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Polymer Concrete: Guidelines for Structural Applications

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Polymer Concrete: Guidelines for Structural Applications

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Polymer Concrete: Guidelines for Structural Applications

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Aly Said

Polymer concrete (PC) can be used in the construction of structural elements with applications, including wall panels withstanding wind and seismic loads, underground vaults resisting lateral earth pressure, vault and utility box covers resisting vehicle loads, and railroad ties resisting static and dynamic rail loads. PC structural elements are used to resist bending moments and axial and shear loads. Creep, fatigue, and service temperature are important aspects for PC structural elements. These guidelines help the defining and understanding of mechanical properties and structural behavior of PC. Industrial standards and design guidelines governing design with PC have been developed and used by the PC industry for the last five decades. These guidelines highlight some of those standards.

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Keywords: beam; creep; equipment foundation; fatigue; fire resistance; fracture; manholes; polymer; polymer concrete; reinforced polymer concrete; utility structures; walls.

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CHAPTER 1—INTRODUCTION

Polymer concrete (PC) has been used in structural applications where strength, stiffness, durability, and ease in molding provide an advantage over other materials. Many types of reinforcement can be used with PC. This guide presents the structural uses of PC.

Polymer concrete is a mixture of aggregates and resins or monomers without portland cement that hardens by polymerization after it is placed. 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. Beginning in the 1970s, other structural products began to appear in 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. By the mid-1970s, PC was used as a repair material for portland-cement concrete structures, mainly on highways and bridges. 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 for PC were developed, and resins tailor-made for PC production became available. This development continues, and important material improvements are often achieved by manufacturers.

Research into the behavior of PC structural elements has been conducted at numerous research labs. Structural research has been conducted on such uses as steel-reinforced beams and panels, ballistic panels (barriers to armed assault on embassies, for instance), electric transmission

poles, structural sandwich elements, building blocks, utility trenches, utility covers, and insulation panels (Fowler 1988).

CHAPTER 2—NOTATION AND DEFINITIONS

2.1—Notation

A_1	=	amplitude of first cycle
A_n	=	amplitude of the n -th cycle
E	=	dynamic modulus, psi (MPa)
f_1	=	frequency of the first mode, Hz
I	=	section moment of inertia, in. ⁴ (mm ⁴)
l	=	specimen length, in. (mm)
n	=	number of amplitude cycles
T_g	=	glass-transition temperature, °F (°C)
W	=	weight of the specimen, lbf (lbf/N)
β	=	I^3/I , in. ⁻¹ (m ⁻¹)
ζ	=	specific damping factor

2.2—Definitions

A/B components—individual parts of a polymer binder system; in epoxy PC, the components typically consist of resin (A) and curing agent/hardener (B); in free radical PC, the components typically consist of resin (A) and initiator (B).

accelerator—chemical used to increase the rate of cure in a free radical system by reacting with the initiator.

catalyst—substance that markedly speeds up the cure of a binder when added in minor quantity.

cross-linking—joining of preformed linear polymer chains to each other to form three-dimensional networks.

cross-linking agent—chemical used to increase the cross-link density of the polymer network.

cure time—the interval after mixing in which a PC system gains adequate strength to support loads, such as foot traffic, vehicular traffic, or both.

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.

fiberglass—a composite material consisting of glass fibers in resin.

flammable liquid—any liquid having a flash point below 38°C (100°F).

flash point—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—additive that gives a rigid plastic flexibility.

gel time—time interval after mixing that a liquid material exhibits a significant viscosity increase.

heat deflection temperature—temperature at which a polymer or plastic sample deforms under a specified load.

inhibitor—substance that slows or stops a chemical reaction.

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

methyl methacrylate—low-viscosity methacrylate monomer that is characterized by high volatility.

organic peroxides—sources of free radicals used in polymerization and cross-linking.

polyester—one of a group of resins, mainly produced by reaction of unsaturated dibasic acids with dihydroxy alcohols; commonly dissolved in a vinyl group monomer such as styrene.

premix—a polymer concrete formulation prepared and packaged in advance of use with compatible ingredients preblended together in the correct ratios for the final mixture. For example, aggregates and the catalyst are frequently premixed as one part and the monomers, additives, and promoters as another part of premixed methacrylate systems.

promoters—reducing agent compounds added to the monomer system to cause the decomposition of the peroxide initiators in the system (often called accelerators).

specific heat—heat required to raise the temperature of the unit mass of a given substance by a given amount (usually 1 degree).

surface failure—loss of top surface aggregates from the polymer binder in polymer concrete.

surface seeding—application of aggregate to the freshly applied polymer concrete overlay.

thermal compatibility—ability of a PC to withstand thermally induced stresses and strains without debonding from a substrate.

thermoplastics—material with a linear polymeric structure that can be reshaped repeatedly when heated and will harden when cooled; for example, styrene polymers and copolymers, acrylics (uncross-linked), polycarbonates, nylons, polyethylene, polypropylene, and various polyfluorocarbons.

thermosets—a polymer that will solidify when first cured and cannot be remelted or remolded without destroying its original characteristics; for example, epoxies, unsaturated polyesters, melamines, phenolics and ureas.

tined surface—a surface that is scored or grooved to provide an architectural finish or to facilitate drainage of water.

unsaturated polyester—a prepolymer resin system reacted with a styrene monomer to form thermoset plastic.

