

Report on Polymer-Modified Concrete

Reported by ACI Committee 548



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Report on Polymer-Modified Concrete

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Report on Polymer-Modified Concrete

Reported by ACI Committee 548

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This report addresses concrete made with organic polymers combined with hydraulic cement and discusses the polymer systems used to produce polymer-modified concrete, including their composition and physical properties. It explains the principle of polymer modification and reviews the factors involved in selecting appropriate polymer systems. The report also discusses mixture proportioning and construction techniques for different polymer systems and summarizes the properties of fresh and hardened polymer-modified concrete and common applications.

Keywords: abrasion; acrylic resins; admixtures; bridge deck; construction; corrosion; curing; durability; epoxy resins; latex; mixture proportioning; mortar; pavements (concrete); plastic; polymer; polymer-cement concrete; repair; resin; resistance to chemical attack; resistance to freezing and thawing; test.

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PREFACE

Polymer-modified concrete (PMC) is developed by mixing a polymer material to portland-cement concrete with the interest of enhancing the concrete durability and bond strength. PMC, also known as polymer portland-cement concrete (PPCC) or latex-modified concrete (LMC), was originally developed during the 1950 and 1960s. The material quickly found its way to awaiting industry to make use of its unique properties and became a common material in bridge deck slab overlays, industrial floors and as repair material with enhanced tensile and bond strength. Extensive research and numerous publications on the behavior of PMC were produced from the late 1970s up to the early 1990s. These publications constitute most of our current knowledge on PMC and polymer-modified mortars (PMM). While the development of PMC has significantly slowed down in the last decade, this document is designed to provide a major source of collective information for the public about PMC. The intent is to provide insight on most up-to-date standards, current practices, and the state of the art on research developments on PMC.

The International Congress on Polymers in Concrete (ICPIC) served during the last four decades as the international forum for research and development (R&D) on all types of polymer concrete including PMC. Proceedings of the ICPIC reflected the state of R&D on PMC and the issues of current interest for both academia and industry. The first ICPIC was held in London (UK) in 1975, and the most recent ICPIC was held in Chuncheon (South Korea) in 2007. For the last three decades, the ICPIC forum has served to connect interested specialists in PMC while providing insight on new technologies and future development trends.

Research on PMC continues to date with little addition to the main body of knowledge that was generated in the last 20 years of the twentieth century. Research developments in the 1980s and 1990s explained the principles of polymer modification of cement hydration (Ohama 1987) and provided the basis for selecting the suitable polymer type for PMC. Today, styrene butadiene rubber (SBR) and styrene-acrylic (S-A) copolymer represent the most usable polymers in PMC. It is therefore evident that PMC production and use has reached a high level of maturity and most research investigations in the last two decades were applications directed to further establish the procedures and standards for the material's use in the field.

Within the past few years, the most interesting developments in PMC are the development of new very-early-strength LMC (Sprinkel 2005) and the use of chopped glass and carbon fibers as additives to reduce LMC plastic shrinkage cracking (Issa et al. 2007). Both developments have found their way to bridge deck slab overlays for their ability to provide fast construction and reduce plastic shrinkage cracking. The recent work by Ohama and Demura (2001) and Ohama (2007a) on self-repair epoxy-modified mortars is definitely worth noting.

CHAPTER 1—INTRODUCTION AND SCOPE

1.1—Introduction

Polymer-modified cementitious mixtures (PMCs), also called polymer portland-cement concrete (PPCC) and latex-modified concrete (LMC), are defined as hydraulic cement combined at the time of mixing with organic polymers that are dispersed or redispersed in water, with or without aggregates. An organic polymer is a substance composed of thousands of simple molecules combined into large molecules. The simple molecules are known as monomers, and the reaction that combines them is called polymerization. The polymer may be a homopolymer if it is made by the polymerization of one monomer, or a copolymer when two or more monomers are polymerized. The organic polymer is supplied in three forms: as a dispersion in water that is called latex; as a redispersible powder; or as a liquid that is dispersible or soluble in water. Dispersions of polymers in water and redispersible polymer powders have been in use for many years as admixtures to hydraulic-cement mixtures. These admixtures are called polymer modifiers. The dispersions of these polymer modifiers are called latexes, sometimes incorrectly referred to as emulsions.

In this report, the use of the general term “polymer-modified cementitious mixture” includes polymer-modified cementitious slurry, mortar, and concrete. Where specific slurry, mortar, or concrete mixtures are referenced, specific terms are used, such as LMC and latex-modified mortar (LMM). Several other terms used in this report are defined in ACI 548.1R.

The improvements from adding polymer modifiers to concrete include increased bond strength, flexural and tensile strengths, split strength, and reduced elastic modulus. These lead to improved physical resistance such as impact resistance and abrasion resistance (Shaker et al. 1997; Wong et al. 2003; Colak 2005). A reduced elastic modulus might be particularly helpful when LMC is applied as a bridge deck overlay or repair surface. The reduced elastic modulus results in a reduction of the stresses developed due to differential shrinkage and thermal strains that would reduce the tendency of the material to crack. PMC can also improve corrosion resistance, resistance to chemical attack and severe environment (such as sulfuric acid attack, penetration by water and dissolved salts, and freezing-and-thawing resistance), and it reduces need for sustained moist curing. These improvements are largely due to reduced water permeability in PMC (Shaker et al. 1997; Ohama 1995b). The improvements are measurably reduced when PMC is tested in the wet state (Popov et al. 1987; Soroushian et al. 1993). The specific property

improvement to the modified cementitious mixture varies with the type of polymer modifier used.

The proportioning of ingredients and mixing procedures are similar to those for unmodified mixtures. Curing of modified mixtures, however, differs in that only 1 to 2 days of moist curing are required, followed by air curing. Applications of these materials include tile adhesive and grout, floor leveling concrete, water tanks, swimming pools, roof deck, concrete patches, bridge deck overlays, and ship decks (Su et al. 1991; Kardon 1997; Pinelle 1995; Cabrera and Al-Hasen 1997; Gerharz 1999; Hare 1999; Jingang et al. 2005).

1.2—History

The use of polymers as an additive to construction material is not new. In Babylonia in 4000 B.C. and in Indus Valley in 3000 B.C., clay brick walls were produced by using natural polymers such as albumen and rice paste (Chandra and Ohama 1994; Kardon 1997). More recently, in 1923, the first patent of a polymer-hydraulic-cement system, issued to Cresson (1923), refers to paving materials with natural rubber latexes where cement was used as filler. The first patent of the modern concept of a polymer-modified system was granted to Lefebure in 1924 (Lefebure 1924). Lefebure appears to be the first worker who intended to produce a PMC using natural rubber latexes by proportioning latex on the basis of cement content; Cresson, in contrast, based his mixture on the polymer content. In 1925, Kirkpatrick patented a similar idea (Kirkpatrick 1925). Throughout the 1920s and 1930s, LMM and concrete using natural rubber latexes were developed. Bond's patent in 1932 (Bond 1932) suggested the use of synthetic rubber latexes, and Rodwell's patent in 1939 (Rodwell 1939) first claimed to use synthetic resin latexes, including polyvinyl acetate latexes, to produce polymer-modified systems.

In the 1940s, patents on polymer-modified systems with synthetic latexes, such as polychloroprene rubber latexes (Neoprene) (Cooke 1941) and polyacrylic ester latexes (Jaenicke et al. 1943) were published. Also, polyvinyl acetate-modified mortar and concrete were actively developed for practical applications. Since the late 1940s, polymer-modified mixtures have been used in various applications such as deck coverings for ships and bridges, paving, floorings, anticorrosives, and adhesives. In the United Kingdom, feasibility studies on the applications of natural rubber-modified systems were conducted by Stevens (1948) and Griffiths (1951). Also, a strong interest was focused on the use of synthetic latexes in the polymer-modified systems. Geist et al. (1953) reported a detailed fundamental study on polyvinyl acetate-modified mortar and provided a number of valuable suggestions for later research and development of polymer-modified systems. The first use of epoxy resins to modify hydraulic cement was reported by Lezy and Paillere (1967).

Research efforts in the 1970s, 80s, and 90s were focused on examining the properties of LMC and selecting the most suitable polymer latex for modifying cement in polymer-modified mortar (PMM) and PMC (Popovics and Tamas 1978; Lavelle 1988; Ohama 1995b; Okba et al. 1997). A major milestone during that time period was revealing the

principles of latex modification of the cement hydration and identifying the mechanism of polymer-cement co-matrix formation (Ohama 1987; Su et al. 1991, 1996; Puterman and Malorny 1998; Jenni et al. 2006). Later efforts examined the long-term behavior of PMC with focus on durability and deterioration resistance aspects as a main characteristic of PMC (Ohama et al. 1985; Shaker et al. 1997; Mirza et al. 2002) and on controlling the rheological properties of LMC (Barluenga and Hernández-Olivares 2004).

Recently, researchers developed and examined very-early-strength LMC using rapid hardening cement (Sprinkel 1999, 2005). The use of the new very-early-strength LMC proved efficient for replacing bridge deck overlays. Moreover, the use of fiber-reinforced LMC has been recently promoted (Cao and Chung 2001; Issa et al. 2007). The use of glass and carbon fiber-reinforced LMC provides a watertight microstructure of LMC with very low permeability and the ability of the chopped fibers to limit plastic shrinkage cracking. Such combined benefits make fiber-reinforced LMC an excellent alternative for bridge deck slabs (Issa et al. 2007). Finally, a bibliography developed and updated by Ohama (2007b) represents an excellent source of information on historical and recent developments of PMC.

1.3—Scope

This report reflects the current state of knowledge of PMC and intends to provide the reader with a credible source of knowledge on PMC reflecting the maturity of that technology and highlighting R&D efforts taking place in the last few years. It is not the intention of this document to cover all research efforts on PMC but rather to highlight the significant efforts that helped shape the current state of knowledge of that material.

CHAPTER 2—ACRONYMS AND DEFINITIONS

2.1—Acronyms

ASTM	—ASTM International
FHWA	—Federal Highway Administration
ICPIC	—International Congress on Polymers in Concrete
ICRI	—International Concrete Repair Institute
LMC	—latex-modified concrete
LMM	—latex-modified mortar
MFFT	—minimum film-forming temperature
PAE	—acrylic polymer and copolymer
PMC	—polymer-modified cementitious mixture
PMM	—polymer-modified mortar
PPCC	—polymer portland-cement concrete
PVA	—polyvinyl acetate homopolymer
R&D	—Research & Development
RH	—relative humidity
S-A	—styrene-acrylic copolymer
S-B	—styrene-butadiene copolymer
SBR	—styrene-butadiene rubber
VAC	—vinyl acetate copolymer
VAE	—vinyl acetate ethylene copolymer
VA-VEOVA	—vinyl acetate-vinyl ester of versatic acid copolymer
VEOVA	—vinyl acetate-vinyl ester of versatic acid copolymer

2.2—Definitions

coagulum—polymer in the form of particles that are larger than intended due to such actions as particle agglomeration or skin formation.

comonomer—a monomer that is mixed with one or more other monomers to react and form a copolymer.

emulsion—a two-phase liquid system in which small droplets of one liquid (the internal phase) are immiscible in, and dispersed uniformly throughout, a second continuous liquid phase (the external phase).

glass transition temperature—the midpoint of the temperature range over which an amorphous material (such as glass or a high polymer) changes from (or to) a brittle, vitreous state to (or from) a plastic state.

latex—a water emulsion of a high-molecular-weight polymer, used especially in coatings, adhesives, leveling compounds, and patching compounds.

minimum film-forming temperature—the minimum temperature at which a synthetic latex or emulsion will coalesce when laid on a substrate as a thin film.

monomer—an organic molecule of relatively low molecular weight that creates a solid polymer by reacting with itself or other compounds of low molecular weight, or both.

nonvolatile content—the portion of a material that remains after volatile matter has been evaporated under specified ambient or accelerated conditions.

plastic-shrinkage crack—surface crack that occurs in concrete prior to initial set.

polymer—the product of polymerization; more commonly a rubber or resin consisting of large molecules formed by polymerization.

polymerization—the reaction in which two or more molecules of the same substance combine to form a compound containing the same elements and in the same proportions but of higher molecular weight.

resin—polymeric material that is rigid or semi-rigid at room temperature, usually with a melting point or glass transition temperature above room temperature.

setting time—the length of time required to set or harden resin or adhesive under heat or pressure.

stability—a measure of resistance to coagulation when a latex is subjected to mechanical action, chemicals, or temperature variations.

surface tension—an internal molecular force that exists in the surface film of all liquids and tends to prevent the liquid from flowing.

surfactant—a substance that markedly affects the interfacial or surface tension of solutions when present, even in low concentrations.

van der Waals forces—the attractive or repulsive forces between molecules (or between parts of the same molecule) other than those due to covalent bonds or to the electrostatic interaction of ions with one another or with neutral molecules.

viscosity—a measure of the resistance of a fluid to deform under shear stress.

CHAPTER 3—GENERAL INFORMATION ON POLYMER MODIFIERS

3.1—Polymer modifiers and their properties

Table 3.1 lists the various polymers that have been used to modify hydraulic cements. The materials in italics are the ones that are in general use today, and those marked with an asterisk are available in a redispersible powder form.

Mixed latexes are blends of different types of latex, such as an elastomeric latex with a thermoplastic latex. Although these blends are occasionally used for modifying cement, the practice is limited.

Each type of polymer latex imparts different properties when used as an additive (or a modifier) to hydraulic-cement mixtures. Moreover, variations within each type of latex, particularly copolymer latexes, yield different properties of hardened mortar and concrete.

With few exceptions, a process known as emulsion polymerization produces the latexes used with hydraulic cements. The basic process involves mixing the monomers with water, a surface-active agent (refer to Section 3.1.1.3 for a description of surfactants), and an initiator. The initiator generates a free radical that causes the monomers to polymerize by chain addition. Examples of chain addition polymerization are presented in Fig. 3.1. A typical formulation for emulsion polymerization is given in Table 3.2.

One method of polymerization is to charge the reactor with the water, surfactants, other ingredients, and part of the monomer or monomers under agitation. When the temperature is raised to a desired point, the initiator system is fed to the reactor, followed by the remainder of the monomer. By temperature control and possibly by other chemical additions, 90 to more than 99% conversion of the reaction normally occurs. Unreacted monomer is reduced to acceptable levels by a process known as stripping. The resultant latex may be concentrated or diluted, and small amounts of materials, such as preservatives and surfactants, may be added.

