polymer used. Performance histories for similar PCs or for glass-fiber reinforced composites with the same polymer system should be reviewed to determine the effects of submersion. Polymers that, by themselves, have a low resistance to water, will also tend to lose strength when used in PCs exposed to water. Strength reductions are generally small and occur only over long exposure times for PC that is properly consolidated with few voids.

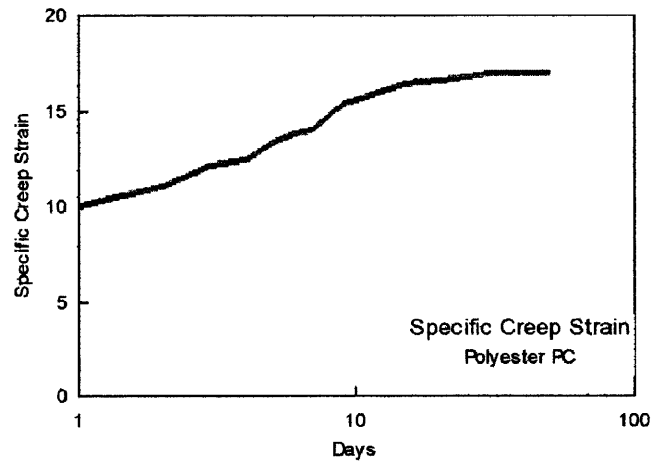


Figure 2

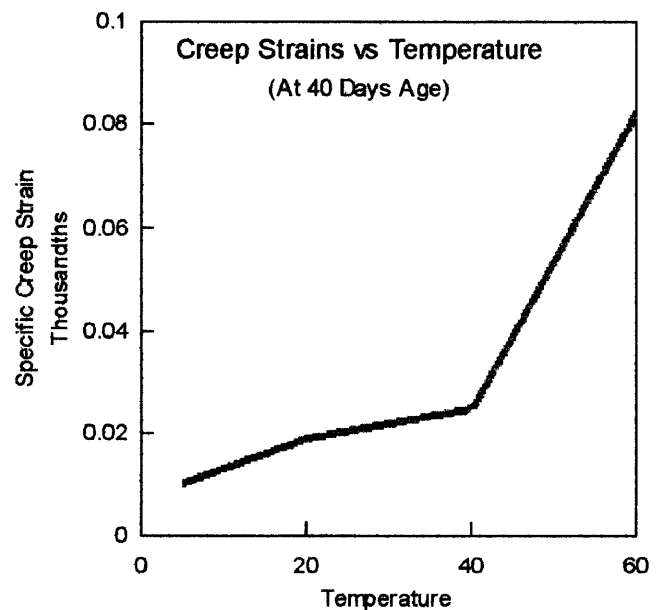


Figure 3

Furan-based PC swells when penetrated by water or other liquids. However, water can be removed from the furan-based PC if the specimens are transferred to a drier environment. In this respect, a furan-based PC is similar to wood, except that it has a lower water content and does not swell or shrink as much as wood.

**2.4.3 Permeability**—PC is less permeable than portland cement concrete or wood but more permeable than metals. PC does not have an interconnected internal pore structure and any voids produced by entrapped air during casting operations are discrete and isolated within the hardened polymer matrix.

**2.4.4 Freeze thaw resistance**—Alternate freezing and thawing degrades non-air-entrained portland cement concrete. Freeze-thaw cycling has little effect on PC since there is no internal pore structure to trap and retain water. Tests have been completed to 1600 cycles with no weight loss exhibited by the PC.

**2.4.5 Curing shrinkage**—Volumetric shrinkage occurs in PCs as the monomer or resin system changes from a liquid to a solid and as the PC cools from the exothermic polymerization reaction. The liquid monomer or resin decreases in volume and increases in density when the liquid is converted by the polymerization reaction into a solid polymer. The polymerization reaction is exothermic and causes expansion as the temperature rises. This temperature rise occurs before or during solidification. As the solid PC cools, the PC shrinks and may crack. The volumetric changes of PC vary depending on the type and amount of the monomer or resin used. Zero and low shrinkage binder systems have been developed to compensate chemically for these shrinkage mechanisms.<sup>36</sup> A gradual cooling of the PC will allow some stress relief due to creep effects that will decrease the likelihood of crack formation.<sup>37</sup>

**2.4.6 Chemical resistance**—One valuable property of PC is its chemical resistance. Aggregate and polymer selection affect the chemical resistance of PC. Polymers are relatively chemically inactive materials. Most PCs are resistant to alkalis, acids, and a wide range of other aggressive media such as ammonia, petroleum products, salt environments, and some solvents. The main exceptions to this resistance are oxidizing acids (such as nitric and chromic) which react with most polymers and alkalies, which react with phenolic and polyester polymers. In acidic environments, aggregates that are resistant to acid attack should be selected. Organic solvents will attack many commonly used polymers but where such an environment is anticipated, polymers are available with high solvent resistance such as vinyl esters.

UP PCs have excellent resistance to weak chemical solutions (salts, acids, etc.). General purpose UP PC has poor resistance to strong alkalis and is attacked by certain strong acids (such as nitric) or high temperature acidic solutions [over 140 F (60 C)]. Certain solvents such as ketones (acetone) and those containing chlorine (carbon tetrachloride and chloroform) attack all polyesters rapidly.

**2.4.7 Vibration dampening**—PC possesses excellent vibration dampening characteristics, leading to its use in machine bases. In a study by Kane,<sup>27</sup> the dampening factor for an epoxy PC was 0.003 to 0.005 compared with 0.0003 for cast iron. With polymer composites, the continuous solid matrix is an interlocked long chain of complex-shaped and configured molecular units. These polymer chains are created through an in situ polymerization reaction from low molecular weight reactive resin monomers. Once complete polymerization (curing) is achieved, structural behavior is primarily controlled by volume, distribution, and characteristics of the polymer, along with composition, size, and distribution of the aggregates. Compared with metals, the less dense polymers have more energy absorbing mechanisms that are available to attenuate vibration.

**2.4.7.1 Dynamic modulus**—Experimental work presented by Kane<sup>27</sup> suggests that a general relationship exists between the dynamic modulus and material density for polymer concretes with between 5.7 percent and 10.7 percent by weight of epoxy polymer where dynamic modulus is defined as

$$E = \frac{f_1^2 \beta W}{4905.944} \quad (1)$$

where

- $E$  = dynamic modulus, psi
- $f_1$  = frequency of the first mode, Hz
- $l$  = specimen length, in.
- $W$  = weight of the specimen, lbs
- $I$  = section moment of inertia, in.<sup>4</sup>

Maximum moduli were observed at a maximum packing density of 6.5 percent binder. Comparison of axial dynamic moduli with separate static elastic moduli testing according to ASTM C 496 showed very close agreement. This type of agreement was not true with the transverse dynamic modulus test results.

**2.4.7.2 Specific damping factor**—A tenfold increase in the specific damping factor with all the epoxy-based PCs tested was found<sup>27</sup> compared with a cast iron control where the specific damping factor is defined as

$$\zeta = \frac{\Delta}{2\pi} \quad (2)$$

where

- $\zeta$  = specific damping factor

and

$$\Delta = \frac{1}{n} \log_e \frac{A_1}{A_n} \quad (3)$$

where

- $n$  = number of amplitude cycles
- $A_1$  = amplitude of the first cycle
- $A_n$  = amplitude of the nth cycle

#### 2.4.8 Thermophysical properties

**2.4.8.1 Response to elevated temperatures**—Organic polymers exhibit a characteristic abrupt change in physical properties at some elevated temperature. This temperature is defined as the glass transition temperature ( $T_g$ ), where the polymer changes from a rigid, glassy state to a more flexible, plastic state. The glass transition temperature can vary over a broad range and is dependent on the molecular structure of the finished polymer. For the polymers commonly used in PC, the glass transition temperature generally ranges from 50 F (10 C) for very flexible PCs to over 400 F (200 C) for rigid, high temperature resistance formulations. Resistance to high operating temperatures is a function of the binder used. Fig. 4 shows an example of strength reductions that may occur as the operating temperature increases.<sup>38</sup> UP-based systems are generally limited to 150 to 200 F (65 to 90 C) as are acrylics and some epoxies. Vinyl ester, furan, and phenolics can generally withstand higher temperatures, up to 250 to 300 F (120 to 150 C). Only very specialized PCs can



withstand temperatures over 300 F (150 C) and these materials are usually expensive or not readily available. The properties of some resins change dramatically during exposure to high temperatures, when the temperature approaches or exceeds the heat distortion temperature (HDT) of the resin. At the HDT, the resin begins to soften and will distort or flow under loading. When formulating PCs, physical property measurements should be made at the upper and lower service temperatures expected. The anticipated response of a particular PC formulation can be measured by determining its heat-deflection temperature using ASTM D 648. For structural applications, a heat-deflection temperature above the highest expected ambient temperature of the structure should be specified.

Where performance at elevated temperatures will be required, it is suggested that specifications require testing over a range of temperatures that includes the highest expected service temperature. A graph of the test results versus temperature would then show any anticipated strength loss.