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 3—MATERIALS AND PROPERTIES

3.1—Materials for structural polymer concrete

Polymer concrete (PC), as described in this guide, includes polymer mortars, polymer grouts, and polymer concretes. Example PC formulations are given in Appendix A. Polymer mortars include materials with aggregate sizes smaller than 1/4 in. (6 mm). Polymer grout includes materials with no aggregate. Differences between mortars and grouts depend on the intended use and affect the fabricator's formulation of the material.

3.1.1 Polymers—The monomers, polymers, or a mixture of monomers and polymers in liquid form are mixed with an aggregate system. Polymerization promoters and initiators are also included in the mixture in precise proportion to cross-link or complete the polymerization of the monomers. Several properties of the monomers or polymers are typically used to define the characteristics of the uncured PC. PC is usually classified using 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 control binder selection.

Thermoset polymers are typically used to form the binder system of structural PC. Unsaturated polyesters are the most popular thermoset used to produce PC. Orthophthalate unsaturated polyester resins are used as binders combined with methyl ethyl ketone peroxide (MEKP) as initiator (Soh et al. 1999; San José and Ramirez Ortiz 1999; Ribeiro et al. 2003; Jo et al. 2008a). Moreover, unsaturated isophthalic polyester resin was observed to produce a hard, rigid polymer that can provide good mechanical properties (Orak 2000). PC binder systems were produced from other thermoset polymers, including low-viscosity vinyl ester resin (Czarnecki and Chmielewska 1999), polystyrene resins (Choi and Ohama 2004; Rai and Singh 2004), and polyurethane (Tokushige et al. 2005). Orthophthalate unsaturated polyester can also be mixed with polyurethane, forming interpenetrating polymer networks to produce lightweight PC (Bignozzi et al. 2001).

Epoxies have been extensively used to form the binder systems to produce PC (Ribeiro et al. 2003; Reis and Ferreira 2004; Barbuta et al. 2010). Epoxies consist of two parts: epoxy resin and epoxy hardener. While the resin contains epoxy reactive groups at the two ends of the polymer chain, the hardener contains free amine hydrogens. A chemical reaction occurs between the two groups to tie polymer chains together and form the solid polymer mass. This chemical reaction is called cross-linking.

The viscosity of the individual or mixed components can be specified to control the coating of the aggregates. Binder resins with low viscosity are more suitable for mixtures with polymer contents lower than 20 percent. Specific chemical resistance and the glass-transition temperature (T_g) are important characteristics for binder selection. A gel time range can be specified to ensure that there is adequate time to place the fresh PC and that the curing will be completed within the time specified for form removal. Additional properties of the uncured binders, such as specific gravity, shelf life, component content, and flash point also may need to be specified (Sprinkel 1991).

Mixing procedures vary with the binder system selected. The combination of monomers, polymers, initiators, promoters, and chemical additives constitutes the binder system. Some binder systems can be formulated as two components, where one component contains the monomers, polymers, promoters, and additives, and the other component is 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, and premix the initiators with the remaining portion. For a specific

binder system, the manufacturer or a qualified polymer chemist should be consulted to select the most appropriate method to mix the required components. Promoters should not be mixed directly with initiators because the mixture can react explosively. Section 3.6 provides guidelines for safety requirements.

3.1.2 Aggregates—Aggregates such as silica sand, granite, river gravel, basalt, fly ash, calcium carbonate, and silica fume are generally acceptable for PC resin systems. Silica sand is generally used as inorganic fine aggregate and calcium carbonate as fine filler material (Soh et al. 1999; Bignozzi et al. 2001; Choi and Ohama 2004). Fly ash, calcium carbonate, and silica fume are also used as fine fillers in PC. They are used to modify mixture rheology, improve workability, and improve placing characteristics of the fresh PC. Individual fly ashes should be tested in trial batches before use because some can adversely affect the polymerization reaction. Most aggregates meeting ASTM C33/C33M will perform adequately in PC. In addition, aggregates should be selected for chemical resistance if that is a factor in the application (Kaeding 1991a). 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 3/4 in. (20 mm) has been used for some overlays and is also suitable for large precast sections. The rounded smooth surface of the coarse aggregate provides a more workable mixture, and less resin is required.