Other ingredients are often used in the polymerization process and are incorporated for many reasons, such as controlling pH, particle size, and molecular weight.

Redispersible powders are manufactured by using two separate processes. The latex polymer is made by emulsion polymerization, and is then spray-dried to obtain the powder (Walters 1992a).

Many latexes and redispersible polymer powders are available on the market, but only about 5% of them are suitable for use with hydraulic cements. The other 95% lack the required stability, and they coagulate when mixed with cement.

Latexes can be divided into three classes according to the type of electrical charge on the particles, which is determined by the type of surfactants used to disperse them. The three classes are cationic (positively charged), anionic (negatively charged), and nonionic (no charge). In general, latexes that are cationic or anionic are not suitable for use with hydraulic cements because they lack the necessary stability. Most of the latexes used with portland cement are stabilized with surfactants that are nonionic.

Typical formulations for the three types of latex used with portland cement are given in Table 3.3.

Table 3.1—Polymers used to modify hydraulic cementitious mixtures

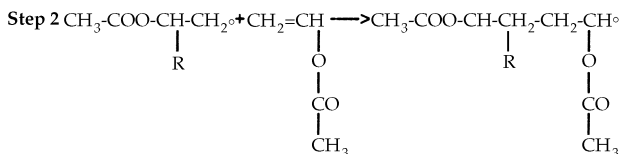
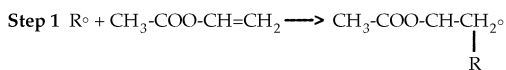
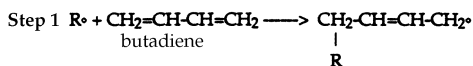
Elastomeric	Natural rubber latex
	Synthetic latexes <i>Styrene-butadiene, polychloroprene (Neoprene), acrylonitrile-butadiene</i>
Thermoplastic	<i>Polyacrylic ester, * styrene-acrylic, * polyvinyl acetate, * vinyl acetate copolymers, * polyvinyl propionate, vinylidene chloride copolymers, polypropylene</i>
Thermosetting	<i>Epoxy resin</i>
Bituminous	Asphalt, rubberized asphalt, coal-tar, paraffin
Mixed latexes	

*Available in a redispersible powder form.

Note: Italics = in general use today.

Table 3.2—Typical formations for emulsion polymerization

Item	Parts by mass
Monomers	100.0
Surfactant	1.0 to 10.0
Initiator	0.1 to 2.0
Water	80.0 to 150.0
Other ingredients	0 to 10.0

Homopolymerization of Vinyl Acetate**Copolymerization of Butadiene and Styrene**

• = reactive valence
R° = free radical

Fig. 3.1—Typical chain addition polymerization.

Preservatives added to latex after polymerization provide protection against bacterial contamination and give improved aging resistance. Sometimes, additional surfactants are added to provide required stability. Antifoaming agents may be added to reduce air entrainment when the latex is mixed with the cement and aggregates.

Not all latexes are made by emulsion polymerization. For these other products, the polymer is made by another polymerization process, and the resultant polymer is then dispersed in water by the dosage of surfactants.

Table 3.3—Typical formulation for latexes used with portland cement

Vinyl acetate, homo- and copolymer latexes	
Item	Parts by mass
Vinyl acetate	70.0 to 100.0
Comonomer (butyl acrylate, ethylene, vinyl ester of versatic acid)	0.0 to 30.0
Partially hydrolyzed polyvinyl alcohol	6.0
Sodium bicarbonate	0.3
Hydrogen peroxide (35%)	0.7
Sodium formaldehyde sulfoxylate	0.5
Water	80.0
Acrylic copolymer latex	
Ethyl acrylate	98
A vinyl carboxylic acid	2
Nonionic surfactant	6*
Anionic surfactant	0.3†
Sodium formaldehyde sulfoxylate	0.1
Caustic soda	0.2
Peroxide	0.1
Water	100.0
Styrene-butadiene copolymer latex	
Styrene	64
Butadiene	35
A vinyl carboxylic acid	1
Nonionic surfactant	7*
Anionic surfactant	0.1†
Ammonium persulfate	0.2
Water	105

*The nonionic surfactants may be nonyl phenols reacted with 20 to 40 molecules of ethylene oxide.

†The low levels of anionic surfactant are used to control the rate of polymerization.

Polymer modifiers in a powder form are redispersed either in water or during mixing of the cementitious mixture. The use of polymer powders allows for the supply of one-part, prepackaged mixtures, requiring only the addition of water at the construction site. Where latex is used, the proportioning of the latex (and water) to the dry cementitious material is performed at the construction site.

3.1.1 Influence of polymer composition—The composition of the polymer modifier has marked effects on the properties of PMC mixtures, both in the wet and hardened states (Ohama 1995a; Walters 1990, 1992b).

3.1.1.1 Major components of polymer—The major components of a polymer modifier are the monomers that form the polymer's bulk, and are generally present in levels of greater than 10% by mass of the polymer modifier. Such monomers include, but are not limited to: acrylic esters (such as butyl acrylate, ethyl acrylate, and methyl methacrylate), acrylonitrile, butadiene, ethylene, styrene, vinyl acetate, vinyl ester of versatic acid (VEOVA), and vinylidene chloride.

These components have major effects on the hardness of the polymer modifier and its resistance to hydrolysis and ultraviolet light. The latter characteristics have significant effects on resistance to water penetration and color stability, respectively, of the PMC. The hardness of the polymer modifier is related to its glass transition temperature T_g .

Table 3.4—Glass transition temperatures T_g of various homopolymers

Monomer of homopolymer	T_g , °F (°C)
Ethylene	< -184 (< -120)
Butadiene	-110 (-79)
N-butyl acrylate	-65 (-54)
Ethyl acrylate	-7 (-22)
Vinylidene chloride	0.0 (-18)
Vinyl acetate	86 (30)
Acrylonitrile	208 (98)
Styrene	212 (100)
Methyl methacrylate	221 (105)

Table 3.4 gives typical T_g values for homopolymers of the listed monomers. In general, the higher the T_g , the harder the polymer and the higher the compressive strength of the PMC; the lower the T_g , the lower the permeability of the PMC.

Where resistance to discoloration by exposure to ultraviolet light is required, the desired polymer modifiers are acrylic copolymers (Lavelle 1988) and, possibly, vinyl acetate-ethylene copolymers (Walters 1990). Butadiene copolymers should not be used in such applications because they exhibit marked discoloration.

Where resistance to penetration of water and dissolved salts is of prime importance, hydrolysis resistance of the polymer modifier is necessary. The highly alkaline environment of hardened wet portland cement mixtures causes severe degradation of some polymer modifiers, such as vinyl acetate homopolymers. The hydrolysis of these homopolymers results in the formation of polyvinyl alcohol and metallic acetates. Both of which are water-soluble and can leach out of the concrete. Such degradation results in a PMC with higher permeability than unmodified mixtures. Hydrolysis resistance of vinyl acetate can be improved by copolymerizing with ethylene, VEOVA, or acrylic esters. These comonomers not only retard the rate of hydrolysis of the vinyl acetate, but even when hydrolysis occurs, the result is formation of a copolymer of vinyl alcohol with the comonomer. Such copolymers are usually not water-soluble and remain in the cementitious mixture with a marginal increase in permeability. Styrene-butadiene copolymers show no tendency to hydrolyze in alkaline environments. The majority of acrylic copolymers hydrolyze slowly, if at all. Consequently, styrene-butadiene or acrylic polymer modifiers should be used where resistance to water penetration is paramount.

Polymer modifiers made from monomers containing chloride groups should not be used in steel-reinforced concrete or mortar. In the alkaline environment of portland cement, some of the chloride groups are liberated in the ionic form and assist in corroding any reinforcing steel or steel surfaces. The primary monomer in this category is vinylidene chloride.

3.1.1.2 Minor components of polymer—The minor components are monomers incorporated into the polymer modifier for their reactivity or some other special property. They are usually present at levels of less than 5% by mass, more often in the 1 to 2% range. Such materials include carboxylic acids, such as acrylic or methacrylic, and N-methylol

acrylamide. These monomers, which form part of the polymer, have side groupings that can combine chemically with other substances in the cementitious mixture. Ohama (1995a) suggests that such reactions improve the bond between the cement and aggregates. Incorporation of carboxylic acids in the polymer modifier may lower the permeability of the resultant PMC (Walters 1992b). Reactive groups, such as acrylic acid and N-methylol acrylamide, have the potential of retarding the hydration of the cement.

3.1.1.3 Colloidal system of the polymer—The colloidal system consists of surfactants used to emulsify the monomers during polymerization and surfactants added later to modify the stability of the system. The colloidal system has effects on the properties of the polymer modifier (Walters 1987), which in turn has effects on the resultant PMC, particularly in the unhardened state. In general, the colloidal system of the majority of polymer modifiers for hydraulic cements is nonionic. Such systems give the latex sufficient stability to the multivalent ions of the cement and stability to freezing and thawing.

Antifoam agents, such as silicone emulsions, are often incorporated to reduce the tendency of the system to entrap air during mixing with the cement and aggregates. Surfactants (also referred to as stabilizers, soaps, and protective colloids) are chemical compounds added during manufacture of the latex that attach themselves to the surface of the latex particles. By doing so, they affect the interactions of the particles themselves as well as the interactions of the particles with the materials to which the latex is added. This is particularly true of portland cement. The surfactant's main effect is probably on the workability of the mixture as it allows for a reduction in the water-cementitious material ratio (w/cm) without reducing the slump of the modified mixture. If excess quantities are used, however, it can also reduce water resistance and adhesion of the hardened concrete.

3.1.2 Influence of compounding ingredients—Compounding ingredients are the materials added after polymerization is complete. They improve the properties of the product, such as resistance to chemical or physical attack. The most common compounding ingredients are bactericides that protect the polymer and surfactants against attack by bacteria and fungi. Antioxidants and ultraviolet protectors are added to provide protection against aging and sunlight attack. The levels of these added materials are relatively low, ranging from parts per million for bactericides to a few percent for surfactants. Other ingredients that may be added are defoaming or antifoaming agents. If the latex does not contain such a material, one of these agents should be added before use to avoid high air content in the hydraulic cement mortar or concrete.

3.2—Test procedures for polymer modifiers

Certain test procedures for measuring colloidal and polymeric properties of polymer modifiers are frequently used for quality-control purposes to ensure a supply of a consistent product. The tests can also be used to assess the suitability of polymer modifiers for specific uses.

3.2.1 Nonvolatile or total solids content—Nonvolatile content is important in that it is the major factor in determining the cost of the product. It is determined by weighing a small representative sample of the latex, drying it under certain conditions, and weighing the residue. The residue is expressed as a percentage of the original mass. Although there are several acceptable published methods, different values may be obtained by different test methods. Table 3.5 shows three different nonvolatile contents of the same latex using three different test temperatures and times of drying. The main difference is in the temperature and time used to dry the latex. If there is a dispute, the generally accepted method is ASTM D1076.

3.2.2 pH value—ASTM D1417 gives the method for testing the pH of latexes. The pH range of latex varies significantly, depending on the type of latex. For styrene-butadiene copolymer latexes used with hydraulic cement, it is usually 10 to 11; for acrylic copolymer latexes, it is usually 7 to 9; and for vinyl acetate homopolymer and copolymer latexes, it is usually 4 to 6. Walters (1992b) showed that with styrene-butadiene copolymer latexes, no significant change in flow, wet and dry density, and permeability properties of the PMC occurred when the pH value was varied from 4 to 10.

3.2.3 Coagulum—The sieve sizes used to measure the coagulum in ASTM D1076 are 150, 75, or 45 μm (formerly No. 100, 200, or 325 mesh). The test measures the quantity of polymer that has particles larger than intended, usually formed by particle agglomeration or skin formation. Typical coagulum values are less than 0.1% by mass.

3.2.4 Viscosity—Viscosity can be determined in many ways and the viscosity of a fluid can vary depending on the test method.

A method used with latex uses a viscometer manufactured by Brookfield (ASTM D1417), but its several speeds of rotation can give different values. Also, the temperature at which the test is run can have a significant effect. A combination of these effects can be dramatic, as illustrated in Table 3.6, which presents the viscosity indications obtained from one latex sample using different methods. When reporting Brookfield viscosity values, the model number, spindle number, speed of rotation, and temperature used in the test should be reported.

The styrene-butadiene and acrylic latexes used with hydraulic cements are very fluid, having viscosities of less than 14,280 psi (100 MPa) when measured at standard conditions (ASTM D445, ASTM D1417). As a reference, the viscosity of milk is approximately 14,280 psi (100 MPa).

3.2.5 Stability—Stability is a measure of resistance to coagulation when latex is subjected to mechanical action, chemicals, or temperature variations:

- Mechanical stability is determined by subjecting the latex to mechanical action, usually high-speed agitation for a specific time, and then measuring the amount of coagulum that is formed, as described in ASTM D1417;
- Chemical stability may be assessed by determining the amount of a chemical required to cause complete coagulation or by adding a quantity of the chemical and measuring the amount of coagulum. A method is described in ASTM D1076; and

Table 3.5—Effect of test method on nonvolatile content of a latex

Test temperature	158 °F (70 °C)	221 °F (105 °C)	257 °F (125 °C)
Time of drying, hours	16.0	0.75	0.50
Nonvolatile content, %	62.7	61.3	58.3

Table 3.6—Effect of test method on viscosity of a latex

Brookfield model	Speed, rpm	Temperature, °F (°C)	Viscosity, cps (Pa·s)
LVF	1.5	60 (16)	8000 (8.00)
RVF	20	75 (24)	1150 (1.15)
LVF	60	90 (32)	480 (0.48)

- Thermal stability is determined by subjecting the latex to specified temperatures for a specific period and determining thermal effects on other properties. An FHWA report (Clear and Chollar 1978) describes a freezing-and-thawing stability test in which the amount of coagulated latex after two cycles of freezing and thawing is determined. Freezing-thawing cycles are performed at a rate of one half-cycle/day. The test indicates the ability of the latex emulsion to resist freezing-thawing cycles prior to use in concrete.

These stability properties are important for latexes used with hydraulic-cement mixtures. Mechanical stability is required because the latexes are frequently subjected to high shear in metering and transfer pumps. Chemical stability is required because of the reactivity of hydraulic cements. Thermal stability is required because the latex may be subjected to wide variations in temperature. The surfactants used in the latex have a major influence on its stability.