Koblischek<sup>39</sup> showed that both compressive and tensile modulus of elasticity began to decrease rapidly as the temperature exceeded 140 F (60 C) for an epoxy PC used in the manufacture of machine tool bases.

**2.4.8.2 Fire resistance**—PC formulations generally will not support combustion if their resin content is 10 percent or less. Most PCs with resin contents over 10 percent require special fire retarding additives if non-flammability is needed. Furan-based PCs have a higher specific heat compared to other PCs and are less likely to burn. However, under conditions of continued heating at temperatures of 360 F (180 C) and above, the strength of a furan-based PC is considerably reduced, followed by decomposition of the material and evolution of gases. Abrupt changes in the mechanical properties of the polymers occur when the temperature approaches the heat distortion temperature of the resin used.

**2.4.8.3 Coefficient of thermal conductivity and specific heat**—Values for the coefficient of thermal conductivity from 11.6 to 13.9 Btu-in./ft<sup>2</sup> to hr/F (1.7 to 2.0 W/m.K) have been reported for PC. The specific heat of PC is 0.19 Btu/lb/F (795 J/kg). Additional values are shown in Appendix 2.

**2.4.8.4 Coefficient of thermal expansion**—The coefficient of thermal expansion will vary over a broad range. PCs with low polymer contents (less than 10 percent) tend to have lower expansion coefficients, being influenced more by the aggregates. As the polymer content increases, the expansion coefficient increases approaching that of the binding polymer. PC may also exhibit one or more changes in its thermal expansion coefficient, occurring near room temperature. Measurements of a UP PC, with a polymer content of 9 percent by weight, showed an expansion coefficient of about  $6 \times 10^{-6}$  in./in. F ( $11 \times 10^{-6}$  mm/mm.K) below room temperature and about  $8.35 \times 10^{-6}$  in./in. F ( $15 \times 10^{-6}$  mm/mm.K) above room temperature. In the same study, a HMWM PC showed a much higher expansion coefficient (approximately double) and an epoxy PC exhibited an expansion coefficient between that of the UP PC and the HMWM acrylic PC.<sup>40</sup>

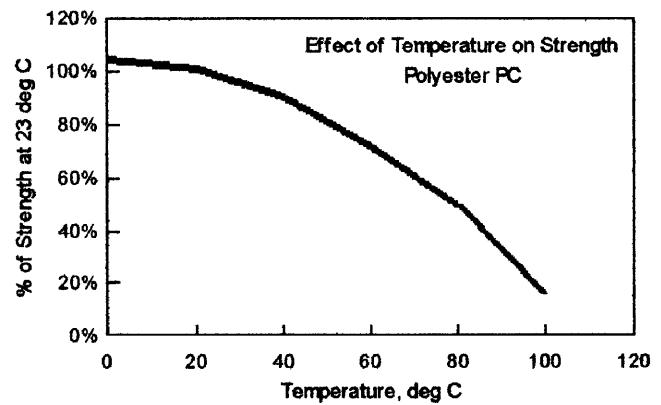


Figure 4

The coefficient of thermal expansion for PC can vary from  $7.2$  to  $70.0 \times 10^{-6}$  in./in. F ( $13$  to  $126 \times 10^{-6}$  mm/mm.K). The coefficient of linear expansion of PC is normally 1.5 to 2.5 times greater than that of steel or portland cement concrete. This property becomes important and significant for PC structures rigidly attached to other materials, such as building fascia panels.<sup>41</sup>

**2.4.9 Electrical properties**—With proper selection of materials, the dielectric properties characteristic of good electrical insulation can be achieved. This characteristic of PC makes it suitable for use as an electrical insulator. Formulations, testing, and casting procedures required to produce insulator grade PC have been developed and are reported by Gunasekaran.<sup>42</sup>

**2.4.10 Density**—The density of PC is principally dependent on the fillers used. With the use of normal concrete aggregates and resin contents of less than 15 weight percent (normal weight PC), densities are about 135 to 150 pcf (2200 to 2400 kg/m<sup>3</sup>). PC mortar generally has a density near the lower end of this scale. Lightweight PC, using low density fillers, is typically in the 70 to 90 pcf (1100 to 1400 kg/m<sup>3</sup>) range with some special materials having been developed with densities as low as 40 pcf (640 kg/m<sup>3</sup>).

## 2.5—Standards and guides applicable to PC

**2.5.1 Design guides**—Service loads are established by governing codes. Building design loads may be found in ASCE A7, *Building Code Requirements for Minimum Design Loads in Buildings and Other Structures*, *The Uniform Building Code*, and *The Standard Building Code*. Design loads for highway bridges are given in AASHTO's *Specifications for Highway Bridges*. Underground structures used under or near roadways should be designed to withstand loads specified in ASTM C 857, *Minimum Structural Design Loading for Underground Precast Concrete Utility Structures*.

The American Concrete Institute has previously published a guide to polymer concrete materials entitled "Guide for the Use of Polymers in Concrete, ACI 548.1R-92."

**2.5.2 Test methods and standards**—Tables 1, 2, and 3 show tests and standards tabulated by Ohama<sup>43</sup> that are currently in use to characterize the properties of PC in Britain, Japan, and the United States. Table 4 shows test methods prepared by S&P

**TABLE 1—ASTM TEST METHODS FOR POLYMER MORTARS AND MATERIALS**

ASTM C 267	Standard Test Method for Chemical Resistance of Mortars, Grouts, and Monolithic Surfacing
ASTM C 307	Standard Test Method for Tensile Strength of Chemical-Resistant Mortars, Grouts, and Monolithic Surfacing
ASTM C 308	Standard Test Method for Working and Setting Times of Chemical Resistant Resin Mortars
ASTM C 413	Standard Test Method for Absorption of Chemical-Resistant Mortars, Grouts, and Monolithic Surfacing
ASTM C 531	Standard Test Method for Linear Shrinkage and Coefficient of Thermal Expansion of Chemical-Resistant Mortars, Grouts, and Monolithic Surfacing
ASTM C 579	Standard Test Method for Compressive Strength of Chemical-Resistant Mortars, Grouts, Monolithic Surfacing, and Polymer Concretes
ASTM C 580	Standard Test Method for Flexural Strength and Modulus of Elasticity Chemical-Resistant Mortars, Grouts, and Monolithic Surfacing and Polymer Concretes
ASTM C 905	Standard Test Method for Apparent Density of Chemical-Resistant Mortars, Grouts, and Monolithic Surfacing
ASTM D 3262	Standard Specifications for Reinforced Plastic Mortar Sewer Pipe
ASTM D 3517	Standard Specifications for Reinforced Plastic Mortar Pressure Pipe
ASTM D 3840	Standard Specifications for Reinforced Plastic Mortar Pipe Fittings for Nonpressure Applications

**TABLE 2—JAPANESE INDUSTRIAL STANDARDS (JISs) FOR POLYMER CONCRETES**

JIS A 1181	Method of Making Polyester Resin Concrete Specimens
JIS A 1182	Method of Test for Compressive Strength of Polyester Resin Concrete
JIS A 1183	Method of Test for Compressive Strength of Polyester Resin Concrete Using Portions of Beams Broken in Flexure
JIS A 1184	Method of Test for Flexural Strength of Polyester Resin Concrete
JIS A 1185	Method of Test for Splitting Tensile Strength of Polyester Resin Concrete
JIS A 1186	Measuring Methods for Working Life of Polyester Resin Concrete
JIS A 5350	Fiberglass Reinforced Plastics Mortar Pipes

**TABLE 3—BRITISH STANDARDS FOR CONCRETE-POLYMER COMPOSITES**

BS 6319	Testing of Resin Compositions for Use in Construction
BS 6319, Part 1	Method for Preparation of Test Specimens
BS 6319, Part 2	Method for Measurement of Compressive Strength
BS 6319, Part 3	Method for Measurement of Flexural Strength
BS 6319, Part 4	Method for Measurement of Bond Strength (Slant Shear Method)
BS 6319, Part 5	Method for Determination of Density of Hardened Resin Compositions
BS 6319, Part 6	Method for Determination of Density of Modulus of Elasticity in Compression
BS 6319, Part 7	Method for Measurement of Tensile Strength
BS 6319, Part 8	Method for the Assessment of Resistance to Liquids

## 2.6—Safety

Current and detailed safety information pertinent to PC production is given in the *Guide for the Use of Polymers in*

**TABLE 4—SPI COMPOSITES INSTITUTE POLYMER CONCRETE TEST METHODS**

1.0	Test Method for Making and Curing Polymer Concrete Specimens
2.0	Test Method for Compressive Strength of Cylindrical Polymer Concrete Specimens
3.0	Test Method for Compressive Strength of Polymer Concrete Cubes
4.0	Test Method for Splitting Tensile Strength of Polymer Concrete Specimens
5.0	Test Method for Flexural Strength of Polymer Concrete (Using Simple Beam with Third-Point Loading)
6.0	Test Method for Compressive Strength of Polymer Concrete Using Portions of Beams Broken in Flexure
7.0	Test Method for Flexural Strength of Polymer Concrete (Using Simple Beam with Center-Point Loading)
9.0	Test Method for Creep of Polymer Concrete in Compression
10.0	Test Method for Specific Gravity and Water Absorption of Polymer Concrete
11.0	Test Method for Flammability of Polymer Concrete
13.0	Test Method for Resistance of Polymer Concrete to Chemical Reagents
14.0	Test Method for Impact Resistance of Polymer Concrete by Means of a TUP (Falling Weight)

*Concrete* (ACI 548.1R). Manufacturers and distributors of the materials being used will also provide information in MSDSs and other publications. This information should be read and thoroughly understood by everyone planning and doing work with PC. The key safety information is presented here since it is vital to the continued safe use of PC.