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. Recycled waste materials and available natural composites could be used as fillers, aggregates, or both, to preserve the environment and reduce the cost. Recycled waste materials that have been used in PC include chipped and crumbed rubber tire particles (Reda Taha et al. 2005), recycled concrete aggregates (Jo et al. 2008b), silica fume (Barbuta et al. 2010), and fly ash (Barbuta et al. 2010), whereas natural composites include ophitic aggregate (San José and Ramirez Ortiz 1999) and wood stumps and roots (Tokushige et al. 2005). Maksimov et al. (2003) reported the use of ground limestone (flour), quartz sand, and crushed granite as mineral fillers in a polyester PC. Moreover, cork granulates partially replaced sand to produce lightweight polymer mortar with improved compressive ductility (Novoa et al. 2004). Waste glass is a major portion of all municipal waste, accounting for approximately 10.5 percent, or 13.5 million tons (12.2 million metric tons), in 1975. This glass fraction of municipal solid waste is an inert aggregate that can be used in PC composites (Fontana 1988). Examples of glass-polymer composites include sanitary pipe, culvert pipe, septic tanks, cesspools, and building blocks or brick (Fowler 1991).

3.1.3 Reinforcement—Reinforcement used in PC includes bars and rods made from steel fiber-reinforced polymers (SFRPs) or glass fiber-reinforced polymers (GFRPs); fabrics made from steel wire, fiberglass, or polymers; and fibers made from steel, glass, carbon, polymers, and crimped wire cloth (Fowler 1991; Bhutta et al. 2011). The addition of various types of fibers can increase the splitting tensile

strength and ductility of PC. Increases in splitting tensile strength of 9 percent for 1 in. (25 mm) long alkali-resistant (AR) glass fibers (2 percent by mass) and from 10 to 50 percent for various steel fibers (2 to 7 percent by mass) have been reported (Fowler et al. 1981). The addition of glass fibers increases PC flexural strength and fracture properties as well as toughness and failure strain (strain at peak stress), but might decrease the compressive modulus (Mebarkia and Vipulanandan 1992). In an unsaturated polyester PC, glass fibers were added at a rate of 6 percent and the flexural strength increased to exceed 6000 psi (41 MPa) (Vipulanandan and Mebarkia 1997). Bignozzi et al. (2000) reported the use of silane-treated waste fibers to improve the mechanical strength of PC. Similar results were reported by Reis (2009a) using recycled textile chopped fibers.

3.1.4 Additives—Additives such as air-release agents, wetting agents, flexibilizers, shrinkage reducers, ultraviolet (UV) inhibitors, fire-resisting agents, and bond enhancers are added to PC 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 entrapped 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 deformability. Shrinkage reducers compensate for polymerization shrinkage. The natural resistance of PC to any structurally significant UV degradation is due to the opacity of the aggregates and filler system and is evidenced by more than 25 years of field exposure of some building panels and utility structures. UV inhibitors, however, are often required to protect exterior surface finishes and color for PC, except for acrylic and methacrylic monomer concretes, which, by their chemical nature, are more resistant to UV exposure and weathering effects. Fire-resistant 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, have been shown to increase strength properties by 10 percent, and decrease effects of water degradation for some systems (Kaeding 1991a). Some research has shown that performance of unsaturated polyester PC is improved by pretreating aggregates with silane (γ -methacryloxypropyltrimethoxysilane). Researchers at the University of Houston found the strength to increase up to 66 percent in compression (15,000 psi [103 MPa]) and as much as 35 percent in flexure over the same PC without silane pretreatment (Mebarkia and Vipulanandan 1994). Silane coupling agents were added to vinyl ester mortars and improved the bond and mechanical strengths (Czarnecki and Chmielewska 1999; Chmielewska et al. 2006).

In many cases, polymers other than the original resin were used as additives to PC. Expanded polystyrene (EPS)-based resin dissolved in styrene monomer (SM) was shown to be used as a low-profile additive to reduce curing shrinkage (Soh et al. 1999). Recycled polyethylene terephthalate from plastic bottles (Rebeiz and Fowler 1996a,b), rubbers (Bignozzi et al. 2000, 2002), and electrical cable wastes (Bignozzi et al. 2000,

2002) were added to polymer mortar to modify its properties. Fly ash was also added to sulfur and sand to manufacture sulfur polymer concrete with improved mechanical and chemical properties (Mohamed and Gamal 2009).

Nanoparticles particles such as nanoclay, carbon nanotubes, and carbon nanofibers were recently used to improve the mechanical properties of polymer concrete. Nanoparticles typically have the size of 1 to 1000 nm. Jo et al. (2008a) reported enhanced mechanical and thermal performance of unsaturated polyester concrete mixed with montmorillonite. However, modified nanoclay was reported to reduce the tensile and flexural strengths of PC (Shokrieh et al. 2012). Carbon nanotubes were also used to improve the mechanical properties of different types of PC, including latex-modified concrete (Soliman et al. 2012) and epoxy-based PC (Daghash et al. 2016).

3.2—Polymer concrete types

Because the polymer forms the continuous phase, behavior of the composite is significantly affected by the choice of the type of polymers (Manson 1981). For that reason, PC can be categorized by the binder type.

3.2.1 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 curing rates and strengths can vary dramatically. Epoxies can be formulated to provide a wide range of gel times and cure rates. Some systems can be designed for gel times as short as 3 minutes whereas others may be as long as 10 hours. They are resistant to many chemicals, and systems are formulated to cure under many moisture and temperature conditions. They have low curing shrinkage, good adhesion properties, high tensile strengths, and excellent abrasion resistance. Some epoxy resins tend to have high viscosity and putty-like mortar consistency that can be sticky to finish, although others with lower viscosities make mortars and concretes with good workability.