3.2.6 Density—Similar to solids or nonvolatile content, density indicates the polymer content of the latex. The density of styrene-butadiene latex is approximately 1.01 kg/L (0.6 lb/gal.), whereas that of an acrylic is typically 1.07 kg/L (0.63 lb/gal.). If both latexes have solids of 47% by mass, the styrene-butadiene latex contains approximately 0.475 kg of polymer per liter (0.28 lb/gal.), whereas a liter of acrylic latex contains 0.503 kg (0.31 lb/gal.).

3.2.7 Particle size—Particle size is a measure of the size of the polymer dispersed in the water. It will vary from 50 to 5000 nm. Particle size can be determined using equipment such as electron microscopes, centrifuges, and photospectrometers. Particle size is dependent, to a large degree, on the levels and types of surfactants.

3.2.8 Surface tension—The FHWA report (Clear and Chollar 1978) describes a procedure that is accepted by most State Departments of Transportation. The lower the value of surface tension, the better the wetting ability of the latex. This property affects the workability or finishability of a latex-modified mixture. The surface tension is dependent, to a large degree, on the levels and types of surfactants. A typical value for a styrene-butadiene copolymer latex is about 40 dynes/cm (2.28×10^{-4} lbf/in.), while that of water is about 75 dynes/cm (4.28×10^{-4} lbf/in.).

3.2.9 Minimum film-forming temperature (MFFT)—Minimum film-forming temperature (MFFT) is defined as

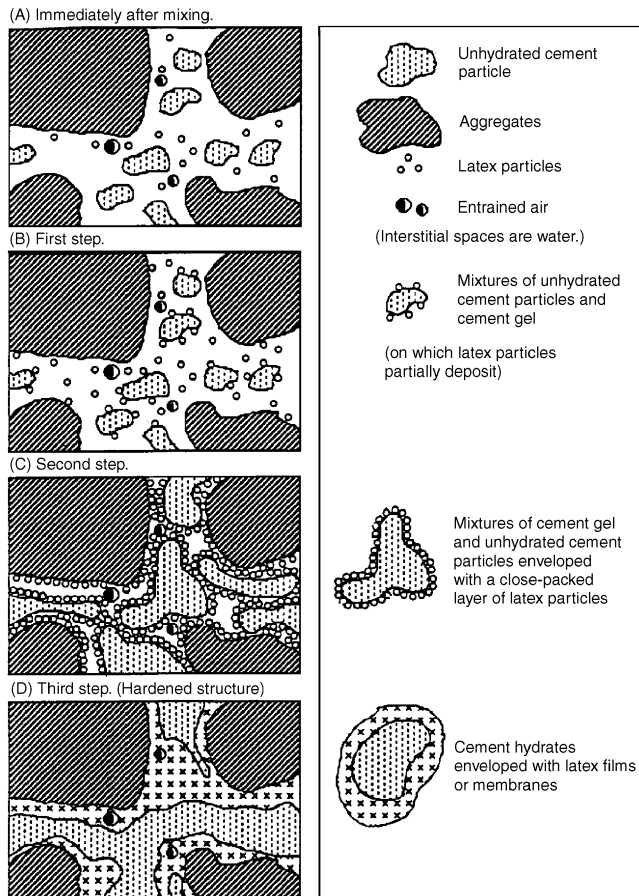


Fig. 3.2—Simplified model of formation of latex-cement comatrix (Ohama 1987).

“the lowest temperature at which the polymer particles of the latex have sufficient mobility and flexibility to coalesce into a continuous film” (Concrete Society 1987). The type and level of monomer(s) used to make the polymer control the MFFT. This temperature might be reduced by the addition of plasticizers. A plasticizer is a chemical added to brittle polymers to increase flexibility.

Generally, for successful application of latex-modified hydraulic-cement mixtures, the MFFT should be lower than the application temperature. In some cases, however, satisfactory performance has been obtained with the application temperature below the MFFT of the latex because the cement reduces the effective MFFT of the latex. ASTM D2354 describes a method for measuring MFFT.

3.3—Principle of polymer modification

Polymer modification of hydraulic cementitious mixtures is governed by two processes: cement hydration and polymer coalescence.

Generally, cement hydration occurs first. As the cement particles hydrate and the mixture sets and hardens, the polymer particles become concentrated in the void spaces. Figures 3.2 and 3.3 indicate the type of change that occurs during polymer modification (Ohama 1973, 1995b; Wagner and Grenley 1978; Lavelle 1988; Puterman and Malorny 1998). With continuous water removal by cement hydration

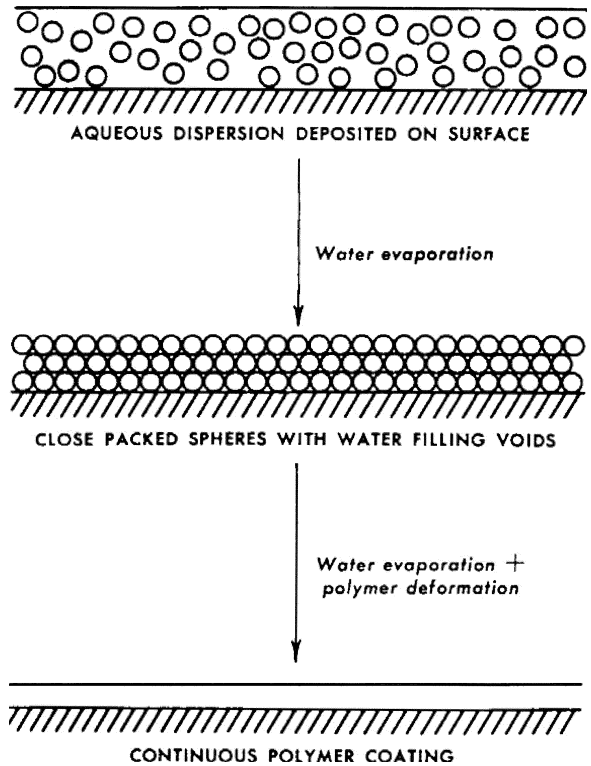


Fig. 3.3—Simplified model of formation of polymer film on cement hydration (Lavelle 1988).

evaporation, or both, the polymer particles coalesce into a polymer film that is interwoven in the hydrated cement, resulting in a mixture or comatrix that coats the aggregate particles and lines the interstitial voids (Fessenden and Fessenden 1998; Afridi et al. 2003).

Unlike conventional cementitious mixtures, PMC does not produce bleed water and, during its fresh state, polymer-modified mixtures are more sensitive to plastic-shrinkage cracking than unmodified mortar or concrete because of the water-reducing influence of the polymer’s surfactant system (De Puy 1996; Beeldens et al. 2001). This phenomenon (plastic-shrinkage cracking) is caused by water evaporation at the surface. Two things can happen, both of which contribute to the problem: 1) the polymer particles may start to coalesce before the cement hydration is complete; and 2) the cement paste may shrink before sufficient tensile strength develops to restrain crack formation. Recognizing that PMC does not produce bleed water, particular care should be taken to restrict surface evaporation by use of various cover systems.

Because latex particles are typically greater than 100 nm in diameter, they cannot penetrate the small capillaries in the cement paste that may be as small as 1 nm. Therefore, it is in the larger capillaries and voids that the latex can be most effective.

Some of the polymers used in portland cement mixtures contain reactive groups that may react with calcium and other metallic ions in the cement, and with the silicate and other chemical radicals at the surface of the aggregates (Wagner 1965). Such reactions would improve the polymer-cement bond and, hence, the strength of the mixture.

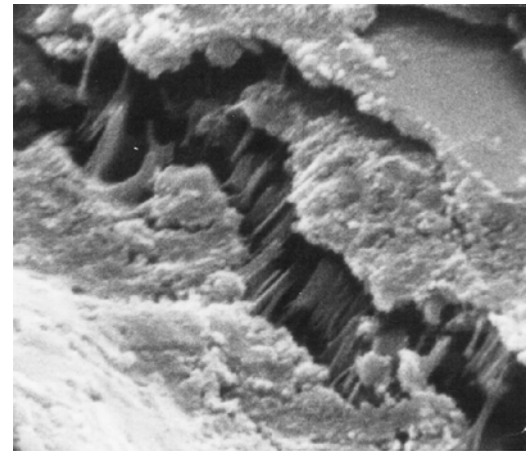
Hardened portland cement paste is predominantly an agglomerated structure of calcium silicates, aluminates, and hydroxides bound together by relatively weak van der Waals forces. Consequently, microcracks are induced in the paste by stresses such as those caused by evaporation of excess mixing water (drying shrinkage). Polymer modification helps in two ways. Not only do the polymer particles reduce the rate and extent of moisture movement by blocking the passages, but when microcracks form, the polymer film bridges the cracks and restricts propagation. Figure 3.4 shows electron micrographs of polymer-modified and unmodified concrete; the micrograph of the PMC shows latex strands bridging a microcrack while such strands are absent in the unmodified concrete. This results in increased tensile strength and flexural strength. The moisture-movement-blocking property naturally works both ways and also restricts the ingress of most fluids (Ohama 1995a), thus reducing permeability and increasing resistance to both chemicals and freezing-and-thawing resistance. PMC does not require additional air entrainment because of its typically high air content of approximately 6%. There is little or no free water in PMC and the polymer restricts ingress and movement of water. The resistance to freezing and thawing of PMC has been shown to be superior to that of unmodified concrete due to the ability of the polymer latex to block water transport in concrete and the air entrained by the polymer latex in the concrete (Maultzsch 1989; Ohama and Shiroishida 1984).

Kim et al. (1999) experimentally investigated the fracture surface of PMC. They observed that the fracture surface of PMC was propagated through the aggregate instead of around the aggregate, and that debonding of the aggregate was rarely observed compared with unmodified concrete. This observation was not reported by other researchers examining fracture of PMC. However, PMC and polymer-modified mortar (PMM) were reported to have relatively higher fracture toughness compared with normal concrete and mortar (Chou et al. 1990; Bureau et al. 2001; Xu et al. 2004).

The optimum degree of polymer modification is usually achieved between 7.5 and 20% dry polymer solids by mass of cement in the mixture. Optimal polymer content is related to enhancing watertightness, durability, cracking strength, and fracture toughness of concrete while maintaining an acceptable compressive strength and workability. The use of excess polymer is not economical, can cause excessive air entrainment, and can cause the mixture to behave like a polymer filled with aggregates and cement. Levels of polymer lower than the recommended optimal content cannot achieve the level of modification necessary for producing the unique characteristics of PMC previously described.

Wagner (1965) studied the influence of latex modification on the rate of surface area development of polymer-modified pastes. This work indicated that although polymer modification can either accelerate or retard the initial setting time, it has little or no effect on the final setting of cement. Zhihong et al. (2003) showed the possible control of the initial setting time by changing the polymer content.

The type of latex used and the latex-cement ratio influence the pore structure of latex-modified systems. According to



Latex-modified concrete



Portland cement concrete

Fig. 3.4—Electron micrograph of latex-modified and portland-cement concrete (magnification = 12,000 \times) (Dow Chemical Co. 1985).

Kasai et al. (1982), Ohama and Shiroishida (1983), and Tantawi (1997), the porosity and pore volume of the PMM differs from unmodified mortar in that the former has a lower number of pores with a radius of 200 nm, but significantly more with a smaller radius of 25 nm or less. The total porosity or pore volume tends to decrease with increasing polymer-cement ratios. This can contribute to improvements in impermeability to liquids, resistance to carbonation, and resistance to freezing and thawing. Similar observations were reported by Shaker et al. (1997).

Walters (1992b) showed that the polymer modification of concrete using styrene-butadiene rubber (SBR) improved flexural strength, permeability resistance, and ductility as the polymer-cement ratio increased at a constant water-cement ratio (w/c). Tubbesing (1993) and Schulze and Killermann (2001) studied the microstructural characteristics of wet-stored PMM. In the study, it was shown that PMM does not show significant damage over 10 years of outdoor exposure. In Su et al. (1991), Cook and Hover (1999), and Silva et al. (2001), the effect of water content on the pore size distributions was investigated. De Belie et al. (1998) and Monteny et al. (1999) performed immersion tests into sulfuric acid. The test showed that the PMC resistance to chemical attack was

significantly improved due to the beneficial effect of interpenetrating network of polymer film (Monteny et al. 2001).

The curing regime used with PMC requires initial moist curing to prevent plastic-shrinkage cracking, followed by air curing. The air curing should be considered drying rather than curing, although there is much data showing the properties of PMC enhance with time, as is the case with unmodified mixtures. After initial moist curing, the latex particles at the surface coalesce into a film, preventing further moisture loss. The entrapped moisture hydrates the cement particles, and as free water is consumed, latex particles in the interior of the mixture form films. As these films develop, reactive groups in the polymer are able to crosslink. Both cement hydration and polymer crosslinking are considered to be components of curing.

3.4—Selection of polymer modifier

The major polymers used for modification of cementitious mixtures are acrylic polymers and copolymers (PAE), styrene-acrylic copolymers (S-A), styrene-butadiene copolymers (S-B), vinyl acetate copolymers (VAC), and vinyl acetate homopolymers (PVA). The major vinyl acetate copolymers are vinyl acetate-ethylene (VAE) and vinyl acetate-vinyl ester of versatic acid (VA-VEOVA). Vinyl acetate-acrylic copolymers are also sometimes used. The selection of a particular polymer for a PMC depends on the specific properties required for the application. The significance of discoloration of concretes incorporating specific types of polymers shall be considered especially when concretes are used for architectural features.

For applications where permeability resistance and high bond strength are required but colorfastness is not important, SBR latex (Clear and Chollar 1978) might be the polymer of choice, based on performance. For applications where colorfastness, permeability resistance, and bond strength are required, PAE or S-A latexes might be used. For applications where some colorfastness, permeability resistance, and bond strength are required, vinyl acetate copolymers might be used. Where only bond strength is required and the product would not be exposed to moisture, vinyl acetate homopolymers can be used (Walters 1990). PVA is known to deteriorate with water exposure due to partial hydrolysis (Ohama 1995b). The significance of water exposure on PMC shall be carefully examined before selecting the appropriate polymer to be used.

Redispersible powders are invariably more expensive than their equivalent latex because the powders are made typically by spray-drying the latex. Consequently, the powders are used where cost is not as critical and convenience is more important, such as in do-it-yourself applications or jobs where smaller quantities are required. Currently, the only polymers available as redispersible powders are PAE, S-A, VAE, VA-VEOVA, and PVA. Another reason for using redispersible powders is that the mixture proportioning is better controlled, with batching of dry ingredients usually occurring in manufacturers' plants and not at the job site, as when latexes are used. Refer to Section 4.4 for more information on redispersible polymer powders.