**2.6.1 Initiators and promoters**—Initiators, or catalysts, required for PC are usually organic peroxides, such as methyl ethyl ketone peroxide (MEKP) or benzoyl peroxide (BPO). By their nature, organic peroxides are combustible and may decompose with explosive violence under certain conditions. Heat and contamination are potential sources of problems when handling organic peroxides. Organic peroxides should not be exposed to any source of heat, such as direct sunlight, steam pipes, radiators, open flames, or sparks. Heat may cause them to decompose violently and they will burn if ignited. The manufacturer's recommended storage temperature should not be exceeded.

Organic peroxides are particularly sensitive to contamination from metals and should not come in contact with easily oxidized metals such as copper, brass, and mild or galvanized steel. Grinding dusts from finishing operations can be a source of contamination for the organic peroxides and care should be taken to prevent exposure. If replacement parts must be installed on peroxide handling equipment, the same materials of construction as were originally used or specified by the manufacturer of the equipment should be used. Organic peroxides should always be stored in their original containers. For transfer of peroxides into process equipment, clean polyethylene, polypropylene, Teflon, or stainless steel containers and funnels should be used.

Dry, granular, pure (98 percent or higher) benzoyl peroxide (BPO) should not be used since it can react explosively if subjected to shock or heat. Dilute forms of BPO are available as dispersions and suspensions at various concentrations.

These forms of BPO are safer to handle and use and are recommended. Additional information on initiator systems, and the use and application of MMA concretes, has been published by Fowler, Paul, and Meyer.<sup>44</sup>

Some solvents, such as acetone, can react with peroxides to form unstable peroxides of their own. Small amounts of these peroxides can cause the explosive decomposition of commercial peroxides.

Promoters (also referred to as activators or accelerators) are generally used in PC formulations when ambient temperature polymerization is desired. A promoter is a chemical compound that greatly increases the decomposition rate of the initiators. The promoter-initiator system can be designed to cause polymerization over a wide range of times and temperatures. More commonly used promoters are di-methyl para toluidine (DMpT), di-methyl aniline (DMA), cobalt octoate (CoO), or cobalt naphthenate (CoN). Promoters and initiators should never come into direct contact with each other, due to the potential for an explosive reaction of some initiator-promoter systems. To reduce the chance of an explosion, the resin or monomer can be divided into two batches and the initiator added to one-half the resin and the promoter added to the other half. Premixing the initiators with an unpromoted portion of the monomer or resin may be done several hours before combining the two premixed components with aggregates to make the PC. Some resin systems can be prepromoted, that is, with the promoters premixed into the resin by the manufacturer before delivery or mixed into the stored resin by the user, and the initiator added at the time of use. Prepackaged materials generally consist of a liquid resin component and a dry aggregate component that contains the initiators and hardeners. These procedures eliminate the danger of combining the promoter and initiator directly. Some of the promoters commonly used are extremely hazardous. Diethyl aniline (DEA) and DMA are particularly toxic and even small splashes should be immediately washed off. Contaminated clothing should be removed immediately.

**2.6.2 Monomers and solvents**—The chemicals used in MMA, UP, VE, and epoxy concretes are flammable and may be toxic. Trained workers and proper handling and safety practices are required during handling, mixing, and placing operations. Eye and skin protection should be used, and also chemical respirators. Extended exposure to the vapors may cause dizziness, headaches, or nausea. Contact with the skin may cause a rash and should be avoided. The resin is flammable, so open flames must be avoided. The cured resin will burn, but will not sustain combustion.

Styrene and MMA are flammable liquids. Accumulations of styrene or MMA vapors within the flammable limits for the chemical can lead to a flash fire or explosion that can be started by any spark or flame.

**2.6.3 Epoxies**—Different epoxy resins can be combined with a number of curing agents, flexibilizers, fillers, and other chemicals to produce several hundred different products. The flash point of epoxies is higher than that of styrene or MMA, so epoxies are less of a fire hazard. Two typical health problems that may be encountered with epoxy materials are skin irritations such as burns, rashes, hives, and skin

sensitization, which is an allergic reaction similar to that of certain people upon contact with wool, strawberries, poison ivy, or other allergens. Sensitization reactions may occur immediately, but in other cases they occur only after long periods of continual exposure. The user should refer to current MSDS information for health and safety effects of each component being used in any epoxy formulation.

**2.6.4 Fire safety**—Fire safety provisions are particularly important in PC manufacture since flammable and reactive chemicals are routinely used. Besides standard fire prevention practices, PC manufacturers must consider: 1) proper storage and handling of flammable or combustible liquids; 2) the possibility of explosive vapor concentrations; and 3) the dangers associated with oxidizing initiators. A comprehensive fire safety plan should be developed and implemented before any work is begun with the chemicals used in PC manufacturing.

**2.6.5 Plant safety programs**—PC manufacturing operations should have a safety program with specific personnel or a department assigned to and responsible for safety. Plant safety inspections, worker training, protective equipment, etc. should all be managed by the safety supervisor. Plants should maintain a separate designated area for the storage and blending of promoters and another separate area for storage of initiators. These two areas should be well separated from each other and the initiator storage should, preferably, be in a separate storage building.

**2.6.6 Toxicity**—Most chemicals used in PC manufacture are considered toxic. Each chemical should be considered separately and then together with chemicals that it may react with to form new chemicals. Chemicals can be hazardous depending on how they enter the body, i.e., through inhalation, taken internally, or absorbed through the skin. Some chemicals are dangerous through only one exposure route; others are dangerous through a combination of entries or all of them. The level of exposure and its duration also influence the toxicity. All contact with toxic materials must be reduced to a safe health level. Liquid resins, monomers, solvents, initiators, and promoters should not be allowed to contact the skin. Protective equipment such as clothing and gloves must be used and all spills should be cleaned up at once.<sup>45</sup>

Breathing or skin exposure to DMA or DEA can lead to headache, nausea, breathing irregularities, or fainting. Prolonged exposures cause even more severe reactions. MEKP initiators are particularly corrosive to the eyes and any such contact should be prevented. Solvents and thinners are toxic. Due to their volatility and frequent use, they can easily accumulate in sufficient quantity to cause a physiological reaction.

## 2.7—Regulatory matters

Local, state, and federal regulations govern PC manufacturing. The key regulations are outlined here. Copies of the regulations and implementation requirements should be obtained from the appropriate agency before beginning any PC manufacturing or construction activity. Federal, state, and local regulations are constantly changing and PC producers must be aware of these changes.

Under the Clean Air Act Amendments of 1990, styrene monomer, the most widely used reactive diluent for UP resins, has been classified as an “air toxin.” Over the next several years it is anticipated that regulatory processes will require precasters and applicators to adopt additional manufacturing controls to reduce styrene monomer emissions. These controls are not likely to prove too onerous to manufacturers involved in casting operations. Losses of styrene to the atmosphere during these processes are low and they respond well to simple engineering controls such as covering mixing vessels.<sup>46</sup> SARA TITLE III (EPA) requires emergency planning, chemical inventory reporting and toxic chemical release reporting.

The Occupational Safety and Health Administration Hazard Communication Standard, 29CFR1910.1200, requires employers to evaluate chemicals used in their workplaces to determine if they are hazardous and to transmit information on hazardous chemicals to employees by means of a comprehensive training and hazard communication program. OSHA also regulates exposure limits for certain chemicals.

The Environmental Protection Agency (EPA) has developed “cradle to grave” regulations governing the generation, storage, treatment, and disposal of hazardous materials and wastes. The Department of Transportation regulates shipment of hazardous materials and wastes. States have regulations concerning hazardous materials, their disposal, odor abatement, and nuisance laws and label requirements. These regulations require specific permits for any discharge of air or water pollutants. Local ordinances govern zoning, fire safety, building permits, and building codes.