The two-component systems for PC are formulated to be mixed at a specific resin-to-hardener ratio either by weight or by volume; the most commonly provided ratios are either one or two parts of resin to one part hardener by volume. Varying the specified ratio of the two components can significantly affect mechanical and chemical properties and gel times. Batching should be done in complete units or by using accurate volumetric or mass measures. The individual components should be thoroughly mixed before combining them with the aggregate or filler system. Equipment is available for automatic metering of resins to ensure that proper mixture ratios are obtained.

Epoxy polymer PCs can be user-prepared with a wide variety of epoxy formulations with resulting physical properties, gel times, and cure rates to meet the requirements of specific applications. The selection of the material for a particular application should be based on a specific manu-

facturer's product information and field-performance data. Epoxy resins are available for use in a range of application temperatures. The ratio of the two components should never be adjusted to change the curing time. Epoxy resins are considered allergenic; therefore, safe handling practices should be incorporated (Kraus 1991). Section 3.6 provides additional safety information.

Koblischek (1991) reported properties for an epoxy polymer PC being used in the manufacture of machine tool bases with a compressive strength of 17,400 psi (120 MPa), tensile strength of 1500 psi (10 MPa), and flexural strength of 3200 psi (22 MPa). He also reported a compressive modulus of elasticity of 5.8×10^6 psi (40 GPa) and a tensile modulus of 4.1×10^6 psi (28 GPa) for the same epoxy polymer PC. The behavior of epoxy polymer PC under various curing conditions, temperatures, and strain rates has been studied and discussed by Vipulanandan and Paul (1990).

3.2.2 Methacrylate polymer concrete—Methyl methacrylate (MMA) and high-molecular-weight methacrylate (HMWM) are the primary monomers used in methacrylate PC. Methacrylate has been used in the PC industry for many years. It has provided a satisfactory level of performance and long-term durability. HMWM was developed to minimize the volatility of the methacrylate monomer, thus reducing odor, flammability hazards, and monomer loss from the PC surface through evaporation. Due to its low viscosity, methacrylate monomer has excellent wetting properties and excellent bond strengths. MMA monomer is a clear, low-viscosity, highly volatile liquid with a pungent odor. Typically, MMA systems are formulated to provide between 15 and 60 minutes of working time, then cure very rapidly. MMA monomers can be formulated to cure over a wide range of temperatures and are suitable for use in cold weather. Methacrylate PCs also have excellent flow characteristics and are well suited for placement around closely spaced reinforcement or formwork for narrow cross sections. Bhutta et al. (2011) reported the possible production of PC panels using MMA solution of waste expanded polystyrene (EPS) with good mechanical properties and improved ductility.

Methacrylate systems require the addition of an initiator and promoter to the monomer to begin the polymerization reaction. Most methacrylate PC systems are packaged with promoters already blended into the monomer. The initiator is typically packaged separately but included in the unit price and shipment, and it is normally provided in the proper proportions for the furnished quantity of monomer or PC. A variety of initiators and promoters are available to provide a range of curing times and physical properties. Unlike epoxies, methacrylate systems will tolerate wide variations in the ratio of initiator to promoter to the monomer. A cross-linking monomer is typically blended with methacrylate to provide a tougher and more temperature-stable polymer (Kraus 1991) for most methacrylate systems.

Koblischek (1991) reported properties for a particular methacrylate PC being used in the manufacture of machine tool bases. The properties reported included a compressive strength of 17,400 psi (120 MPa), a flexural strength of 3200 psi (22 MPa), a tensile strength of 1500 psi (10 MPa), and

a Poisson's ratio of 0.35. [Koblischek \(1991\)](#) also reported several values of the modulus of elasticity, including 3.5×10^6 psi (24 GPa) in tension and 4.5×10^6 to 5.7×10^6 psi (31 to 40 GPa) in bending.

3.2.3 Unsaturated polyester polymer concrete—Most commercially produced precast PC products made in the United States and Europe are made with polyester resins. The resins are typically extended with styrene monomer and supplied prepromoted with cobalt salts. Before mixing with the aggregate system, an initiator is added that reacts with the promoter and causes a cross-linking reaction between the styrene monomer and the unsaturated polyester. Typical initiators are methyl ethyl ketone peroxide (MEKP) or ketone peroxide blends. The resulting thermoset polymer is a strong and durable binder. The type of polyester selected is based 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 polyester or vinyl ester can be selected.

3.2.4 Furan polymer concrete—Furfuryl acetone (FA)-based PCs have been used extensively in the former Soviet Union and South Africa. The FA monomer is manufactured from grain by-products. FAs are typically cured by the addition of an acid catalyst, and water is a by-product. Working time and curing rate are controlled by the choice of acid and through the addition of buffers for the acid. Cured FA 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 FA PC. Because of the need for an acid catalyst, FA resins should not be used with alkaline aggregates, which when wetted by water, produce a pH higher than 7.