3.5—Specification and test methods for PMC

In 1999, ASTM issued ASTM C1438, a specification for latex and polymer modifiers for hydraulic-cement mixtures. At the same time, test method ASTM C1439 for polymer-modified mixtures was issued. In the latter, PMC specimens are cured by being covered with plastic sheeting for 24 hours followed by air curing at 23 °C (73 °F) and 50% relative humidity (RH) until the time of the test. These standards do not apply to epoxy-modified hydraulic cementitious mixtures.

CHAPTER 4—POLYMER MODIFIERS FOR LATEX-MODIFIED CONCRETE

4.1—Styrene-butadiene latex

4.1.1 Background—The development of synthetic SBR latex as an admixture to portland-cement mortar began in the U.S. in the mid-1950s. Initial applications were in mortar for patching kits, stucco, ship-deck coatings, floor-leveling compounds, and tile adhesives. In 1956, application to bridge decks as a protective mortar overlay began. The increased use of deicing salts and the recognition of their destructive effects paralleled the evolution of modified mortar mixtures into concrete, and styrene-butadiene LMC became a common protection system used for bridge decks in the U.S. (Clear and Chollar 1978). In 1991, Walters (1991) estimated that over 10,000 bridges were protected with this system. Because parking garages suffer from the same deicing salt deterioration problems as bridge decks, LMC is also used as a protective overlay on the decks of parking garages. Since the mid-1990s, the use of this system has been reduced due to replacement by less expensive systems.

Styrene-butadiene latex-modified mortars and concrete are useful for a variety of applications by means of a variety of improved material characteristics. For most of these applications, bond to substrate and low permeability are most beneficial properties. In outdoor applications, resistance to freezing and thawing is important. These and other primary properties are discussed in the following sections.

4.1.2 Mixture proportioning—The inclusion of styrene-butadiene latex in portland-cement mortar and concrete results in less water being required for a given consistency. Components in the latex function as dispersants for the portland cement and, thus, increase flow and workability of the mixture without additional water. Therefore, the selection of the amount of latex will affect the physical properties of the hardened system in two ways: by the amount of latex included, and by the amount of water excluded.

The effects of the amount of latex on the properties of the mortar and concrete are discussed in detail in the next section.

A common value for latex addition is a latex solids-cement mass ratio of 0.15. Using this ratio, the mixture proportions shown in Table 4.1 are typical of what is used. ASTM C150 Types I, II, and III portland cements are used in styrene-butadiene LMC and mortar. Typically, Type I cement has been used, but Sprinkel (1988a, 1993, 2003) reported the use of Type III cement to achieve early strength where the overlay is to accept service loads within 24 hours. Minimum and maximum cement contents have not been established for other mortars or concrete mixtures containing latex. The

Table 4.1—Typical proportions for LMC and mortar mixtures

Mortar	
Ingredient	Amount
Cement	100 lb (45.4 kg)
Sand	290 lb (131.5 kg)
Latex*	3.7 gal. (14.1 L)
Water	2.6 gal. (10.0 L)
Yields approximately 3 ft ³ (0.1 m ³).	
Concrete	
Ingredient	Amount
Cement	658 lb (299 kg)
Sand	1710 lb (776 kg)
Coarse aggregate	1140 lb (517 kg)
Latex*	24.5 gal. (92.7 L)
Water	19.0 gal. (71.9 L)
Yields approximately 1 yd ³ (0.765 m ³).	

*Assumed 48% solids, 52% water by mass.

particular cement content used has been based on the application of the modified mixtures. For LMC, the most common cement content has been approximately 230 kg/m³ (15 lb/ft³). For mortar applications, cement content varies with the end use. Most of the reported data included in this report are based on a sand-cement ratio of 3.

The fine-coarse aggregate ratio will vary with the specific aggregate used, but with the aforementioned proportions, a workable concrete having a slump of 100 to 200 mm (4 to 8 in.) and a maximum *w/cm* of 0.40 should be possible. It is noted that the *w/cm* of latex-modified mixtures is used in this report, and it includes the water in the latex, the free water in the aggregates, and the added water.

4.1.3 Properties

4.1.3.1 Film properties—To help understand what effect the environment of freshly mixed portland cement might have on the latex addition, films of styrene-butadiene latex were immersed in saturated lime solutions and tested for tensile strength (Shah and Frondistou-Yannas 1972). Figure 4.1 shows that the film is not weakened by exposure to the lime solution, but, in fact, gains in tensile strength after immersion. Figure 4.2 indicates that during this immersion period, the film increased in mass by about 5% during the first 2 days, but gained no additional mass thereafter. The pH of the lime solution remained nearly constant during this immersion period.

4.1.3.2 Properties of fresh mortar and concrete

4.1.3.2.1 Air content—Because of the surfactants used in the manufacture of latex, excessive amounts of air can be entrained when latex is mixed into a portland cement system, unless an antifoam agent is incorporated in the latex. For styrene-butadiene latexes, these are usually silicone products, and are often added by the latex supplier. Figure 4.3 shows an example of the relationship between the antifoam agent (expressed as a percentage of the latex) and the air content of the mortar (Ohama 1973). Okba et al. (1997) reported the ability of defoaming agents to control the air content of LMC incorporating SBR latex.

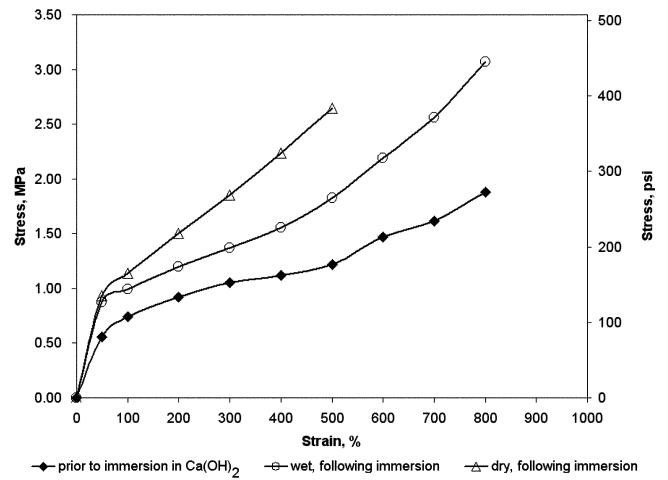


Fig. 4.1—Tensile stress-strain curves of styrene-butadiene films. (Data from work by Shah and Frondistou-Yannas [1972].)

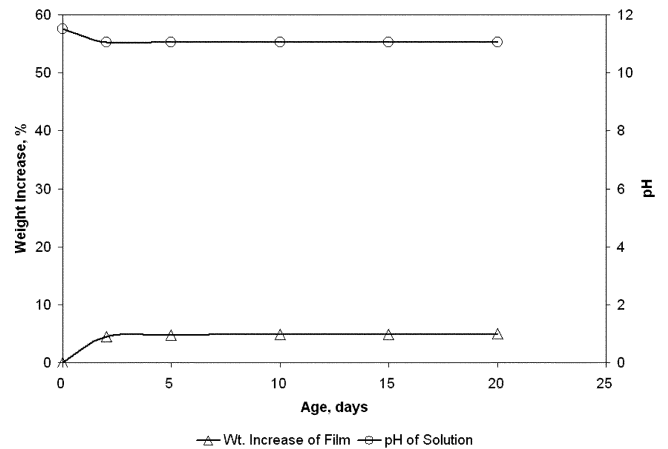


Fig. 4.2—Effects of immersion in lime solution on styrene-butadiene films. (Data from work by Shah and Frondistou-Yannas [1972].)

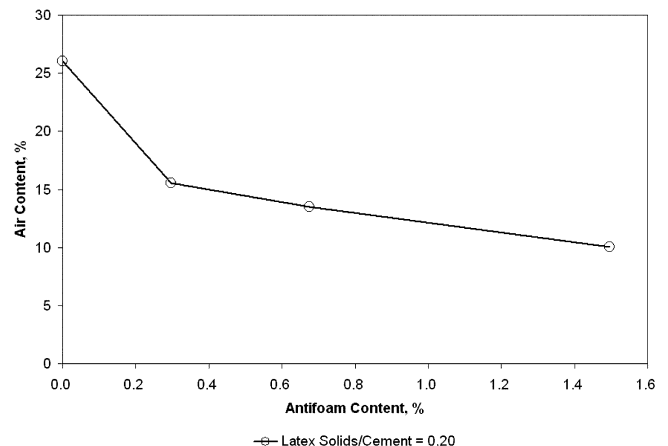


Fig. 4.3—Antifoam content versus mortar air content. (Data from work by Ohama [1973].)

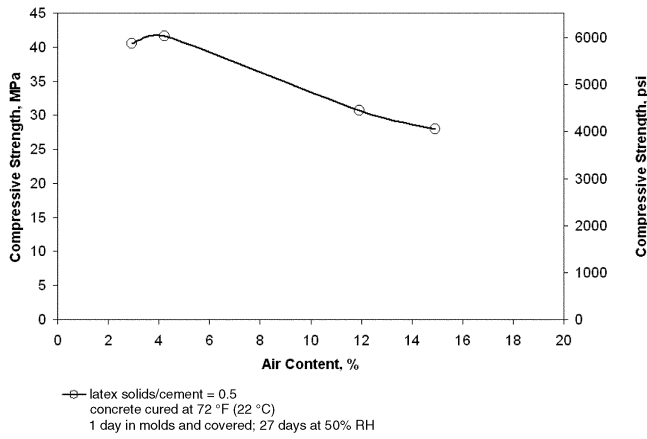


Fig. 4.4—Air content of styrene-butadiene LMC versus compressive strength. (Data from work by Kuhlmann and Foor [1984].)

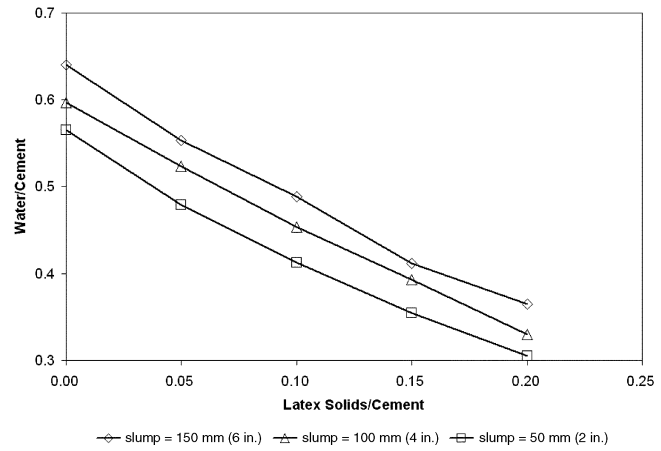


Fig. 4.6—Effect of styrene-butadiene latex content on w/c to maintain a constant slump. (Data from work by Ohama [1995a].)

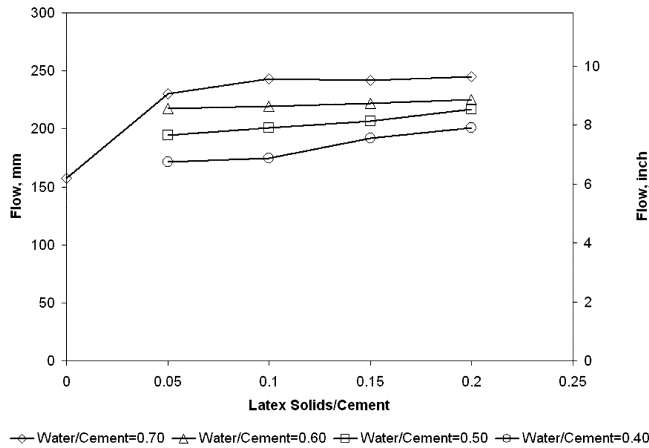


Fig. 4.5—Workability of styrene-butadiene latex-modified mortar. (Data from work by Ohama [1973].)

The relationship between air content and antifoam agent content is a function of the specific latex, in particular, the level and type of its surfactant system and antifoam agent used. Field experience has shown that the composition of the cement and the aggregates can affect air content, so it is important to evaluate the mixture before use. No reported work has been done to identify the components of the cement or aggregates that affect the air content. Figure 4.4 shows that the compressive strength of concrete decreases as the air content increases. The concretes of this figure were made with latexes having different antifoam agent contents.

Unlike conventional concrete, the addition of an air-entraining agent is not required in PMC for resistance to freezing and thawing. The latex provides this protection, as some air is entrained by the latex and water during the mixing process. ACI 548.4 has a maximum air content of 6.5%, but not a minimum. LMC does not have the air-void system necessary to pass ASTM C666/C666M (temperature range of +4 to -18 °C [40 to 0 °F]); however, more than 30 years of experience has shown that resistance to freezing and thawing is not a problem with LMC for reasons discussed previously. This can be attributed to the water-tight

microstructure of LMC, which blocks water passage and the polymer latex network that enables LMC to resist tensile stresses due to freezing-and-thawing cycles without being cracked. Research investigations showed LMC to have excellent resistance to freezing and thawing (Rixom and Mailvaganam 1999; Yun et al. 2004; Won et al. 2006).

4.1.3.2.2 Workability—Mortar and concrete modified with styrene-butadiene latex have improved workability compared with conventional mortar and concrete. This is due to the dispersing effect of components in the latex combined with the water, and is evident from the data shown in Fig. 4.5, where workability of latex mortar was measured using a flow table (ASTM C230/C230M). The data show that this dispersion effect is not a function of latex content. Even at the lower latex solids-cement ratio of 0.05, a LMM with a w/cm of 0.40 gave at least equal flow to that of an unmodified mortar with a w/cm of 0.70. It is clear that for all of the w/cm tested, the styrene-butadiene latex significantly improved workability.

The same properties are evident in concrete. Figure 4.6 shows the relationship between the w/cm and latex content for concretes of constant slump. Significant reductions of w/cm, without reductions in slump, can be achieved by the inclusion of latex.

Clear and Chollar (1978) reported slump loss, as shown in Fig. 4.7. In this study, the change in slump of three LMC mixtures was compared with that of a conventional concrete mixture and reported as percent of initial slump for each mixture. The test demonstrated that the loss in slump of these LMC mixtures was similar to that of the conventional concrete. Other researchers showed LMC to have a significant slump loss compared with conventional concrete (Soroushian and Tlili 1993). Recent experiments for controlling LMC rheology using SBR latex were reported by Barluenga and Hernández-Olivares (2004).