## 2.8—Materials research

The commission of the European Communities (EC), Directorate General for Science, Research and Development, is funding a major materials research project, Epoxy PC for Precision Engineering (EPOC) to be completed during the years 1991-1994. The major objective of this project, as reported by Sasse,<sup>47</sup> is to improve the manufacturing technology of PC structural elements. Priorities of this research program include: development of methods for predicting and controlling the influence of processing conditions on the product performance; polymeric materials with optimized packages of both mechanical and nonmechanical properties; new approaches for overall optimization of building materials; prefabricated products; and new construction technologies and methods, with respect to specific applications. Specific aims for the project include:

- Development of a PC mix design method
- Development of a numerical method for the investigation of the thermal and reaction shrinkage induced internal strains, and of the deviations from the ideal geometric dimensions
- Development of a numerical method for the prediction of internal stress distributions (due to thermal history and reaction shrinkage) and for the risk of crack formation

- Optimization of manufacturing technology (including mix design) and thermal curing
- Development of specific quality control systems for materials and production

This research project has been divided into seven identified tasks that are to be accomplished:

**Task 1:** Determination of characteristic polymer binder properties

**Task 2:** Development of a PC mix design method

**Task 3:** Formulation of characteristic material properties

**Task 4:** Prediction and experimental verification of time dependent temperature fields, deformations, and residual strains and stresses within structural elements

**Task 5:** Determination of the formation and propagation of cracks in PC

**Task 6:** PC element manufacturing techniques

**Task 7:** Performance of PC structures

While this project is directed primarily at prediction and optimization of epoxy PCs for use in machine tool construction, the results will increase understanding of PCs in all structural applications.

## 2.9—Suggested additional research

Materials research parallel to that being undertaken in Europe described should also be carried out in the United States. A U.S. effort should concentrate on additional polymers including polyesters and acrylics. Such research efforts should be directed at determining:

- Definition of working stress limits based on short term ultimate strength testing
- Characterization of the effects of creep on long-term performance
- Studies of the fatigue properties of the materials,
- Development of equations for design of tensile reinforcement
- Design parameters required to prevent radial cracking around tensile reinforcement near the surface

## CHAPTER 3—STRUCTURAL MEMBERS

### 3.1—Flexural members

Many structural PC applications to date are in the form of flexural members. The ultimate moment resistance of steel reinforced sections may be determined by, satisfying the compatibility of the strains and equilibrium of internal forces. The stress distribution at ultimate load may be assumed to be an equivalent rectangular stress block, similar to that for conventional concrete. Hsu<sup>38</sup> found that a value of 0.87 for  $\beta$  and 0.86 for  $k$  best approximated actual stress response for PC where  $kf'_c$  is the compressive stress intensity and  $\beta c$  is the depth of an equivalent rectangular compressive stress block. However, he also suggested that for simplicity, values of 0.85 can be used for  $\beta$  and  $k$  similar to conventional concrete. PC has been found to have a higher modulus of rupture than conventional portland cement concrete. Yeon<sup>39</sup> reported the increase to vary from 17 to 73 percent.



Limited PC shear testing data have been published to date including work done by Knab,<sup>40</sup> Helal,<sup>41</sup> and Dang.<sup>42</sup> As the result of his work, Dang proposed a shear equation similar to the one proposed by ACI-ASCE Committee 326 (now 426) for reinforced concrete.<sup>48</sup>

### 3.2—Compression members

Currently, there are no known applications or research results in the United States for components subjected to predominantly axial loads. Some research work done in Russia was reported at the Seventh International Congress on Polymers in Concrete and may be found in ACI Publication ICPI-1.

### 3.3—Reinforced PC

Precast PC is frequently reinforced with a high-tensile-strength material, generally fiberglass or steel in either rod or fiber form. When steel reinforcement is used, it must be mechanically bonded to the PC, either with a deformed surface or through mechanical shear devices designed to transfer stresses between the steel and the PC. Where fiberglass rods are used, they should be deformed. All rod reinforcements must be embedded deeply enough in the PC to prevent the radial tension developed by the deformed bars from causing tensile cracks in the nearby surface.

Surface fiberglass fabric is also frequently used as a reinforcement. Sections reinforced in this manner generally experience one of two failure modes. The first is a brittle failure with a sudden breaking of the fiberglass. In these cases, the section is under-reinforced. The PC portion of the section has a sufficiently high flexural strength so that when tensile cracking begins, the fiberglass reinforcement is immediately overstressed in tension and fails. The second mode of failure is evidenced by tearing and delamination of the surface fiberglass reinforcement in areas of high tensile stress. This mode indicates that the failure is caused by excessive shear buildup at the interface between the surface fiberglass reinforcement and the underlying PC. Both failure mechanisms should be examined during design.<sup>49</sup>

### 3.4—Unreinforced PC

Cast-in-place PC bearing and leveling pads have been used for bridge rehabilitation in the US and Europe. They are designed so that all of the stresses in the PC are compressive. Since PC is brittle under tensile or flexural stresses, unreinforced PC should not be used for structural applications in which the load and/or supports could produce these stresses, possibly leading to a sudden, catastrophic failure.

### 3.5—Sandwich panels

Research performed by Fridley et al<sup>50</sup> examined the behavior of PC as a facing material over three different core materials in sandwich panels. The results indicated that flexural and shear behavior of the beams could be predicted by conventional sandwich beam theory. PC sandwich beams provide durable, lightweight structures in corrosive environments.

## CHAPTER 4—APPLICATIONS IN STRUCTURES

Precast PC utility components include a variety of structures used in various industries and in general construction projects. The types of PC structures and structural components currently being commercially produced are shown in Table 5.

### 4.1—Architectural panels and facades

Precast PC panels have been commercially available since 1958. PC made from UP resins and silica sand was used to produce single skin panels 0.75-in. (19-mm) thick or sandwich panels with 0.75-in.- (19-mm)- thick facings that encapsulated polyurethane foam. Fiberglass cloth and, in some cases, steel bars were used as reinforcing for spans up to 15 ft. (4.5 m) to withstand wind load. Exposed aggregate was typically used on the exposed face. Prusinski<sup>51</sup> gives many examples of PC panels and facades used around the world (Fig. 5). Many companies produced PC panels. Some of these companies were unsuccessful due to failures in the panels. Reasons for failures included:

- a) Laminated panels that delaminated in service
- b) Steel reinforcing bars placed too close to the surface which resulted in cracking
- c) Inadequate reinforcement
- d) Use of impure silica sand which caused blotchiness or discoloration
- e) Irregular placement of aggregate on the surface that caused an unsightly finish
- f) Warping and bowing due to improper fabrication

UP PC panels reinforced with fiberglass have been produced since about 1970 in the Netherlands. Flat single skin panels are 0.6-in. (15-mm) thick; panels that have returns or which form corners are 0.8-in. (20-mm) thick. Insulating sandwich panels are produced in thickness of 4 in. (100 mm). Spandrel panels, channel-shaped in cross section, are made using sandwich construction in lengths up to 17 ft (4.5 m).<sup>52</sup>

Since 1972 a Quebec firm has been producing precast PC panels using UP resins and a variety of surface finishes including (a) ribbed with granite filler; (b) exposed aggregate; and (c) gel coat. Single skin facing panels are generally used, although some panels use 1-in. (25-mm) PC skins with 3 in. (75 mm) of polyurethane foam sandwiched between. Some panels are curved at the top and bottom, and some interior panels used in subways have a bench formed monolithically within the panel. Some panels are reinforced with a metallic lattice.<sup>53</sup>

Spence<sup>54</sup> gives examples of thin facing panels used for facades and column covers in the UK. UP resin PC with a wide range of aggregate fillers, and in some cases with pigments, is used. Other sources in the UK indicate a wide range of interior and exterior wall panels using PC have been used.

An innovative composite panel has been produced which consists of a thin 3/16-in. (5-mm) polymer mortar facing bonded to a reinforced plastic panel that has foam-filled ribs

**TABLE 5—STRUCTURAL APPLICATIONS**

Component	Description and advantages	Ref.
Wall fascia panels	Exterior building cladding; strength, weight durability	51
Median barriers	Highway lane separators; color, reflectivity, strength, weight	51
Electrical insulators	Support electrical conductors; electrical properties, mechanical strength	37
Underground handholes	Cable splice enclosures; lightweight, toughness, durability	58, 46
Service boxes	Gas, water, etc. metering boxes; lightweight, toughness, durability	58, 46
Equipment vaults	Underground equipment housings; strength, impermeability, corrosion resistance	58, 46
Controlled environment vaults	Underground housing for delicate phone equipment; impermeability, high strength	58
Cable trenches	Control cable enclosures; easy accessibility, strength to weight characteristics	58
Equipment pads	Support for power and telephone equipment; strength to weight characteristics	58
Shunt reactor stands	Support tower for electrical equipment; non-magnetic, insulation properties	58
Catch basins	Collect surface water; impermeability, strength, corrosion resistance	58
Separators	Separate sludge, etc. from effluents; corrosion resistance, impermeability	58
Drainage systems	Collect and transport surface water; strength, impermeability, corrosion resistance	58
Pipe and pipe liners	Transport corrosive fluids; corrosion resistance, impermeability	58
Machine bases	Precision machine tool assemblies; strength, vibration, thermal properties, cost	33, 34
Hazardous waste containers	Enclose or encapsulate wastes; impermeability, chemical and physical inertness	65

to provide stiffness. The panels were developed as an alternative to glass-fiber reinforced panels that were too heavy for recladding an old church.