3.2.5 Lightweight polymer concretes—[Aninabhai et al. \(1987\)](#) 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 concrete 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 its glass transition temperature (T_g). [Novoa et al. \(2004\)](#) reported the production and mechanical properties of lightweight cork-modified-polymer mortar with cork representing up to 45 percent of the total aggregate volume, as shown in Fig. 3.2.5.

3.3—Mechanical properties

The mechanical properties of PC, such as compressive strength, are similar or higher than those of portland-cement concrete, but the flexural strength, tensile strength, and shear strength are typically higher than for portland-cement concrete. The compressive and flexural moduli are gener-

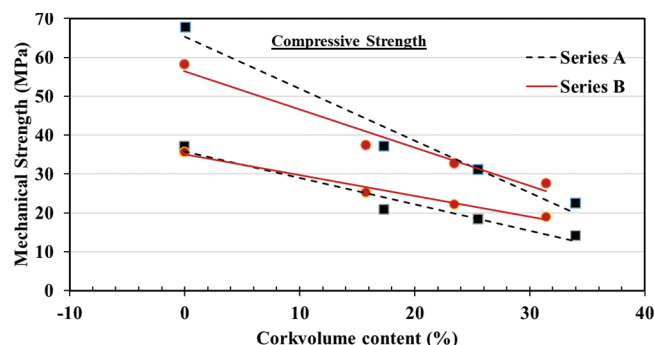


Fig. 3.2.5—PC produced using cork-modified-polymer mortar showing the effect of cork volume content on the compressive and flexural strength of PC ([Novoa et al. 2004](#)).

ally lower, although for some PCs, particularly those made of epoxy, are sometimes higher. When the mixing proportions, materials, and procedures are held constant, the resulting PC has very consistent properties. The variation in properties of test specimens taken from several batches is commonly less than 2 percent ([Cowan et al. 1975](#)). Different polymers used in PC production will impart different properties to the finished material. For instance, [Vipulanandan and Paul \(1990\)](#) published results of extensive research into the effects of curing conditions, temperatures, aggregate sizes, and strain rates on the mechanical properties of epoxy polymer PC and unsaturated polyester PC. It was 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](#) relationships for calculating the compressive modulus and the tensile strength using the compressive strength do not apply to PC. A constitutive model capable of modeling both strain softening and strain hardening has been developed for the stress-strain relationships of epoxy polymer PC and unsaturated polyester PC ([Vipulanandan and Paul 1990](#)).

3.3.1 Compressive strength—PC has 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 typically ranges from 5 to 10. As load duration is increased, the tensile strength decreases due to the viscoelastic nature of the binder and creep effects. The effects of load duration on compressive strength are less pronounced ([Davydov and Ivanov 1972](#)). Figure 3.3.1 shows a typical stress-strain curve for unsaturated polyester PCs and methyl methacrylate (MMA) PCs in compression and flexure loading ([Rebeiz and Fowler 1995](#)).

PCs have demonstrated compressive strengths of 9000 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). Compressive strength measurements were made using ASTM C579. Isophthalic polyester PC with 15 to 20 percent of fly ash demonstrated a compressive strength of approximately 14,000 psi (95 MPa) ([Rebeiz et al. 2004](#); [Gorminski et al. 2007](#)). Orthophthalic polyester PC reinforced with nonmetallic aggregate and reinforced polymer bars developed a compressive strength of

14,800 psi (102 MPa) (San José et al. 2008). Moreover, the compressive strength and strain of a polymer concrete made from waste tire rubber were 13,600 psi (93.4 MPa) and 6.7 percent, respectively (Chung and Hong 2009).

In addition, compressive strength of PC is affected by curing, and filler and aggregate used in the mixture. Barbuta et al. (2010) reported epoxy PCs with compressive strengths ranging from 6305 to 10,127 psi (43.47 to 69.82 MPa) using different dosages of fly ash and silica fume as fillers. Polyester PC with marble of different particle size added as aggregate and submitted to gamma radiation doses reached a compressive strength of 13,000 psi (89.1 MPa) (Martínez-Barrera and Brostow 2010). Furthermore, epoxy incorporating micro-marbles was reported to obtain a compressive strength of 10,150 psi (70 MPa) under different conditions of curing (Haidar et al. 2011).

Different mortars made of polymers were also investigated under axial compression. Soh et al. (1999) reported unsaturated polyester resin mortar added to polystyrene resin with compressive strength of approximately 12,000 psi (85 MPa). Moreover, compressive strengths of 18,500 psi (128 MPa), 7550 psi (52 MPa), and 4100 psi (28.5 MPa) were obtained from vinyl ester mortar with silane coupling agents (Chmielewska et al. 2006), epoxy polymer mortar (Reis 2009b), and unsaturated polyester mortars manufactured from polyethylene terephthalate bottles (Mahdi et al. 2013), respectively.

3.3.2 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 can 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.

Static flexural properties of PC have been determined using the same test methods used for portland-cement concrete (ASTM C293/C293M or C78/C78M), but the method currently specified for chemical-resistant mortars, grouts, monolithic surfacings, and polymer concretes (ASTM C580) is more suitable for PC.