Kuhlmann and Foor (1984) demonstrated that workable concrete at low w/cm were produced using aggregates from Michigan and Maryland. Both mixtures had a latex solids-cement ratio of 0.15, fine-coarse aggregate ratio of 1.20, and

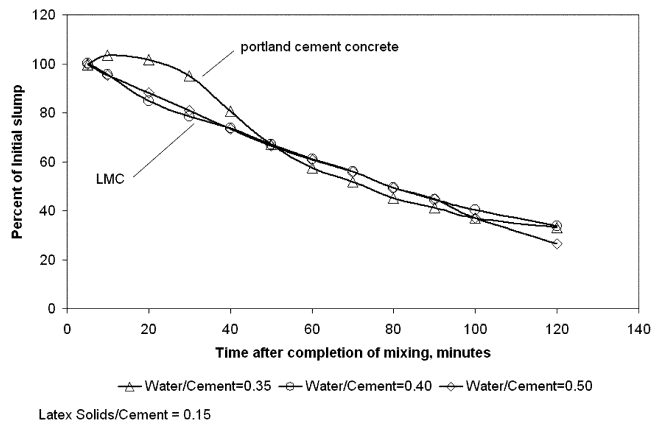


Fig. 4.7—Slump loss of concretes. (Data from work by Clear and Chollar [1978].)

a cement content of 229 kg/m^3 (14.6 lb/ft^3). The aggregate from Michigan produced a slump of 200 mm (8 in.) at a w/cm of 0.33, while the aggregate from Maryland produced a concrete with 150 mm (6 in.) slump at w/cm of 0.37. It is obvious that the workability is a function of the fine aggregate proportion and its fineness modulus.

4.1.3.2.3 Setting and working time—The setting time of concrete modified with styrene-butadiene latex has been reported to be longer than conventional concrete. Figure 4.8 contains data from two independent studies on this property (Ohama et al. 1980; Smutzer and Hockett 1981). The data show that the time of setting increases with increasing latex-cement ratios up to about 0.10, with little increase after that.

There is, however, a difference in the working time of LMC that is not related to setting time. Whereas setting time is a function of the hydration of the cement, working time is influenced by the drying of the surface. If the surface of a latex-modified mixture becomes too dry before finishing is complete, a skin or crust forms, and tears are likely to result. The time required to form this crust depends on the drying conditions, that is, air temperature, humidity, and wind speed (prevention of this phenomenon is discussed in Section 4.1.5.5). Generally, the time available to work and finish the material is 15 to 30 minutes after mixing and exposure to air. Because the maximum recommended mixing time is 5 minutes, use of transit mixers is not feasible.

4.1.3.3 Properties of hardened concrete and mortar

4.1.3.3.1 Compressive strength—The accepted curing procedure for styrene-butadiene LMC is 100% RH for the first 24 to 48 hours, followed by air curing—50% RH if in a laboratory. During this air-curing period, excess water evaporates and allows the polymer film to fully form within the internal structure. In general, PMC has lower compressive strengths than unmodified concretes with similar cement, aggregate, and water contents (Shaker et al. 1997; Rossignolo and Agnesini 2002).

Because of the influence of drying on curing of LMC, several studies were conducted on the effect of specimen size on compressive strength. Figures 4.9 and 4.10 show the results of studies by Ohama and Kan (1982) and Clear and Chollar (1978). In both studies, the influence of specimen

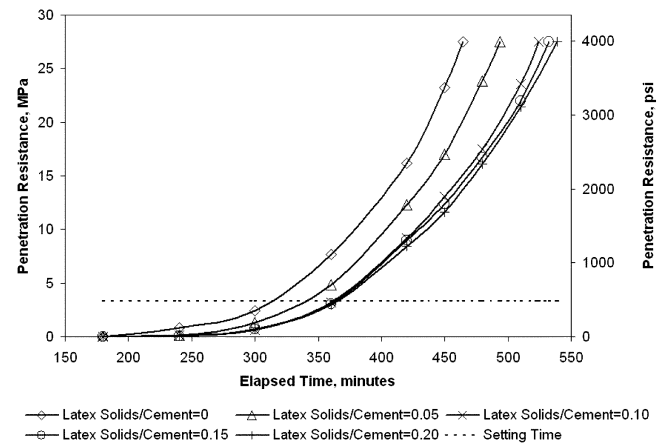


Fig. 4.8—Setting time of styrene-butadiene LMC. (Data from work by Ohama et al. [1980].)

size was considered negligible. In conventional concrete, larger specimens usually fail at lower average stress than small ones. It is postulated that the smaller-sized coarse aggregate used in LMC, together with the better binding capability of the polymer-cement matrix, provides specimens of more uniform composition, irrespective of size. This type of LMC is used for overlays with a thickness of less than 40 mm (1.6 in.). Another study by Folic and Radonjanin (1998) examined the variation of maximum compressive strain according to polymer-cement ratio. It was reported that the maximum compressive strain of LMC increases with an increasing polymer-cement ratio. This is depicted in Fig. 4.11. With continuing increases in traffic and reluctance to close lanes for repairs, use of LMC bridge deck overlays that can be opened to traffic with only 3 hours of curing has continued to increase since the overlay was first used in 1997 (Sprinkel 1999).

4.1.3.3.2 Shrinkage—The addition of latex to concrete does not increase its total shrinkage as demonstrated by Ohama and Kan (1982) who used three latex contents in concrete specimens of three different sizes. Slump was held constant by adjusting the w/cm . Shrinkage measurements after various curing times indicated that shrinkage was influenced by the water content, not the latex. The mixture proportions are given in Table 4.2 and the shrinkage results in Fig. 4.12.

In another shrinkage study, latex-modified and conventional concrete with similar w/cm were compared (Michalyshin 1983). The properties of each mixture are shown in Table 4.3, and the shrinkage results in Fig. 4.13. The experimental data show that the shrinkage of concrete does not increase with the addition of SBR latex. While drying shrinkage is reduced when latex is used, the tendency for plastic shrinkage cracking is increased.

4.1.3.3.3 Bond and tensile strength—The adhesion of styrene-butadiene-modified mortar and concrete has been proven for many years in applications such as stucco, metal coatings, and overlays on bridge decks (Sprinkel 1993, 2000). Laboratory experiments by Ohama et al. (1986),

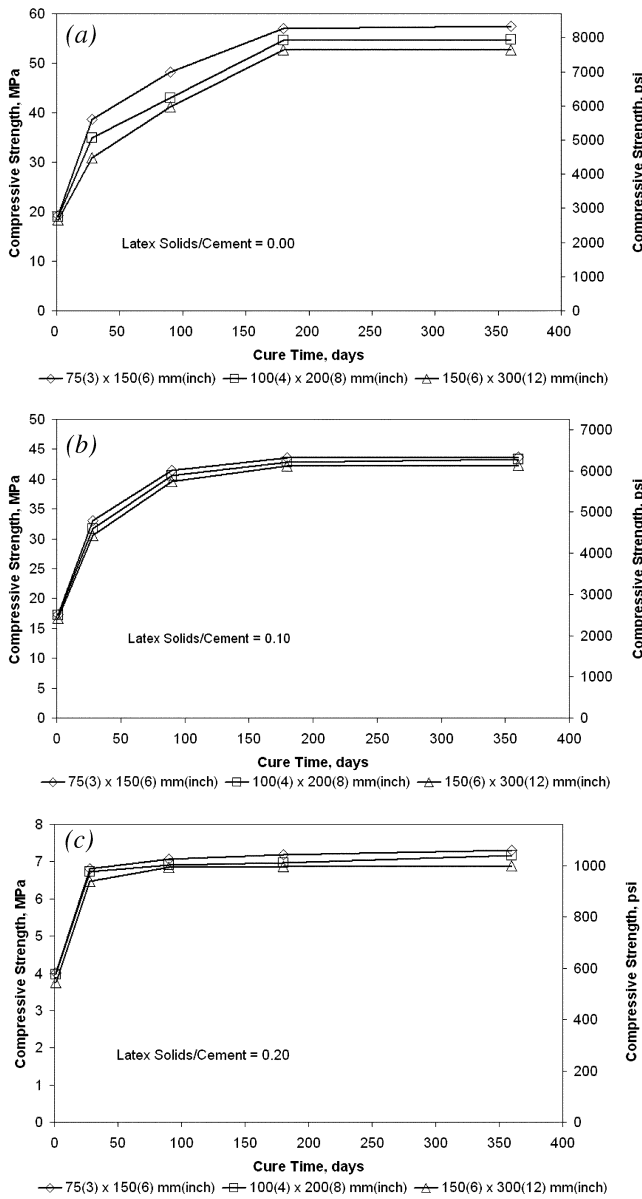


Fig. 4.9—Compressive strength versus cylinder size. (Data from work by Ohama and Kan [1982].)

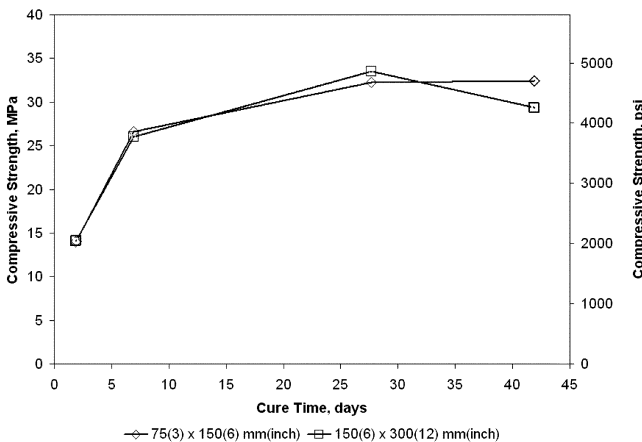


Fig. 4.10—Effect of cylinder size on compressive strength of styrene-butadiene LMC. (Data from work by Clear and Chollar [1978].)

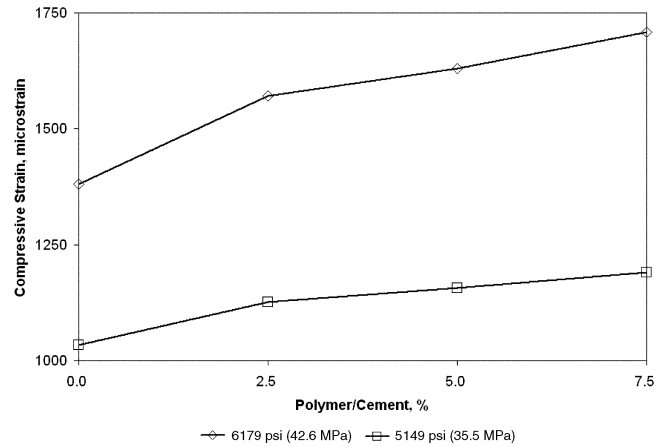


Fig. 4.11—Variation of compressive strain according to polymer-cement ratio. (Data from work by Folic and Radonjanin [1998].)

Table 4.2—Mixture proportions of concretes used in linear shrinkage study*

Type of concrete	Cement content, lb/ft ³ (kg/m ³)	Latex/cement	w/cm	Fine/coarse aggregate	Slump, in. (mm)
Unmodified	20 (300)	0	0.67	0.45	0.63 (16.0)
Latex-modified	20 (300)	0.05	0.58	0.45	0.63 (16.0)
		0.10	0.50	0.45	0.61 (15.5)
		0.20	0.41	0.45	0.63 (16.0)

*From Ohama and Kan (1982); see also Fig. 4.12.

Knab and Spring (1989), Kuhlmann (1990), and Folic and Radonjanin (1998) measured this adhesion. According to these test results, as the polymer-cement ratio increases, the bond strength increases. Some of these test results are shown in Fig. 4.14 and 4.15. In the latter, it is shown that the bond strength increases with time as well. Recent investigations by Almeida and Sichieri (2005) showed styrene-acrylic LMC to have excellent bond to existing tiles.

Another study by Ohama et al. (1986) examined mortar modified with SBR latex and tested for adhesion in tension. The specimens were tensile briquettes of conventional mortar made according to ASTM C190, cut in half, with the mortar being tested cast against the cut face.

The tensile bond strength of LMC has been measured by the tensile splitting test using halves of conventional concrete cylinders as substrate material (Pfeifer 1978). The cylinder halves were prepared by splitting 150 mm (6 in.) diameter by 300 mm (12 in.) long cylinders of conventional concrete in the axial direction. Test specimens were prepped by placing one of the halves in a mold and filling the other half of the mold with LMC. The LMC with a 0.15 latex solids-cement ratio was tested after 28 days. All six specimens failed through the aggregate at an average tensile splitting strength of 3.6 MPa (520 psi), indicating improved bond strength of the aggregate-mortar interface.

The shear bond strength of LMC has been measured frequently in the U.S. using a guillotine-type device to shear a cap of LMC off a cylinder of conventional concrete (Dow Chemical Co., 1985). The average shear strength from

Table 4.3—Mixture proportions for concrete used in linear shrinkage study*

Type of concrete	Cement	Slump, in. (mm)	WR, %	AEA, %	Air content, %	w/cm	Compressive strength, 28 days, psi (MPa)
LMC	I	5.5 (140)	—	—	5.0	0.33	6005 (41.5)
	I	7.9 (200)	—	—	4.7	0.37	5510 (38.1)
	I	9.8 (250)	—	—	3.7	0.42	5210 (36.0)
	III	3.9 (100)	—	—	4.5	0.37	7400 (51.5)
Conventional†	I	1.6 (40)	0.42	0.05	9.2	0.42	5170 (35.7)
	I	8.7 (220)	0.42	0.05	8.5	0.42	6475 (44.7)
	I	3.9 (100)	0.20	0.03	5.8	0.42	7170 (48.5)

*From Michalyshin (1983). Conventional mixtures containing a water reducer (WR) and air-entraining agent (AEA) are by mass based on cement.

†All mixtures had fine-to-coarse aggregate ratio of 1.5/1.0, and a cement factor of 658 lb/yd³ (390.2 kg/m³); latex solids to cement of latex-modified concretes ratio was 0.15.