#### 4.2—Transportation

Several applications of PC for the transportation industry have been identified. For several years, median barrier systems consisting of shells have been produced which are used to encase existing deteriorated concrete barriers. Portland cement concrete is used to fill the void between the PC shell and the existing barrier. The shell serves as the permanent form that provides a durable, reflective surface and results in considerable savings in construction time.<sup>55</sup> Half shells can be used to provide a new surface for bridge parapets or tunnel walls with concrete used to fill the void.

PC curb facing is also produced with dowels that permit it to be attached to cast-in-place portland cement concrete. The stay-in-place form comes in heights of 4 to 18 in. (100 to 450 mm) and lengths up to 10 ft (3 m).\*

Ribbed PC railroad crossing panels have been produced in the UK. The panels have a waffle-like pattern on the bottom and are heavily reinforced. The panels span between and rest on the bottom flanges of the rails with the top surface at the same elevation as the rail.



Figure 5

A PC railroad tie under development uses two elongated shells connected by two struts (Fig. 6). The weight is about one-half that of a normal concrete tie. Advantages are reduced weight, greater durability, greater stability on the ballast, and significantly improved damping of the PC compared to concrete.\*\*

#### 4.3—Electrical insulators

High-voltage PC electrical insulators have been produced for many years as an alternative to porcelain. Both MMA and UP resins have been used to produce the insulators. The advantages compared to porcelain are low-cost, simple process technology, energy conservation since less fuel is required to produce PC insulators, durability, strength, excellent dielectric properties, and great design flexibility. Several companies in the U.S. are producing PC insulators.

#### 4.4—Utility structures

**4.4.1 Underground structures**—Many types of underground enclosures, handholes, vaults, and manholes are produced from PC. These units typically use glass-fiber reinforcing. The smaller units are generally cast monolithically while the larger units are cast segmentally and erected at the site.

PC underground equipment enclosures are used by power and communication utilities throughout the United States and in other countries. The primary advantage of PC enclosures is the light weight compared to portland cement concrete. PC enclosures are produced by several manufacturers in sizes varying from about 1 ft<sup>3</sup> (0.03 m<sup>3</sup>) to units that are 8 ft wide by 8 ft high by 8 ft deep (2.4 x 2.4 x 2.4 m). Most of these units can be placed manually by two workers. The larger units require only a light boom hoist on the delivery truck. Design requirements for underground enclosures include use of high-strength materials to reduce product weight, low total creep to reduce deformation under soil loading conditions, and high fatigue and impact strength to resist traffic loads on the tops or covers.

\* "Visi-curb<sup>TM</sup>," Transpo Industries, Inc., New Rochelle, NY.

\*\*Chettiar, G.M., Fowler, D.W., and Wheat, "Development of a Polymer Concrete Railroad Tie," *Proceedings of the Composite Institute's 45th Annual Conference and Expo*, Washington, DC, February 1990, pp. 12-C/1 to 12-C/9.

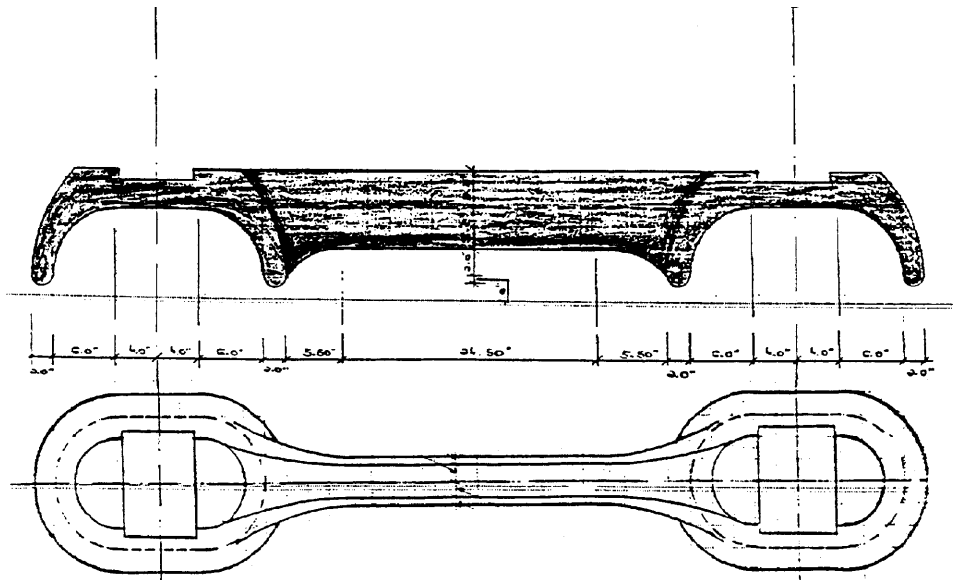


Figure 6

Enclosures are designed for loads from light vehicles such as cars, pickups, and light trucks, or heavier vehicles such as heavy commercial trucks and tractor-trailer trucks. Designs available account for the standing weight or slowly moving weight of the vehicle, either on the cover or on the soil or pavement adjoining the enclosure. To date, PC enclosures have not been designed to withstand the heavy, high-speed traffic encountered in primary and secondary roadways.

Typical construction of an enclosure includes a four-sided box, generally without a bottom, but with a cover (Fig. 7). Sometimes, an extension is included that can be installed below the box to produce a deeper enclosure. The covers are fiberglass-reinforced PC (FRPC). The boxes are either FRPC or a composite of fiberglass reinforced polymers (FRP) and FRPC. In the composite construction, the upper or collar section is of FRPC to provide rigidity and abrasion resistance. The lower wall portion of the box is FRP, providing very high strength and low weight. FRPC/FRP composite boxes provide lightweight, strong enclosures and are preferred by many utilities.

Vaults are used for housing larger equipment and are characterized by their size, fixtures and accessibility. Vault sizes vary from 30-in. wide by 48-in. long by 24-in. deep (750 x 1200 x 600 mm) to 48-in. wide by 96-in. long by 60-in. deep (0.12 x 0.25 x 0.15 m). They are typically equipped with cable support racks, bell ends, and/or duct terminators. Bell ends and terminators are fittings to which the utility can connect underground conduits feeding the vault. Vaults are available completely preassembled or packaged in components for assembly at the construction site. Several manufacturers also offer an adjustable upper ring or collar to permit field changes to the top grade and level.

The smaller vaults are called handholes. Handholes are used to enclose cable splices for underground distribution systems. These splices may be in fiber optics communication lines, wire telephone service distribution lines, or underground power distribution splices and taps. The handhole is

typically 12 to 26-in. (300 to 650-mm) deep and 12 x 24 to 30 x 48 in. (300 x 600 to 750 x 1200 mm) in plan area. These handholes are generally installed within a street or road right-of-way. PC handholes are generally one-third to one-fifth of the weight of an equivalent portland cement concrete handhole. This lower weight results in covers that can easily be removed by one person without special lifting devices and substantially decreases the risk of injury. The handhole and its covers are also extremely tough. Utilities, as a result, have a much lower replacement rate for covers cracked or broken by handling or unexpected heavy traffic on the enclosure.

Handholes are also used as service boxes. Service boxes are used to house meters for water or gas distribution. Their sizes are similar to those of handholes. An added feature in service boxes is a small hinged or lift-out reader lid that allows servicemen to read the meters inside the enclosure. Service boxes are generally installed in residential and commercial areas in sidewalks, lawns, and boulevards.

The largest underground structures used by the utilities are manholes. They can be similar in size and construction to vaults but are deep enough to permit a worker to completely enter the enclosure, typically 7 ft (1.8 m) or more. At these sizes and depths, the primary design concern is the lateral soil loading on the walls. A higher safety factor is also required because the life safety of anyone entering the enclosure is involved and the soil pressures are continuous long-term loads subject to creep effects.<sup>58</sup> This increased safety factor may be applied by reducing the maximum design stress used. A value of 50 percent of the ultimate stress is suggested for these structures. Precast PC manholes have been used extensively in Japan since 1967. These manholes were first developed by Nippon Telephone and Telegraph Public Corporation. Annual production was reported to be about 20,000 tons (18,000 Mg) in 1978.<sup>59</sup> The greater strength, lighter weight, and better chemical resistance are cited as reasons for their popularity. Typical dimensions are 5.2-ft (1.4-m) wide by 6.3-ft (1.65-m) high by 9.2-ft (2.4-m)

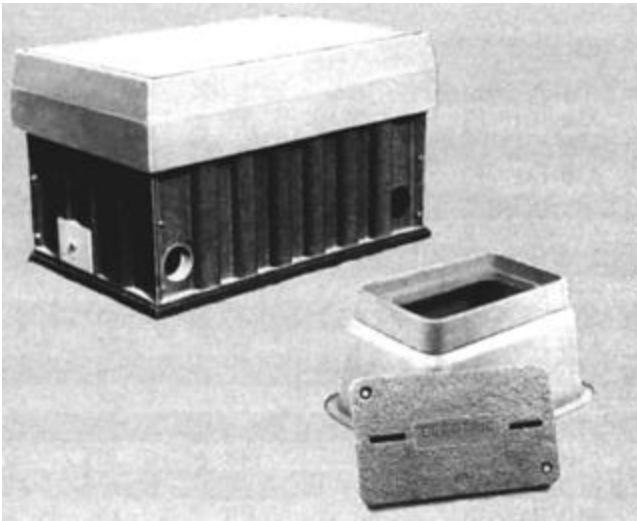


Figure 7



Figure 8

long, with wall thicknesses ranging from 2 to 3.5 in. (50 to 90 mm). The units weigh about 3.3 tons (3 Mg). Based on testing and field experience, units that develop cracks in the endwalls are still capable of carrying the design loads. However, it is necessary to repair the cracks with glass-fiber cloth and polymer mortar to prevent water intrusion.<sup>60</sup>