PC made with flexible polymers exhibits more ductile behavior than those made with rigid polymers. The stiffness for PC beams is lower than for concrete control beams. The strain distribution along the depth in the compression zone of flexural beams is linear. Hsu (1984) showed that a conservative value of 0.008 in./in. (mm/mm) can be assumed for the maximum compressive strain at the extreme fiber.

PC made of polyester resin incorporating 15 to 20 percent fly ash developed a flexural strength of approximately 3050 psi (21 MPa) (Rebeiz et al. 2004; Gorninski et al. 2007). Beams manufactured of orthophthalic polyester resin reinforced with nonmetallic glass-reinforced polymer bars demonstrated a flexural strength of 3771 psi (26 MPa), modulus of elasticity of 5,500,000 psi (37.9 GPa), and

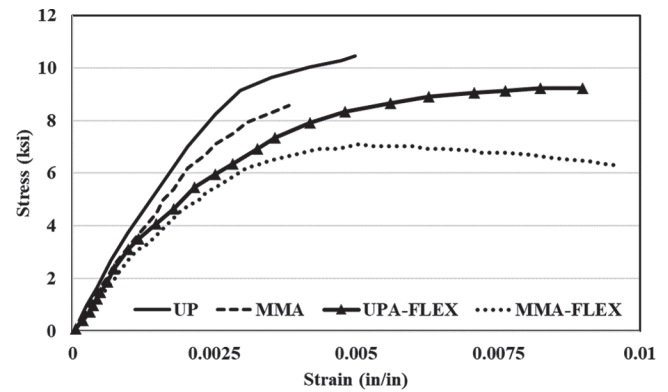


Fig. 3.3.1—Typical stress-strain curves for unsaturated polyester PCs and MMA PCs in compression (Rebeiz et al. 1994).

maximum strain of 0.98 percent (San José et al. 2008). Furthermore, Rebeiz and Fowler (1996a) reported flexural strength of 13,977 psi (96 MPa) and failure strain of 0.87 percent for steel-reinforced polymer concrete beams made of unsaturated polyester resins based on recycled polyethylene terephthalate. Reis and Ferreira (2003) investigated the fracture behavior of epoxy polymer concrete reinforced with chopped glass fibers and reported flexural modulus of elasticity of 1,400,000 psi (9.5 GPa).

Similar to the compressive strength and other mechanical properties, the filler and aggregate used would affect the flexural strength of the mixture. Flexural strengths of 3050 psi (21 MPa), 2180 psi (15 MPa), and 4060 psi (28 MPa) were obtained for PC mixtures using calcium carbonate and recycled concrete aggregate (Jo et al. 2008b), fly ash and silica fume (Barbuta et al. 2010), and a graded mixture of coarse and fine sand (Haidar et al. 2011), respectively.

Flexural strength for different polymer mortars was investigated. Soh et al. (1999) obtained flexural strengths of approximately 3770 psi (26.5 MPa) using unsaturated polyester mortar and adding polystyrene resin. Silane coupling agents mixed with polyester (Bignozzi et al. 2000) and vinyl ester (Chmielewska et al. 2006) mortars demonstrated flexural strengths of 4915 psi (33.9 MPa) and 5932 psi (40.9 MPa), respectively. Moreover, epoxy mortar showed a flexural strength of 6184 psi (42.64 MPa) (Ribeiro et al. 2004).

3.3.3 Tensile strength—Direct tensile testing of PC is rare because 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 dog-bone specimen can be used, but care should 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/C496M). Tensile strengths (from splitting tension tests) of 1000 to 2500 psi or (10 to 17 MPa) are typical. Tavares et al. (2001) and Guedes et al. (2004) suggested reinforcing PC under tension with fiber-reinforced polymer (FRP) bars.

3.3.4 Modulus of elasticity—The deformation response of PC depends on the modulus of elasticity and maximum elongation of the polymer binder, with plastic modulus up to 5000 ksi (35 GPa) for rigid polymers. 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 modulus is increasingly influenced by the aggregate and reinforcements. Elastic moduli range from 500 ksi (3.5 GPa) for a flexible resin-rich system up to 5000 ksi (35 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 flexural (Mendis 1985).

3.3.5 Poisson's ratio—Very few measurements of Poisson's ratio for PC have been reported. A value of 0.35 was given for a methacrylate PC used for machine tools (Koblischek 1991), and Mantrala and Vipulanandan (1995) reported work with a unsaturated polyester PC where the average dynamic Poisson's ratio was 0.22 compared to the static value of 0.20.

3.3.6 Shear strength—Most shear failures in PC structural elements are actually diagonal tension failures or rarely 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 (Fowler 1991). Rebeiz et al. (2004) achieved shear strength of 1160 psi (8 MPa) for polyester PC after replacing 15 percent of sand by fly ash. Steel-reinforced PC beams using polyester resin and based on recycled polyethylene terephthalate demonstrated shear strengths ranging between 0.53 and 19 MPa (77 and 2754 psi) (Rebeiz and Fowler 1996b; Mahdi et al. 2013).