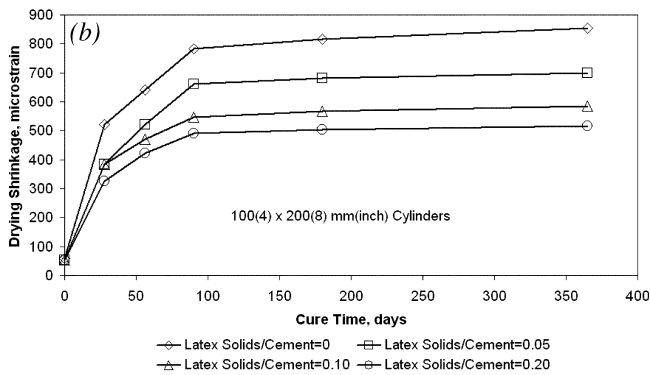
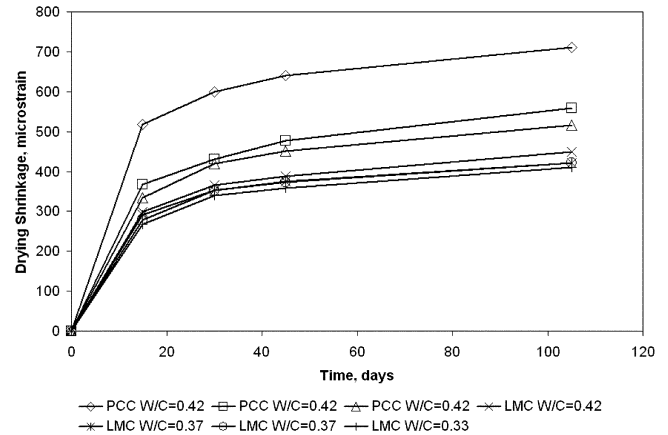
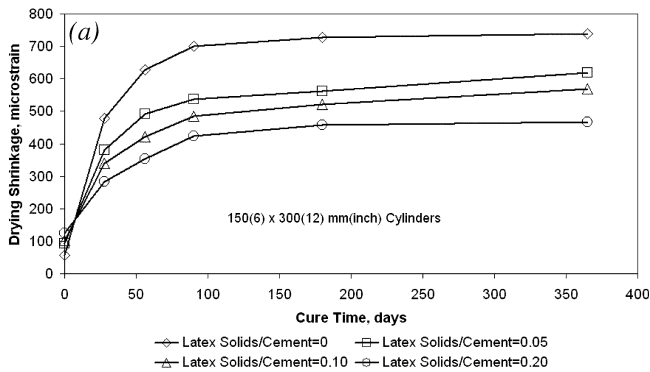


Fig. 4.13—Drying shrinkage versus time (courtesy of Dow Chemical Co.).

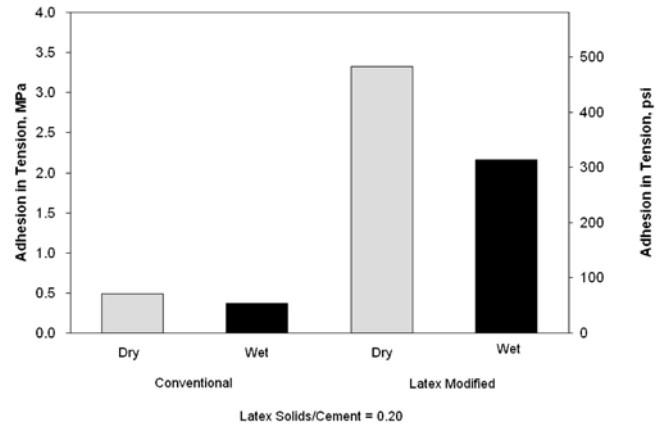
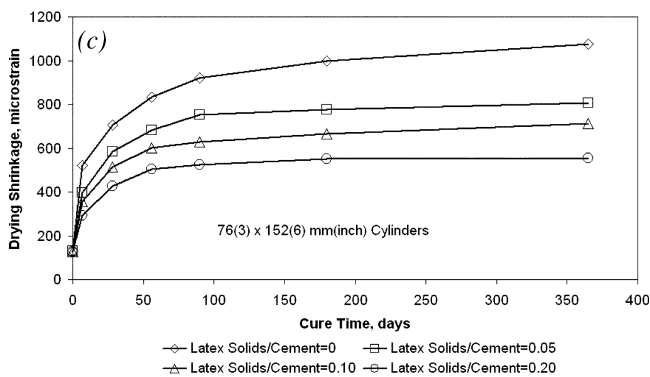


Fig. 4.12—Shrinkage versus curing time of styrene-butadiene latex-modified concrete. (Data from work by Ohama and Kan [1982].)

Fig. 4.14—Tensile bond strength of mortar. (Data from work by Kuhlmann [1990].)

experiments conducted over several years were 1.75 MPa (250 psi) at 7 days, and 3.20 MPa (460 psi) at 28 days. The LMC was made with a 0.15 latex solids-to-cement ratio and

cured 1 day at 100% RH and the remainder of time at 50% RH, all at 22 °C (72 °F) (Dow Chemical Co. 1985).

The bond of LMC to reinforcing steel has also been evaluated (Carl Walker and Associates 1982). In this study, epoxy-coated and uncoated steel bars, 460 mm (18 in.) long, were embedded 40 mm (1.6 in.) deep in a 50 mm (2 in.) thick LMC overlay, on a conventional concrete base. The results, shown in Table 4.4, indicate that the design capacity of the bars was achieved in the LMC overlays. To use the full bonding potential of latex-modified mixtures, the surface

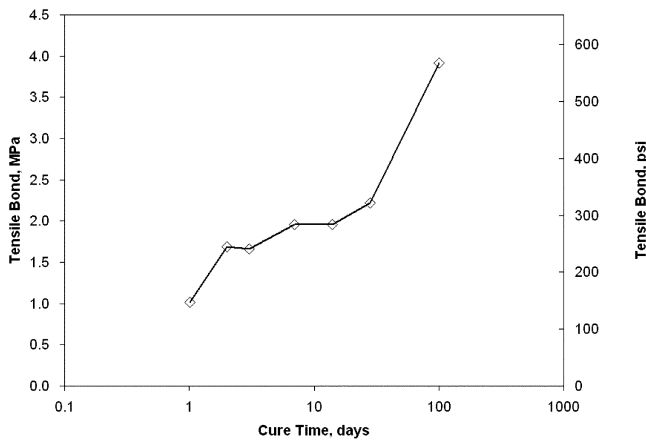


Fig. 4.15—Tensile bond strength of styrene-butadiene LMC. (Data from work by Knab and Spring [1989].)

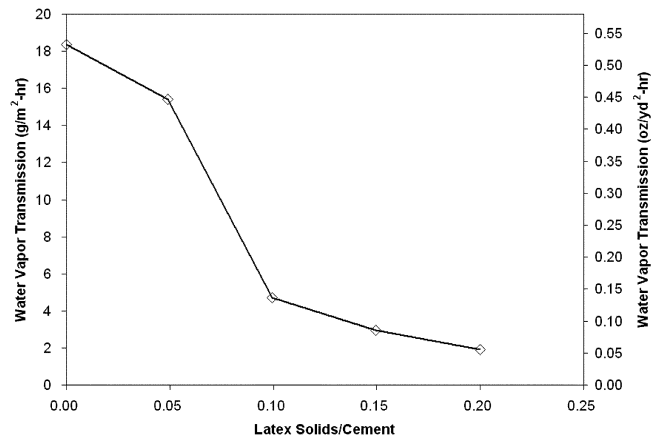


Fig. 4.18—Effect of latex/cement on water vapor transmission of styrene-butadiene LMC. (Data from work by Mori et al. [1962].)

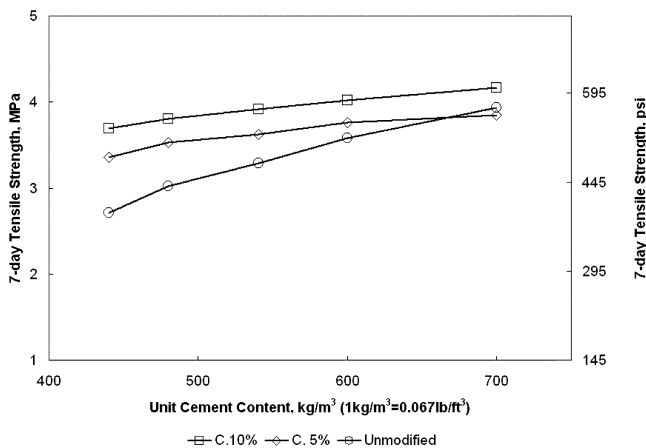


Fig. 4.16—Relation between tensile strength and unit cement ratio. (Data from work by Rossignolo and Agnesini [2002].)

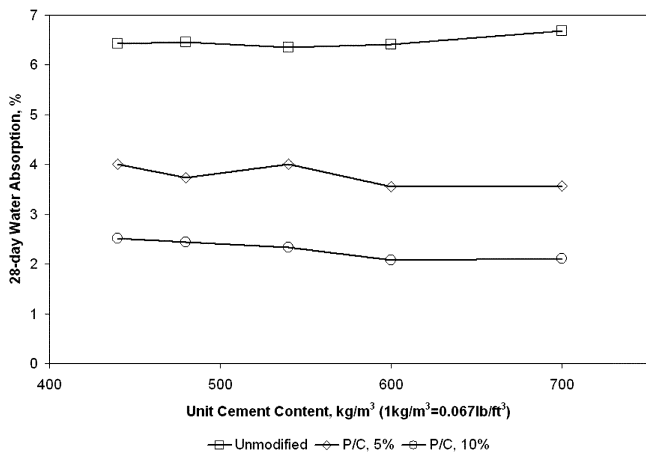


Fig. 4.17—Water absorption of styrene-butadiene latex-modified mortar with unit cement ratio. (Data from work by Rossignolo and Agnesini [2002].)

should be properly prepared. Proper techniques for surface preparation are described in Section 4.1.5.2.

The tensile strength was measured by tensile splitting test using 100 x 200 mm (4 x 8 in.) cylinder specimens (Rossignolo

Table 4.4—Test results of bond study of LMC to reinforcing steel (Carl Walker and Associates 1982)

Steel reinforcing bar	Nominal yield strength, lb*	Bar condition	Number of tests	Average of maximum applied load during test, lb*
No. 4 ($d^{\dagger} = 12.7$ mm)	12,000	Plain	8	13,000
No. 4 ($d^{\dagger} = 12.7$ mm)	12,000	Epoxy coated	8	13,700
No. 5 ($d^{\dagger} = 15.9$ mm)	18,600	Plain	4	20,000
No. 4 ($d^{\dagger} = 15.9$ mm)	18,600	Epoxy coated	7	19,800

* 1 lb = 0.453 kg.

$^{\dagger}d$ is the bar diameter.

and Agnesini 2002). The test results proved that the tensile strength of SBR LMC has improved tensile strength (Fig. 4.16).

4.1.3.3.4 Permeability—The structure of LMM and LMC is such that the micropores and voids normally occurring in hardened portland cement paste or hardened portland cement matrix are partially filled with the polymer film that forms during curing (Ohama 1973). This film is the reason for the mixture's reduced permeability and water absorption. These properties have been measured by several tests, including water-vapor transmission, water absorption, carbonation resistance, and chloride permeability. There are indications that the permeability of LMC decreases significantly beyond an age of 28 days (Kuhlmann 1984).

Results of water absorption tests (Rossignolo and Agnesini 2002) of mortar modified with SBR latex are shown in Fig. 4.17. The data show the significant reduction of water absorption of concrete containing SBR latex compared with the unmodified concrete, with an increasing improvement in absorption as latex content increases.

Water-vapor transmission of LMM has been measured (Ohama 1973) and is shown in Fig. 4.18. The effect of increasing the latex content is a decrease in water-vapor transmission.

The carbonation resistance of LMC has been studied (Ohama et al. 1984; Walters 1990) and was found to be superior to that of the unmodified control concrete. In Fig. 4.19, the white area indicates the carbonated mortar. The study

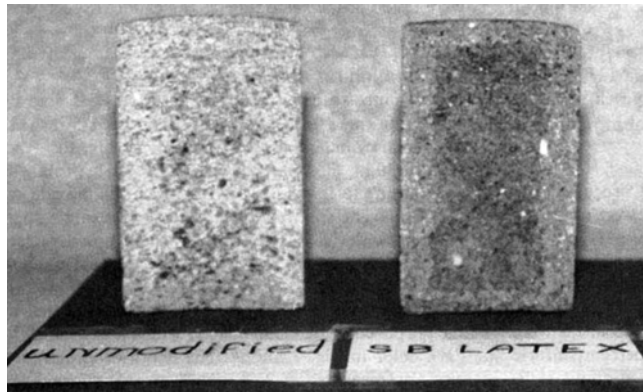


Fig. 4.19—Carbonation resistance of latex-modified mortars and unmodified mortars (Walters 1990).

Table 4.5—Average corrosion time (hours) for LMC and conventional concrete (Okba et al. 1997)

Concrete	Test age, days		
	28	56	90
Conventional concrete	48	48	50
LMC	230	245	285

included LMC exposed to carbon dioxide gas and carbon dioxide in solution (carbonic acid). After exposure, the samples were split and the cross sections tested for carbonation depth using a phenolphthalein solution. The results indicate that for both types of exposure, carbonation is significantly reduced by the inclusion of latex in the mortar (Fig. 4.20). The decrease of the compressive strength after immersion into sulfate solution for PMC and conventional concrete was measured by Shaker et al. (1997). In Fig. 4.21, it is clear that PMC shows less deterioration of compressive strength than that of conventional concrete.

The resistance to chloride ion penetration in LMC has been measured by several tests. Clear and Chollar (1978) reported on results from a 90-day ponding test. The results are shown in Fig. 4.22 and illustrate that PMC has lower permeability than conventional concrete. Okba et al. (1997) investigated the corrosion resistance of LMC using an accelerated corrosion cell. Table 4.5 shows the average corrosion time (hours) for LMC and conventional concrete. It was reported that LMC incorporating 15% SBR latex was capable of increasing the corrosion time from 48 to 230 hours (379% increase). Corrosion time was defined as the time for corrosion to be initiated. This experimental investigation confirmed that LMC has a significantly improved corrosion resistance compared with conventional concrete.

Ohama et al. (1985) conducted a soaking test in which cylinders were submerged in salt solutions for 28 and 91 days. After the cylinders were split, the penetration of chloride was measured with an indicator solution on the concrete surface. The results are shown in Fig. 4.23(a) and (b). In Fig. 4.23(a), the solution of sodium chloride was approximately the same as that of typical ocean water. Both figures indicate that

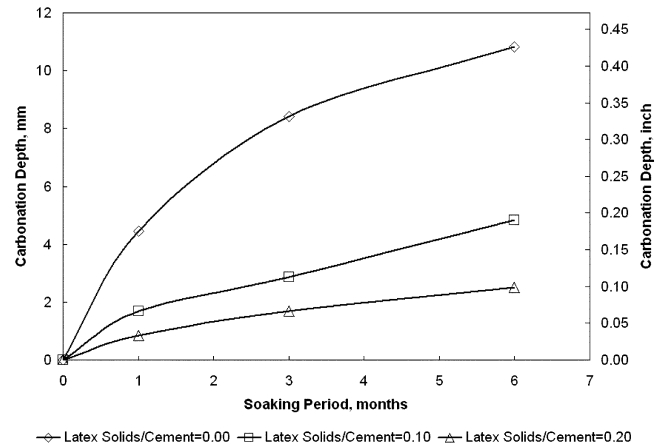


Fig. 4.20—Soaking period in sodium bicarbonate solution versus carbonation depth of styrene-butadiene LMC. (Data from work by Ohama and Miyake [1980].)