**4.4.2 Equipment pads and support structures**—PC equipment foundations are lighter than equivalent portland cement concrete foundations because of the thinner sections used. This weight reduction allows the use of precast foundations

for many applications where previously cast-in-place concrete was used. Installed costs are lower since less equipment and smaller crews are required to install the lightweight PC foundations. In northern climates, PC foundations have a much longer service life than concrete due to PC's better resistance to freeze-thaw damage. Tests conducted on polymer concrete have shown no specimen weight loss after 2000 cycles of freezing and thawing.<sup>61</sup> There are many U.S. producers for precast PC equipment foundations. Primary design parameters include physical strength, resistance to UV and water exposure, dimensional stability, resistance to dilute acid or base solutions, resistance to salt solutions, and resistance to transformer oils and fuels.

There is a variety of surface, pad mounted telephone equipment being used in the communications industries. This equipment is generally light, weighing 250 to 1000 lbs (100 to 450 kg). The primary criteria for supporting pads are dimensional stability and resistance to UV and weather exposures. Composite FRPC/FRP pads (Fig. 8) provide these characteristics in addition to being very lightweight. Typically, the precast FRPC/FRP pads are light enough to allow their installation by the same crew and with the same equipment used to install the cabinet. As a result, only one trip to the worksite with one crew is required to provide an installation.

Power transformers and switches are also frequently pad-mounted. This equipment is typically much heavier than telephone cabinets, weighing from 600 to 6000 pounds (270 to 2700 kg) for secondary distribution equipment and up to 30,000 pounds (13,600 kg) for primary transformers. Support pads vary in size from about 3 by 3 ft (0.9 by 0.9 m) to 10 by 11 ft (3.0 by 3.4 m) and are typically 3 to 6 in. (75 to 150 mm) thick. Composite FRPC/FRP construction again provides a very strong, durable pad with very low weight.

Large shunt reactors, equipment used on high voltage, 3-phase transmission lines have been supported by FRPC stands. Shunt reactors are installed at the ends of long distance transmission lines and can weigh 15,000 pounds (6800 kg) or more. A shunt reactor is a large electromagnetic device. The magnetism around the shunt reactor precludes the use of any metal in the support structure. For electrical safety, the preferred mounting height for a shunt reactor is 8 ft (2.4 m) above the ground. PC reinforced with glass-fiber rods and glass-fiber mats has been found to provide a superior support stand for these units.

**4.4.3 Cable trenches**—Cable trenches are typically used to hold control cables in electrical switch yards, extending from the control house to the equipment on the power lines in the yard. The trench is usually 2- to 3-ft (0.6- by 0.9-m) wide by 12- to 18-in. (300- by 450-mm) deep and has only a partial bottom. The trench is also equipped with covers. Trenches are preferred for control cable distribution because of the easy accessibility they provide for repairs and changes. Covers are commonly designed to support pedestrian loads. Where the trench crosses a service road in the yard, however, the covers are required to support loaded line trucks and must be designed for these loads.



#### 4.5—Hydraulic structures

Hydraulic structures include drainage components (catch basins, separators, and drain trenches), pipe, and lined pipe.

**4.5.1 Drainage systems**—Drainage systems, in the form of catch basins, sand and grease interceptors and trench drains are also produced in PC and have been widely used during the last 15 years. PC area drainage systems consist of modular, presloped trench sections. Sections interlock to form continuous drain trenches up to 200-ft (60-m) long. Manufacturers supply a variety of cover gratings with the trenches including fiberglass, cast iron, and galvanized steel. The units are installed at the site. Portland cement concrete is usually placed around the sides and bottom of the drainage system. Drainage systems are produced in the U.S., Europe, and Japan. PC drains are lightweight so that one or two workers can lift and install each of the modular components. The drains are used in exterior areas, such as parking lots, to intercept sheet water runoff and at tennis courts and playing fields. Inside applications include auto or truck maintenance garages, agricultural facilities, and food processing plants.

Precast modular interlocking components are manufactured with a built-in slope. The built-in slope permits surrounding surface areas to be designed with less grade than would be required with a single catch basin design. PC drainage systems are corrosion resistant and can be used to collect and transport chemical effluents. The low porosity and smooth finish possible with PC also make these systems easy to clean and, therefore, acceptable to the United States Department of Agriculture for use in food-producing operations. These systems typically have a bottom radius to provide superior hydraulic characteristics and a high degree of self-cleaning.

Catch basins are used to collect surface water and route it into the drainage piping underground. Precast PC catch basins are used where inflows might be corrosive, in areas subject to freeze thaw cycling, and where weight is a concern.

Another form of catch basin is a separator. These units are partitioned internally to separate floating and settling materials carried by the effluent. These materials include oils, greases, sand, and dirt. Separators are required by many building codes and by EPA regulations governing discharges into public waters. PC separators are frequently used where USDA regulations require a high degree of clean ability in food processing installations. PC provides a smooth, impervious surface that can be easily scrubbed and disinfected. PCS formulated with corrosion resistant resins are also unaffected by the strong cleaners used in these installations.

**4.5.2 Pipes and pipe liners**—PC pipe and PC-lined pipe are used where advantage can be taken of PC's impermeability and corrosion resistance. Both portland cement concrete pipe and steel pipe have been successfully lined with PC for various applications. Pipe and liners for geothermal power plant piping have been developed by Brookhaven National Laboratory.<sup>62</sup> PC materials used in this application have to withstand operating environments of 460 F (280 C) and 600 psig (42 kgf/cm<sup>2</sup> gauge) and contain acidic fluids with high dissolved solids contents.\* The PC developed for this use has performed well and is currently in commercial use at geo-

thermal sites in the Salton Sea area of southern California. Pipe and liner design must include a review of chemical resistance, water resistance, mechanical strengths, and operating temperature requirements.

PC-lined portland cement concrete pipe has been used to produce pipes and other components for a sewer system in Czechoslovakia.<sup>64</sup> PC-lined pipe was chosen to provide resistance to alternately acid and alkaline effluents being transported. The PC-portland cement concrete composite pipe resulted in the use of a thinner wall pipe and reduced the overall cost of the project. Similar work has been completed in Japan with PC mortar lined portland cement concrete pipe. Kawakami et al.<sup>65</sup> described development of sewer pipe lined with a polymer mortar. Portland concrete pipe will corrode if it is exposed to effluents with a pH of 4 or less. An epoxy-based mortar liner was chosen that is resistant to the low pH environment. The liner was applied centrifugally immediately after the portland cement concrete was also cast centrifugally. The epoxy liner was then polymerized with infrared radiation before the portland cement portion was steam-cured.

#### 4.6—Hazardous waste containment

Many approaches used to solidify or stabilize hazardous wastes originated in radioactive waste management. For the past several decades a great deal of development and research has taken place in the solidification and/or containment of radioactive, industrial, and other waste materials.<sup>66</sup>

Geothermal resources are inexpensive and environmentally clean energy sources compared to coal and oil, yet they can present a variety of pollution problems. The disposal of spent brines and waste waters generated in drilling, construction, and operation of a geothermal plant presents a major problem associated with geothermal energy.

Geothermal fluids generally contain a variety of inorganic compounds and heavy metals. If these contaminated fluids and residues are not properly disposed of, surface and/or ground waters can be polluted. The special procedures required for the handling and disposal of hazardous materials will result in a significant increase in the cost of geothermal energy. Considerable savings can be realized if the waste materials can be encapsulated or solidified to render them nonhazardous. Studies conducted by Brookhaven National Laboratory<sup>67</sup> have suggested that geothermal wastes can be solidified in polymer composites and portland cement mortars that will render them nonleachable and therefore nonhazardous.

#### 4.7—Machine tools

A machine tool is a device used to shape solid materials by grinding, cutting or forming. It is an assemblage of parts that transmit or modify forces, motion and energy in a predetermined manner. The machine builder must consider all possible design considerations required simultaneously. These considerations include: 1) low-cost manufacturability, 2) machine performance specifications (degree of precision), 3) machine function (grinding, milling, turning, etc.), 4) avail-

\* Kukaaka, Lawrence E., "Polymer Concrete Pipe for Use in Geothermal Energy Processes," *Proceedings, Volume, Second International Congress on Polymers in Concrete*, The University of Texas at Austin, Austin, 1978.

able materials and component technology, 5) configuration, structure and joints, 6) vibration control, 7) control and analysis systems, and 8) assembly, reliability, safety, and service. PC is being used to replace cast iron in the manufacture of the frame or base of these machines (Fig. 9).