3.3.7 Fatigue strength—Tests (Hsu and Fowler 1985) have shown that fatigue loading increases both flexural strength and the modulus of elasticity. The maximum applied stress is the most important factor influencing the fatigue life of PC beams. As the maximum applied stress increases, fatigue life decreases. The stress range between maximum and minimum applied stress also has a significant effect; the wider the stress range, the shorter the fatigue life. PC beams were superior to portland-cement concrete beams in fatigue life. Wheat et al. (1993) investigated the fatigue behavior of beams made of portland-cement concrete overlaid by epoxy PC. The composed beams survived 2 million load cycles without significant loss of stiffness or delamination. Beams were statically loaded to failure after load cycles, and the obtained stiffness was found to be close to the initial stiffness. Therefore, it was concluded that fatigue was not the primary cause of failure. Furthermore, Tavares et al. (2001) tested PC prisms reinforced with glass fiber-reinforced polymer (GFRP) rods in three-point bending fatigue tests. The PC prisms, which were made of epoxy resin, lasted for 1 million cycles without rupture. The observed fatigue strength was attributed to both PC and the GFRP rods. Experiments by Garner et al. (2015) showed the significant improvement of PC fatigue life incorporating multi-walled carbon nanotubess. One order of magnitude improvements in fatigue life in excess of 1 million cycle was reported by incorporating

multi-walled carbon nanotubess in the polymer matrix prior to PC fabrication.

3.3.8 Creep—PC exhibits the general creep behavior of the polymer binder. Several studies of creep in PC (Dharmarajan and Armeniades 1987; Hsu and Fowler 1985) have shown that sustained loads at stress levels substantially below short-term ultimate strength will cause some PCs to creep to failure. As the level of maximum applied stress increases, creep strain also increases, as has been shown in portland-cement concrete. At some level of stress, however, creep proceeds rapidly to failure. The closer the maximum applied stress is to the short-term ultimate strength, the faster that creep to failure occurs. By connecting the inflection or failure points on a family of creep curves, a creep rupture envelope may be developed for that particular PC, but the envelope will vary with different polymers and other mixture and load variables. The creep rupture envelope permits the maximum allowable design stresses for the PC at different anticipated load durations by using an appropriate factor of safety. For most PCs, the service stress level should be 30 percent or less than the short-term ultimate strength. All stresses used for design should include appropriate factors of safety to account for this behavior of PC under long-term loading.

PC has a significantly higher (two to three times) creep compliance than portland-cement concrete. The specific creep for both is approximately the same. Figure 3.3.8a shows the specific creep strain for a specific unsaturated polyester PC, for example, and Fig. 3.3.8b shows the effect of ambient temperature on specific creep for the same PC (Okada et al. 1976). The static strength of PC is 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 with portland-cement concrete. For stress levels of more than 50 percent of ultimate strength, creep strain in fly-ash-based PCs is extremely high, and the specimens will creep to failure in as little as 2 months (Davydov and Ivanov 1972). When design loads will be applied continuously for 10 days or more, reductions for creep effects should be applied. A design stress of less than 30 percent of ultimate strength should be used for strength design for these cases.

PC creep behavior is also influenced by ambient temperature and resin content. Creep increases with increased temperature. PC should not be used in environments where the temperature approaches the glass transition temperature of the polymer matrix.

Creep is important in PC design calculations of long-term deflections and deformations. Perform creep tests using the specific mixture proportion design and service temperatures to be used. 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 affect the creep behavior of the PC (Fowler 1991). ASTM C1181/C1181M may be used to measure the creep behavior of PC at both ambient and elevated temperatures.

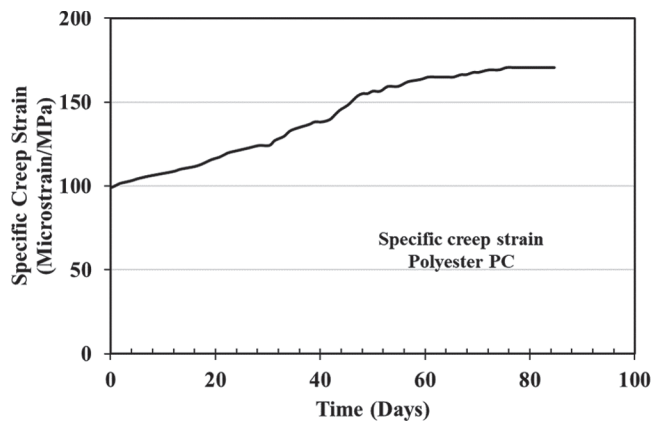


Fig. 3.3.8a—Specific creep strain.