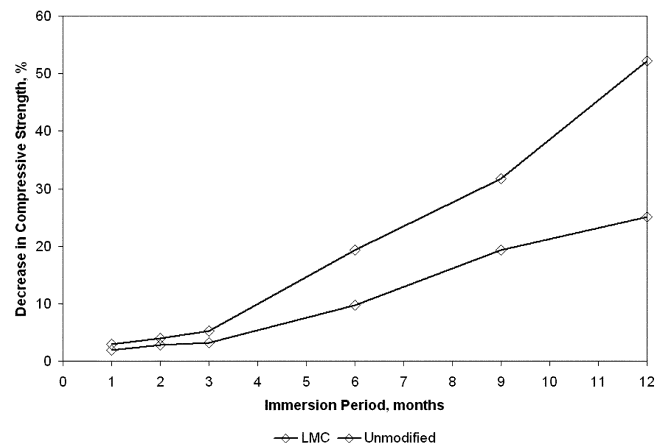


Fig. 4.21—Decrease of compressive strength after different immersion periods for LMC and conventional concrete. (Data from work by Shaker et al. [1997].)

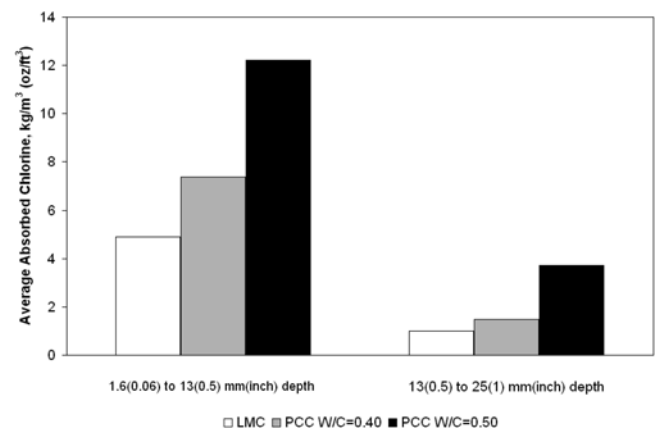


Fig. 4.22—Chloride permeability by 90-day ponding test. (Data from work by Clear and Chollar [1978].)

resistance to chloride ion penetration increases with increasing latex-cement content.

Several studies using ASTM C1202 have been conducted. Kuhlmann and Foor (1984) investigated air content versus permeability in LMC and found that even at high air contents,

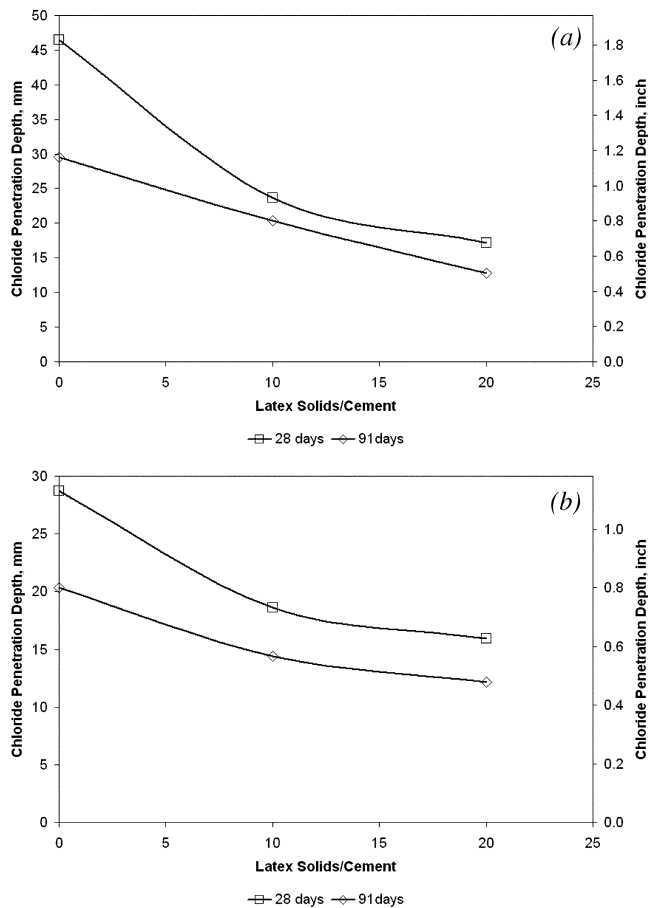


Fig. 4.23—Styrene-butadiene latex solids/cement versus chloride penetration. (Data from work by Ohama et al. [1985].)

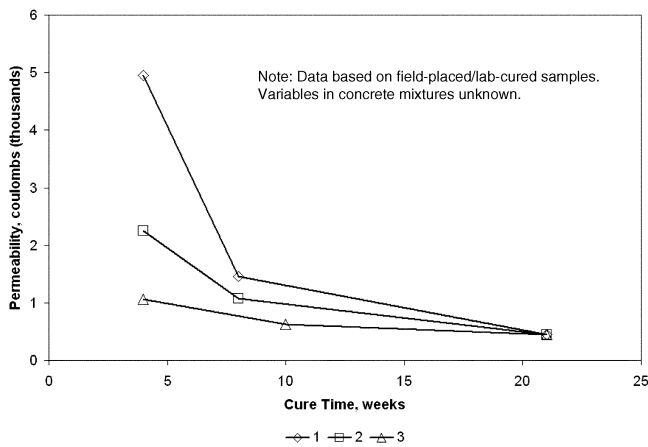


Fig. 4.24—Effect of age on permeability of field samples. (Data from work by Dow Chemical Co.)

the air voids were small and well distributed, and permeability did not increase. Table 4.6 summarizes these results.

Kuhlmann (1984) looked at the effect of time on the permeability of LMC and found that permeability was significantly reduced with time. One-hundred millimeter (4 in.) cylinders were prepared from field-placed LMC at three different locations in the U.S. using different aggregates and cement but the same specification. They were cured for the

Table 4.6—Total coulombs for experimental LMC having various air contents (Kuhlmann and Foor 1984)

Air content, %	Age, days	Total coulombs*
3.0	63	650
	69	740
4.5	28	520
	35	455
	91	240
5.6	28	935
	29	870
7.5	16	1105
	24	835
	63	530
12.0	70	780
	41	760
15.0	50	510
	35	705
	91	425

*Whiting (1981) provides the following comparisons for this test:

Chloride permeability	Charge passed, coulombs
High	4000
Moderate	2000 to 4000
Low	1000 to 2000
Very low	100 to 1000
Negligible	100

first day at 22 °C (72 °F), 100% RH, and for the remaining time at 22 °C (72 °F) and 50% RH. As shown in Fig. 4.24, even though the permeabilities of the three concrete cylinders differed significantly after 28 days, after 90 days, they all approached a similar low value. Shaker et al. (1997) showed a significant reduction of water penetration depth in LMC compared with conventional concrete (75% reduction). Water penetration depth was measured in the permeability test using concrete prisms under water pressure as per DIN 1048 (Deutsches Institut Fur Normung 1991).

Permeability data on field-placed, field-cured LMC are shown in Table 4.7 (Dow Chemical Co. 1985). The low permeability properties of LMC are evident in a variety of projects at different locations throughout the U.S. (Sprinkel 1993, 2000).

4.1.3.3.5 Resistance to freezing and thawing—The resistance of LMC to damage from freezing and thawing has been demonstrated both in the laboratory (Ohama 1995a; Smutzer and Hockett 1981) and in the field (Bishara 1979). One study (Smutzer and Hockett 1981) compared the deicer scaling resistance, according to ASTM C672/C672M, of LMC and unmodified concrete and reported, “The scaling resistance of LMC slabs at 50 cycles was excellent, with all receiving an ASTM C672/C672M rating of 0, while the air-entrained conventional concrete control block received a rating of 2. These ratings indicate no scaling and light-to-moderate scaling, respectively.” In this study, air-void determinations of the LMC, according to ASTM C457, indicated that none of the samples examined contained an

Table 4.7—Permeability of field-placed LMC (Dow Chemical Co. 1985)

Type of project	Location	Overlay		Age	Permeability, coulombs [‡]	Test by
		Date of placement	Thickness, in. ^{*†}			
Bridge	Indiana	11/83	1-3/8	5 months	524	FHWA
			1-3/4	5 months	302	FHWA
			1-7/8	5 months	346	FHWA
			1-3/8	5 months	257	FHWA
			1-1/2	5 months	214	FHWA
			1-1/4	5 months	323	FHWA
			1-3/4	5 months	285	FHWA
			1-1/2	5 months	274	FHWA
Bridge	Pennsylvania	1978	1-7/8	6 years	243	Dow
			1-7/8	6 years	215	Dow
			1-3/4	6 years	366	Dow
			1-5/8	6 years	160	Dow
			1-7/8	6 years	249	Dow
			2	6 years	104	Dow
Parking garage	Pennsylvania	Summer 1985	2	4 months	619	Dow
			2	4 months	538	Dow
Bridge	Washington	—	2	5 months	260	Dow
			2	5 months	260	Dow
Bridge	Illinois	1982	2	4 years	287	Dow
			2	4 years	277	Dow
Bridge	Illinois	1982	2	3 years	433	Dow
			2	3 years	441	Dow
Stadium	Illinois	1981	2	3 years	48	Dow
			2	3 years	65	Dow
			2	3 years	43	Dow
			2	3 years	65	Dow
			2	3 years	26	Dow
Parking garage	North Dakota	Unknown	2	2 years	397	Dow
			2	2 years	379	Dow

*All samples were 2 in. (50 mm) thick when tested; therefore, some samples contained conventional deck concrete.

†1 in. = 25.4 mm.

‡Whiting (1981) provides the following comparisons for this test:

Chloride permeability	Charge passed, coulombs
High	4000
Moderate	2000 to 4000
Low	1000 to 2000
Very low	100 to 1000
Negligible	100

adequate air-void system according to guidelines developed for durable conventional concrete by the Portland Cement Association. The properties of the air-void system are primarily of academic interest for two reasons: first, LMC is not required to meet any specification regarding air content except that it be less than 6.5% in the plastic state (ACI 548.4); and second, no durability problems related to freezing and thawing have been experienced to date with LMC.

The excellent performance of LMC is the result of the resistance of the paste to water penetration. Therefore, additional air entrainment is not required. Until the paste has been properly dry cured, however, air entrainment will improve resistance to the expansive forces of freezing. The minimum air content required for resistance to freezing and

thawing is not known. One study (Ohama and Shiroishida 1983) showed that when cured only 13 days in air and exposed to ASTM C666/C666M Procedure A, LMC with 4.5% air content did not perform as well as samples with 6.5% air content. In the field, LMC has frequently been placed during the season when freezing temperatures occurred before 28 days of curing with no apparent harm. It is theorized that the relatively dry conditions of cool weather are beneficial because LMC cures by drying.

Styrene-butadiene LMC does not perform well when tested for freezing-and-thawing resistance in accordance with ASTM C666/C666M Procedure A. (Sprinkel 2005). LMC, however, has never shown signs of freezing-and-thawing deterioration in deck overlays, even after 30 years.

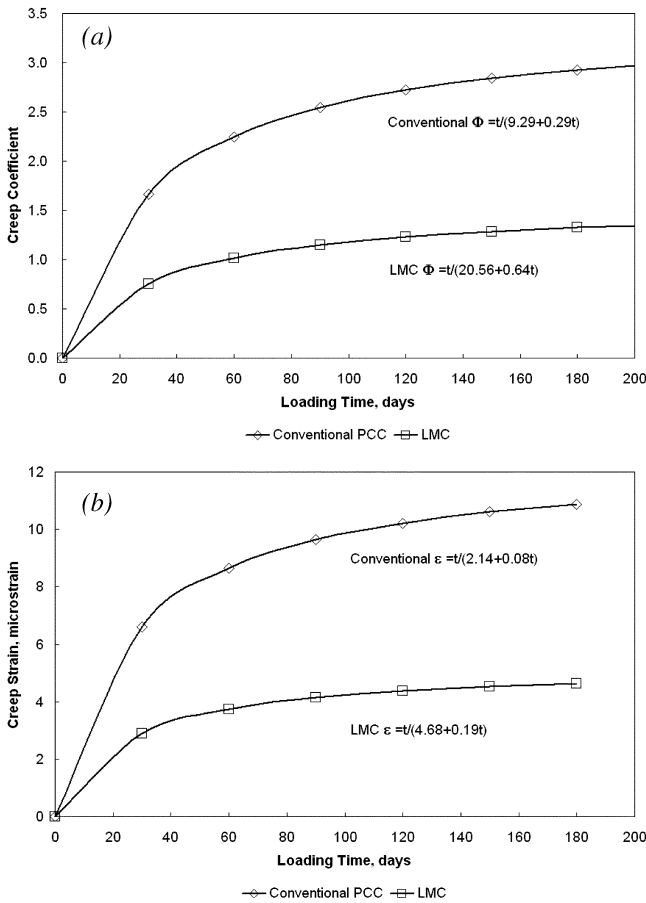


Fig. 4.25—(a) Creep coefficient (Ohama 1995a); and (b) creep strain and creep coefficient (data from work by Ohama [1995a]).

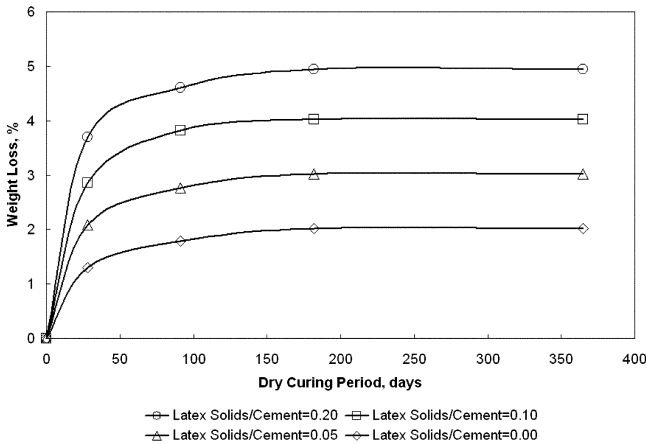


Fig. 4.26—Dry curing versus mass loss of styrene-butadiene LMC. (Data from work by Ohama and Kan [1982].)