PC used for machine tool casting specifically requires castable composite materials having low resin content and predictable performance. Less than 10 percent by weight of a rigid polymer resin is normally used as the composite binder. The binders are typically ambient temperature-cured epoxy resin systems, or other specially designed reactive resins, having low viscosities, i.e., less than 300 centipoise, low shrinkage and high heat deflection temperatures, over 200 F (93 C). The extenders for these PCs are inexpensive commodity aggregates, usually of specific igneous origin, and certain mineral fillers. However, special ceramic, metal oxide, or metal fillers are also used to provide special properties.

Polymer composites used in machine tools are designed to be homogeneous, stiff, and temperature-insensitive over the operating range of the machine that may differ between machine types. The composite castings must meet the performance specifications and production requirements of either general purpose or high precision machine tools. As such, machine specifications dictate the design of the particular PC material and process.

An important requirement for a PC used in machine tool applications is that it must be reliable and predictable. This predictability is especially necessary in terms of the PC's reactions to deformation produced from external or internal forces, either static, dynamic, or thermal. Consequently the stiffness-to-weight ratio and dynamic stability of the PC component is important in design and construction of any type of machine.

Machine tool bases must be designed so that vibration from either external sources or moving components in the machine is reduced or completely attenuated. Surface finish, part tolerances, and tool life are directly related to the amount of vibration transmitted in the loop between the tool and the part being machined. Increased machining speed, heavier cuts, or higher productivity produces greater vibration.

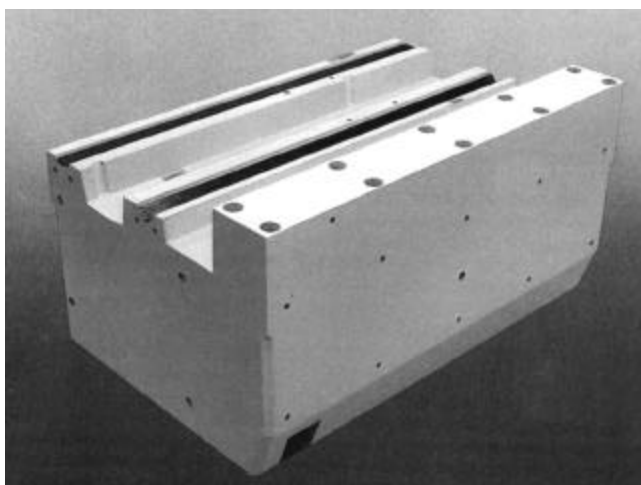


Figure 9

Machine components must remain rigid so that during their warm-up and operating cycles they do not greatly influence the tolerances or surface finishes of the parts being machined. Overall machine resistance to deflection during operation, i.e., directly related to base and joint stiffness, and vibration damping are the two key parameters to which premium machining characteristics are associated.

Precision machine tool builders achieve machine and machining specifications through optimizing machine design stiffness, vibration damping, and the machine controls. Part of this machine optimization was traditionally accomplished by using careful component and joint design and use of massive cast iron bases. Vibration damping, dynamic and thermal stability, rigidity, and chemical resistance are inherent PC characteristics.

When properly designed, a high-performance PC will show superior stiffness-to-weight and vibration damping performance versus conventional gray cast iron. Since a PC casting does not involve a metal liquid-solid transformation over a large temperature range, the volume change, that is, the PC casting shrinkage, is much less than that of cast metals. Near-net-shape castings are achievable with PC, eliminating post metal-casting machining operations.

Along with better as-cast tolerances, PC also offers the design opportunity to reduce weight or produce complex shapes that otherwise could not be cast or machined. Weight reduction is realized with castable polymeric materials having material stiffness-to-weight ratios greater than cast iron, if the machine bases are designed to have equal stiffness.<sup>68</sup> Examples of machines using or able to use PC bases include grinders, milling machines, turning machines, saws and cut-off machines, drilling machines, honing and lapping machines, and surface plates and blocks. Instrumentation applications include coordinate measuring machines; acoustical, optical and electronics test equipment; and vibration test equipment. PC has also been used in the manufacture of pump bases, gear housings, and motor mounts.

## CHAPTER 5—GLOSSARY OF TERMS

**A/B components**—The individual parts of a polymer binder system. The components typically consist of (a) promoted resin and (b) curing agent/hardener.

**Accelerator**—A chemical used to increase the rate of cure of a resin at 68-86F (20-30 C). The accelerator increases the formation of free radicals by reacting with the initiators. Examples are dimethyl aniline (DMA), diethyl aniline (DEA), cobalt naphthenate (CoN), and cobalt octoate (CoO) (see also **Promoter**).

**Catalyst**—A substance that markedly speeds up the cure of a binder when added in minor quantity as compared to the amounts of primary reactants (see also **Initiator**).

**Cross-linking**—The reaction between a monomer and a polymer system. The monomer reacts with the polymer because the unsaturated groups in each will react with each other. This reaction cross-links or ties together the polymer chains, producing a solid, thermoset polymer mass. This reaction takes place by a free radical mechanism.

**Cross-linking agent**—Bifunctional or polyfunctional monomer or polymer whose addition to a polymer system increases the rigidity, resistance to solvents, and softening point of the polymer.

**Cure time**—The interval after mixing in which a PC system gains adequate strength to support loads such as foot and/or vehicular traffic; see also **Curing, Working life**.

**Curing**—The change in properties of a chemical by an increase in molecular weight via polymerization or cross-linking, usually accomplished by the action of heat, catalyst, cross-linking agent, curing agent, or any combination, with or without pressure.

**Curing agent**—The chemical component that causes the resin to cure (see also **Catalyst** and **Initiator**).

**EC**—European Community

**EPA**—Environmental Protection Agency

**EPOC**—Epoxy PC for Precision Engineering

**Exotherm**—Heat produced by the polymerization reaction.

**Exotherm curve**—A graph of temperature plotted against time during the curing cycle. The peak exotherm is the highest temperature of a resin during the curing period.

**Fiberglass**—Fibers similar to wool or cotton fibers, but made from glass; sometimes called fibrous glass. Glass fiber forms include cloth, yarn, mat, milled fibers, chopped strands, roving, and woven roving.

**Fire point**—The lowest temperature at which a liquid in an open container will give off enough vapors to continue to burn once it is ignited. The fire point is generally only slightly higher than the flash point.

**Flammable liquid**—Any liquid having a flash point below 100 F (38 C).

**Flash point**—The minimum temperature at which a liquid gives off vapor within a test vessel in sufficient concentration to form an ignitable mixture with air near the surface of the liquid.

**Flexibilizer**—A monomer added to the PC formulation that decreases the modulus of elasticity and may increase the toughness of the finished PC. Compressive strength and flexural strength are also reduced by the addition of a flexibilizer.

**Gel**—The state of the resin just before its becoming a hard solid. At this time, the binding material has the consistency of a gelatin and can no longer be “worked.”

**Gel time**—The time required to change a flowable liquid resin into a nonflowing gel.

**Impermeable**—Not permitting passage, as of a fluid, through its substance. See **Permeability**.

**Inhibitor**—A substance that retards polymerization, thus extending the shelf life of a resin or monomer. Also used to influence gel time and exotherm. Inhibitors seek out free radicals (which can be formed in a resin by sunlight, heat, and other sources) and prevent them from reacting with the monomer or polymers in the resin system.

**Initiator**—A substance capable of causing the polymerization of a monomer by a chain reaction mechanism; often incorrectly called a catalyst.

**Methyl methacrylate (MMA)**—A monomer frequently used in PC systems. MMA is typically cross-linked with trimethylpropane trimethacrylate (TMPTMA) or another

multifunctional acrylate to produce a rigid thermoset polymer. MMA-based PCs are particularly weather and UV resistant and can be mixed at low resin-to-aggregate ratios because of the low viscosity of the monomers.

**MSDS**—Material safety data sheet.

**Mold release**—A substance used to coat PC molds or forms to prevent the part being cast from sticking to the mold, thus facilitating the removal of the part from the mold. Examples: polyvinyl alcohol; wax; certain greases, etc.

**NIOSH**—National Institute for Occupational Safety and Health.

**OSHA**—Occupational Safety and Health Act.

**Organic peroxides**—Sources of free radicals used as 1) initiators for free radical polymerization and/or copolymerization of vinyl and diene monomers, 2) curing agents for thermoset resins, and 3) cross-linking agents for elastomers.

**Polyester**—A condensation product resulting from a chemical reaction between a dicarboxylic acid and a dihydroxy alcohol or by the polymerization of a hydroxy carboxylic acid.

**Polymerization**—A chemical reaction in which the molecules of a monomer are linked to form large molecules whose weight is a multiple of that of the original substance.

**Premix**—A polymer concrete formulation prepared and packaged in advance of use with compatible ingredients preblended together in the correct ratios for the final mix. Aggregates and the catalyst are frequently premixed as one part and the monomers, additives, and promoters as another part of premixed methacrylate systems, for instance.