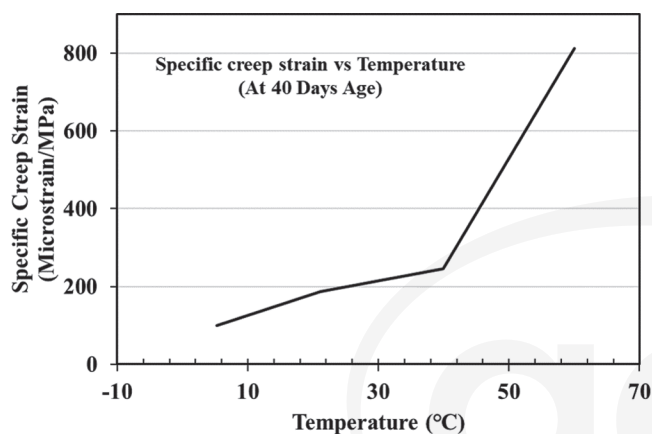


Fig. 3.3.8b—Specific creep strain versus temperature.

Some additives will increase the cross-linking of the binder system, resulting in reduced slip between the molecules and, hence, reduced creep strains. Moreover, using fillers and aggregate in the mixture proved to restrict the resin deformation and decrease creep (Jo et al. 2007). Fly ash proved to decrease the creep compliance of PC by approximately 5 percent (Rebeiz et al. 2004). However, calcium carbonate used as filler proved to have better creep behavior than using fly ash (Jo et al. 2007). The effect of calcium carbonate of creep of PC is shown in Fig. 3.3.8c. This could be due to the relatively large surface area of calcium carbonate compared with fly ash, resulting in higher bond area with polymer resin and stronger bond with aggregate than with fly ash. Furthermore, it was suggested that the fineness of fly ash interrupts the bond between the polymer and the aggregate (Jo et al. 2007).

3.3.9 Impact and abrasion resistance—Neelamegan and Parameswaran (1992) 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 increased impact resistance with fiber contents of more than 2 percent by volume. Fiber length also affected the improvement, with longer fibers providing higher impact-resistance values. Abrasion resistance also

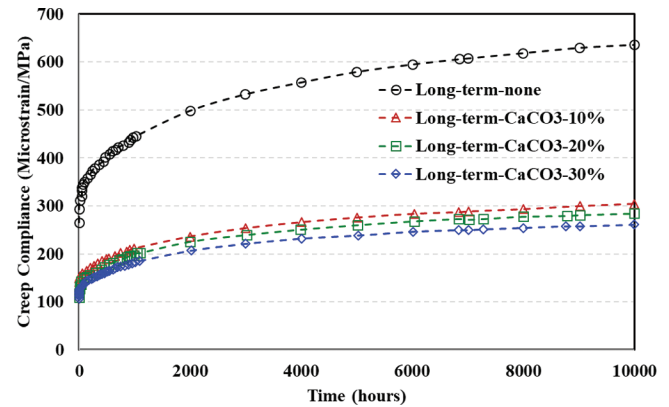
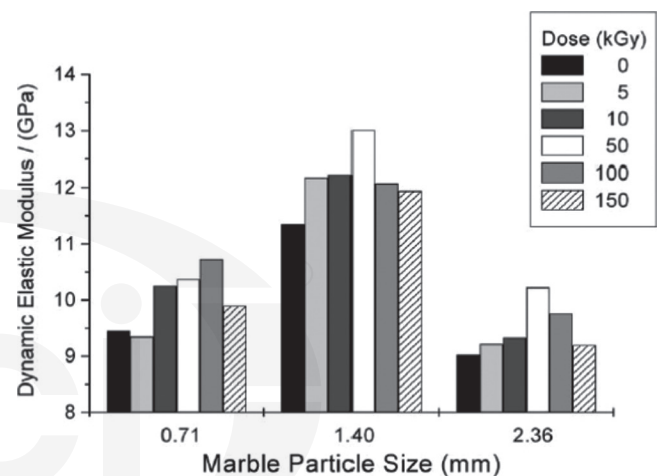
Fig. 3.3.8c—Creep compliance of polymer concrete with varying CaCO_3 filler content (Jo et al. 2007).

Fig. 3.3.9—Dynamic elastic modulus of PC with different marble particle size and irradiated to different levels of gamma rays (Martínez-Barrera and Brostow 2010).

increased with addition of 2 to 3 percent of the longer fibers by volume. Fiber lengths were between 1/4 and 1 in. (6 and 25 mm). Martínez-Barrera and Brostow (2010) showed an increase in the dynamic modulus of elasticity of polymer concrete by adding marble particles and subjecting the PC to gamma radiation, as shown in Fig. 3.3.9.

PCs also exhibit excellent energy absorption. Toughness, measured as the area below the stress-strain curve, is related to the ability of the PC to absorb energy before failure and, thus, directly correlates to its impact strength. Daghash et al. (2016) showed that it is possible to significantly improve epoxy PC toughness and impact resistance by up to 36 percent by dispersing 1 percent multi-walled carbon nanotubes by weight of epoxy in the epoxy matrix prior to fabrication of PC.

3.3.10 Bond strength—Polymer concrete has been used as an overlay to cover concrete pavements and steel bridge decks. With its low water and acid permeability, PC can protect concrete or steel substrates, repair damaged portland-cement concrete pavements, and provide high skid resistance. The superior mechanical and durability properties of PC compared to conventional concrete allows the use of thin overlays, which reduces the structure dead load and