**Prepolymer**—A polymer, often of low molecular weight, i.e., a few hundred or thousand, which is subsequently to be converted to a higher molecular weight polymer.

**Promoters**—Often called accelerators, promoters are reducing agent compounds added to the monomer system to cause the decomposition of the peroxide initiators in the system.

**Resin**—Certain liquid prepolymer products, such as unsaturated polyester and epoxy prepolymers, which are subsequently cross-linked to form a hardened polymer.

**SARA**—Superfund Authorization and Reorganization Act.

**Substructure**—Material surface on which a PC overlay is placed.

**Surface failure**—In PC, the loss of top surface aggregates from the polymer binder.

**Surface seeding**—Application of aggregate to the freshly-applied PC to provide an architectural finish.

**Surface tyning**—Scoring or grooving of the PC to provide for an architectural finish.

**Thermal compatibility**—Ability of a PC to withstand thermally-induced stresses and strains without debonding from a substrate.

**Thermoplastics**—Materials that will soften and reform repeatedly when heated and harden when cooled. Typical thermoplastics are styrene polymers and copolymers, acrylics (uncross-linked), polycarbonates, nylons, and the various fluorocarbons.

**Thermosets**—Materials that will undergo or have undergone a chemical reaction by the action of heat, catalyst, ultraviolet light, etc., leading to a relatively infusible state.

Typical materials are aminos (melamine and urea), most polyesters, alkyls, epoxies, and phenolics. Thermosets are not reformable upon heating.

**Ultraviolet (UV) light**—Invisible light having a wave length between 290 and 400 nm.

**Unsaturated polyester (UP)**—See “Polyester.”

**Wear**—Deterioration of a surface due to traffic, use, and/or the environment.

**Working life**—Time period between the mixing of a PC and the point at which its viscosity has become too high to be workable, or too high to bond properly to the substrate.

## CHAPTER 6—REFERENCES

### 6.1—Recommended references

The documents of the various standards-producing organizations referred to in this document are listed below with their serial designation.

#### American Association of State Highway and Transportation Officials

Standard Specifications for Highway Bridges

#### American Concrete Institute

- 318 Building Code Requirements for Reinforced Concrete
- 548.1R Guide for the Use of Polymers in Concrete
- 548.2R Guide for Mixing and Placing Sulfur Concrete in Construction
- 548.3R State-of-the-Art Report on Polymer Modified Concrete
- ICPIC-1 Proceedings of the 7th International Congress on Polymers in Concrete
- SBM-1 ICPIC Working Papers
- SP-40 Polymers in Concrete
- SP-58 Polymers in Concrete
- SP-69 Applications of Polymer Concrete
- SP-89 Polymer Concrete: Uses, Materials and Properties
- SP-116 Polymers in Concrete: Advances and Applications

#### American National Standards Institute

- A58.1 Minimum Design Loads in Buildings and Other Structures

#### American Society for Testing and Materials

- C 33 Specifications for Concrete Aggregates
- C 78 Test Method for Flexural Strength of Concrete (Using Simple Beam with Third-Point Loading)
- C 293 Test Method for Flexural Strength of Concrete
- C 496 Test Method for Splitting Tensile Strength of Cylindrical Concrete Specimens
- C 580 Test Method for Flexural Strength and Modulus of Elasticity of Chemical Resistant Mortars, Grouts and Monolithic Surfacing
- C 857 Minimum Structural Design Loading for Underground Precast Concrete Utility Structures
- D 648 Test Method for Deflection Temperature of Plastics Under Flexural Loads

#### International Conference of Building Officials (ICBO)

The Uniform Building Code (UBC)

#### International Congresses on Polymers in Concrete

*Polymers in Concrete*, Proceedings of the First International Congress on Polymer Concretes, The Concrete Society, The Construction Press Ltd., England, 1976.

*Second International Congress on Polymers in Concrete*, Proceedings of the Second International Congress on Polymers in Concrete, University of Texas, Austin, 1978.

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*Polymers in Concrete*, Proceedings of the Seventh International Congress on Polymers in Concrete, BETECOM, Moscow, Russia, 1992.

#### Society of the Plastics Industry, Inc.

Polymer Concrete Test Methods

#### Southern Building Code Congress International, Inc.

Standard Building Code (SBC)

### 6.2—Reference organizations

American Association of State Highway and Transportation Officials (AASHTO)  
444 N. Capitol St. NW, Suite 225  
Washington, DC 20001

American Concrete Institute  
P.O. Box 9094  
Farmington Hills, Mich. 48333-9094

American National Standards Institute (ANSI)

ASTM  
100 Barr Harbor Dr.  
West Conshohocken, Pa. 19428-2959

American Society of Civil Engineers (ASCE)

International Conference of Building Officials  
5360 S. Workman Mill Rd.  
Whittier, Calif. 90601

Southern Building Code Congress International, Inc.  
900 Montclair Rd.  
Birmingham, Ala. 35213-1206



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**APPENDIX 1—EXAMPLE PC FORMULATIONS**

The following formulations are given as presented in the reference. The reader should refer to the appropriate reference for complete details before using these formulas.

**MMA-TMPTMA PC FORMULATION<sup>69</sup>**

Component	Composition	Weight, percent
Aggregate	3/4-in. to flour sand	92
Monomer	MMA - 90 percent TMPTMA - 5 percent	8

Initiator	PMMA - 5 percent Benzoyl peroxide - 70 percent (percent of monomer)	3
Promoter	DMA (percent of monomer)	1

**VE PC FORMULATION<sup>70</sup>**

Component	Composition	Weight, percent
Aggregate	3/4-in. to flour sand	93
Resin	Vinyl ester - 90 percent Styrene - 10 percent	7
Initiator	MEK peroxide - 70 percent	1.5
Promoter	Cobalt naphenate	0.75
Additives	Silane (percent of resin)	0.5

**POLYESTER-STYRENE PC FORMULATION**

Component	Composition	Weight, percent
Aggregate	1/2-in. to flour sand	88
Resin	Polyester - 55 percent Styrene - 45 percent	12
Initiator	MEK peroxide - 70 percent	1.5
Promoter	Cobalt naphenate	0.75
Additives	Silane (percent of resin)	0.5

**EPOXY PC FORMULATION**

Component	Composition	Weight, percent
Aggregate	1/4 in. to 200 mesh	80
Resin	Resin - 50 percent Hardener - 50 percent	20

**APPENDIX 2—TYPICAL PC PROPERTIES**

Binder	MMA-TMPTMA	Epoxy	Furan	Polyester-Styrene	Vinyl Ester
Binder, percent by weight	6 12	20	—	8 18	7
Flexural strength, psi (GPa)	1200 (8) 9000 (62)	2500 (17) 4900 (34)	3000 (21) 3500 (24)	4000 (28) 8600 (59)	2500 (17) 22,000 (149)
Flexural MOE, psi (GPa)	4.5 x 10 <sup>6</sup> (31) 5.7 x 10 <sup>6</sup> (40)	4.1 x 10 <sup>6</sup> (28)	—	—	—
Compressive strength, psi (MPa)	10,000 (70) 20,000 (140)	8500 (59) 17,400 (120)	9000 (62) 15,000 (102)	10,000 (70) 20,000 (140)	9000 (62) 16,000 (110)
Compressive MOE, psi (GPa)	1.0 x 10 <sup>6</sup> (7) 5.3 x 10 <sup>6</sup> (37)	1.2 x 10 <sup>6</sup> (8) 5.8 x 10 <sup>6</sup> (40)	4.0 x 10 <sup>6</sup> (28)	—	4.8 x 10 <sup>6</sup> (33)
Tensile strength, psi (MPa)	1200 (8) 2100 (14)	1300 (9) 3500 (24)	1400 (9.6) 2000 (14)	1600 (11) 10,000 (70)	1400 (10) 13,000 (90)
Shear strength, psi (MPa)	3700 (26)	—	—	275 (2)	—
Density, lb/in. <sup>3</sup> (kg/in. <sup>3</sup> )	149 (2388)	136 (2180) 162 (2596)	—	—	150 (2404)
Poisson's ratio	0.23 0.35	—	—	—	0.22
Linear shrinkage, percent	1.5 5.0	0.02 0.20	0.1 0.2	0.3 3	—
Water absorption, percent	0.6	—	—	—	0.1
Freeze-thaw resistance	1670 cycles, 0 percent weight loss	—	—	—	2024 cycles, 0 percent weight loss
Coefficient of thermal expansion, 10 <sup>-6</sup> in./in. F	5.3 (2.9) 26 (14)	3.1 (1.7) 14.2 (7.9)	11 (6.1) 12 (6.7)	1.2 (0.67) 7.2 (4.0)	12 (6.7) 15 (8.3)
Working time, min	20 40	30 60	—	15 40	—
Cure time, hrs at 65-90 F	1 4	1 48	0.25 12	2 96	2168

Note: The table contains a normal range of values reported in the literature. A particular formulation will not normally give results with all high values or all low values. The reader should refer to the references to determine the properties obtained from particular formulations.