The test should not be used to evaluate the freezing-and-thawing performance of LMC (Sprinkel and Celik 1999). Research reports confirmed the superior resistance to freezing and thawing of LMC (Rixom and Mailvaganam 1999; Yun et al. 2004; Won et al. 2006).

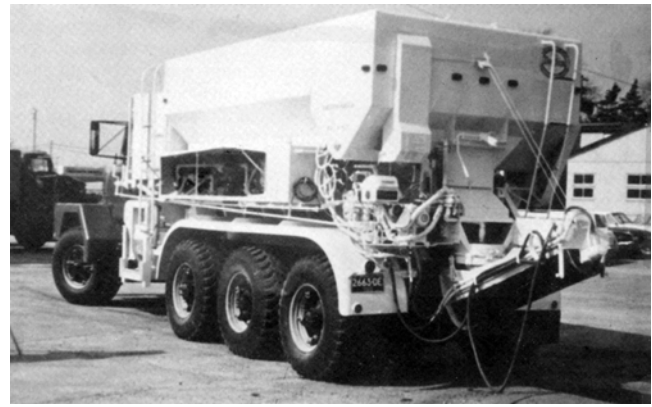


Fig. 4.27—Mobile mixer.

4.1.3.3.6 Creep—Information on the creep characteristics of LMM and LMC is limited. One study by Ohama (1995a,b) showed that both the creep strain and creep coefficient of styrene-butadiene LMC are lower than those of unmodified concrete (Fig. 4.25(a)). The work also showed that the relationship between the time t after the load is applied and creep strain ϵ_c fits the same general hyperbolic equation as that for unmodified concrete, that is, $\epsilon_c = t/(A + Bt)$, where A and B are constants.

4.1.3.3.7 Mass—Ohama and Kan (1982) reported a loss in mass with time (Fig. 4.26). Their work included concretes with varying latex contents, and showed that mass loss decreased with increased latex content.

4.1.4 Uses—SBR latex is used in a variety of applications with portland cement mixtures, ranging from concrete bridge deck overlays to thin mortar coatings on swimming pools. The properties most desired are bond strength and impermeability, although flexural strength, tensile strength, and durability are also important.

SBR latex-modified portland cement mixtures are used in tile grouts and adhesives, stuccos, pipe linings, skid-resistant coatings, floor leveling, swimming pool coatings, and patching concrete. Styrene-butadiene LMC is used primarily for overlays of bridges and parking decks, but also is used in the repair of stadiums and patching of concrete pavements.

4.1.5 Construction techniques—Construction techniques for styrene-butadiene LMC are specified in ACI 548.4.

4.1.5.1 Mixing—Most LMC is mixed in a mobile mixer (Fig. 4.27). The equipment is designed for accurate proportioning of ingredients with continuous mixing at a rate of 6 to 46 m³/h (215 to 1650 ft³/h). Job site mixing eliminates most of the problems with working time because concrete is mixed as it is needed. A mixing time of 3 to 5 minutes is recommended for LMC, depending on the mixer (ACI 548.4).

In cases such as parking garages and building repairs, LMC can be pumped, as shown in Fig. 4.28. No change in mixture proportioning is needed for pumping.

For small projects, the use of on-site drum mixers is acceptable. The size of mixed batches should be limited to ensure placement before the working time of the concrete is exceeded. The use of transit-mixing trucks should be avoided because of limits in handling the additions of latex



Fig. 4.28—Pumping LMC.



Fig. 4.29—Double roller finisher.

and water accurately at the site, the difficulty of adequately cleaning the drums, and ensuring acceptable air contents.

4.1.5.2 Surface preparation—When LMC is to be bonded to existing concrete, the proper preparation of the conventional concrete substrate is extremely important to fully develop the bonding capabilities of LMC.

Concrete slabs should be clean and have aggregate exposed. All weakened surface material, dirt, and contaminants, such as oil, should be removed. Other bond-breaking materials, such as polymer concrete and mortar, should also be removed. Cleaning may be done by mechanical scarification, chipping, hydrodemolition, sandblasting, shotblasting, or any other method suitable for concrete surface preparation. This should be followed by thorough cleaning with a vacuum, air, or water. The International Concrete Repair Institute has issued a guideline (No. 310.2) for preparation of concrete surfaces.

The prepared surface should then be thoroughly wetted for preferably 1 hour before placement; however, all standing water should be removed before placing the LMC.

4.1.5.3 Placement—Styrene-butadiene LMC does not require a separate bonding agent if the normal practice is to place some of the LMC in front of the finishing machine and manually brush the paste into the surface. If this procedure is not followed, a slurry of SBR latex and portland cement (typically 10% polymer/cement ratio) should be brushed onto the surface immediately before application. Excess aggregate is removed, and the LMC is placed before the paste has hardened or dried.

4.1.5.4 Finishing—Self-propelled roller finishers (Fig. 4.29) have proven to be the most popular method of screeding and finishing LMC on bridge decks. The auger, rollers, and vibrating pan combine to provide the proper thickness of overlay. Before placement, the finisher is calibrated to ensure that the proper thickness of LMC will be applied to the deck. A burlap drag or broom finish is accomplished by an attachment on the self-propelled finishing machine. If a grooved finish is required, a worker with a rake is positioned on a work bridge directly behind the finishing machine. In either case, the finishing operation should be completed before the surface of the LMC overlay begins to form a skin or crust.

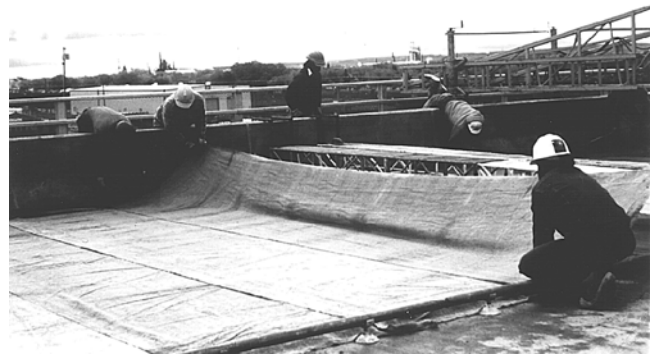


Fig. 4.30—Damp burlap being placed on LMC.

In projects such as parking garages, building floors, or projects of limited size and access, vibrating screeds or hand-operated screeds may be applicable. The limiting factor in selection of equipment is the need to complete placement, compaction, and finishing of surfaces in a continuous operation before the LMC forms a crust on the surface.

4.1.5.5 Curing—Almost immediately after the surface is textured, wet burlap or burlene is applied (Fig. 4.30), followed by white or clear polyethylene film. The intent is to keep the surface damp for 24 to 48 hours. This maintains a high enough RH at the surface of the mixture to prevent the latex from forming a skin or crust before the mixture reaches its initial set. If this skin or crust is allowed to form, the surface is likely to exhibit plastic-shrinkage cracking. The burlap should be fully wet, but not dripping, and the polyethylene film should be held down at the edges with suitable weights to prevent it from being blown off. After this initial damp period, the burlap and film should be removed to allow air curing. It is during the air-curing period that LMC gains most of its physical properties. If, after removing the burlap and film, wet weather occurs, the LMC will still develop its compressive strength, but air curing is required to reduce permeability and for full development of tensile and flexural strength. Widespread field reports indicate that failure to follow this particular curing procedure has resulted in the development of plastic-shrinkage cracking (Sprinkel 1988b).

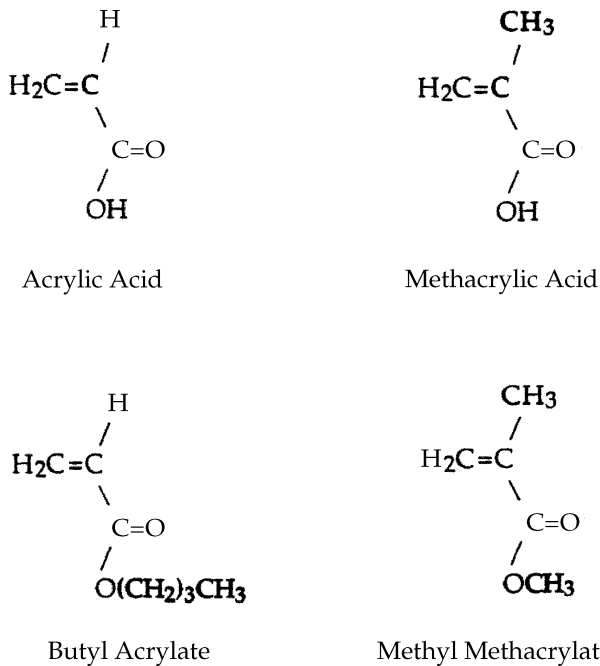


Fig. 4.31—Derivatives of acrylic and methacrylic acids.

Experimental latexes for curing (Walters 1988) have been successfully applied at several installations.

4.1.5.6 Cleanup—The latex is water-dispersible in its initial state, and cleanup of equipment is done with water immediately after use. Latex begins its set within 15 minutes after exposure to air and readily adheres to most objects and surfaces. Latex and LMC, which is allowed to accumulate due to poor housekeeping, are difficult to remove.

4.1.6 Limitations—Although it is a versatile and useful material, LMC has some limitations that should be considered.

4.1.6.1 Weather—LMC hydrates at approximately the same rate as conventional concrete. Initially, however, it will form a skin or crust on the surface if exposed to dry air for prolonged periods, even though the concrete underneath is still quite plastic. This phenomenon is caused by rapid evaporation of moisture from the surface layer, and can result in tearing during the finishing operation. This condition is aggravated by hot, dry, sunny, windy weather, and can be minimized by using the evaporation-reducing methods given in ACI 305R. A maximum evaporation rate of 0.50 kg/m²/h (0.10 lb/ft²/h) is recommended. Generally, care should be considered in placing LMC that is not dependent on working time of the concrete but rather by the time required for the polymer latex to coalesce. Generally, LMC should be placed within 30 minutes from mixing. LMC may be less sensitive to low temperatures than conventional concrete. There are some unpublished data that indicate that in 4 days at 4 °C (40 °F), LMC will gain the same compressive strength as at 22 °C (72 °F). Most state's department of transportation specifications have either adopted a 7 °C (45 °F) minimum for placing LMC or follow procedures given in ACI 306R.

4.1.6.2 Underwater—Because latex-modified systems achieve their potential properties by air curing, placement of LMC underwater is not recommended.

Table 4.8—Film properties of polymethacrylates and polyacrylates using Test Method ASTM D412 (Lavelle 1988)

	Tensile strength, psi (MPa)	Elongation, %
Polymethacrylate		
Methyl	9000 (62.1)	4
Ethyl	5000 (34.5)	7
Butyl	1000 (6.9)	230
Polyacrylates		
Methyl	1000 (6.9)	750
Ethyl	33 (0.23)	1800
Butyl	3 (0.023)	2000

4.1.6.3 Chemical resistance—LMC has demonstrated good resistance to water penetration, but only moderate chemical resistance. Generally, LMC is only suitable for low-to-moderate chemical exposure. Other materials should be considered for severe chemical exposure.

4.2—Acrylic latex

4.2.1 Background—Acrylic latexes have been used for modifying hydraulic-cement mixtures for more than 35 years. These polymers are designed to improve specific properties of cement mixtures such as adhesion, abrasion resistance, impact strength, flexural strength, and resistance to permeability.

Acrylic latex-modified portland-cement mortars retain their strength and adhesion under wet and dry conditions and their resistance to weathering and ultraviolet exposure (Mangat 1978; Lavelle 1988; Chew et al. 2004; Aggarwal et al. 2007). Aggarwal et al. (2007) compared the behavior of polymer-modified mortars using acrylic-based and epoxy-based emulsions. Acrylic latex-modified hydraulic-cement mortars are used primarily in thin coatings for concrete restoration.

4.2.2 Properties of acrylic polymers—Acrylics are defined as a family of polymers resulting from the polymerization of derivatives of acrylic and methacrylic acids, such as butyl acrylate and methyl methacrylate, respectively (Fried 2003; Erbil 2000; Amstock 2000).

An example of each type is shown in Fig. 4.31. The properties of each type are strongly influenced by various factors; however, the two critical factors are:

- Presence of CH₃, or H on the alpha carbon; and
- Length of the ester side chain.

The alpha carbon is the carbon that shares a double bond next to carbon atoms that share a double bond. An ester side chain is the grouping resulting from the reaction of an organic acid and an organic compound containing an aliphatic hydroxyl group (OH).

The acrylate polymers have more rotational freedom than methacrylates. The substitution of methyl (CH₃) for the hydrogen atom, producing a methacrylate polymer, restricts the freedom of rotation of the polymer (steric hindrance), and thus produces a harder polymer having higher tensile strength and lower elongation than the acrylate counterpart.

The length of the ester side chain group also affects the polymer's properties; as the side chain becomes longer, the

Table 4.9—Typical physical properties of acrylic latex-cement admixture (Lavelle 1982)

Appearance	White, milky liquid
Solids content, %	46.0 to 48.0
pH value, when packed	8.8 to 10.0
Specific gravity	1.06
Density, lb (kg)	8.83 (3.75)
Resistance to freezing and thawing (Rohm and Haas 1989), cycles	5
Minimum-film-formation temperature, °F (°C) (ASTM D2354)	50 to 54 (10 to 12.2)

Table 4.10—Typical formulation for acrylic latex-modified cement mortar by weight (lb)^{*} (Lavelle 1988)

Ingredient	Parts by mass
Fine aggregate	300.0
Portland cement, Type I	100.0
Acrylic latex (47% solids) [†]	21.0
Antifoam	0.1
Water	29.0
w/cm	0.4 [‡]
Aggregate-cement ratio	3.0
Polymer-cement ratio by mass	0.1

^{*}1 lb = 0.425 kg.

[†]Latex as described in Table 4.9.

[‡]Includes water in latex.

tensile strength of the polymer decreases, and elongation increases. These features are summarized in Table 4.8 for a series of acrylate polymer films showing that methacrylates have higher tensile strengths and lower elongations than the corresponding acrylate of equal side chain length. These trends continue until chain lengths of approximately 12 carbon atoms are reached. Beyond these lengths, other factors begin to influence properties. The information in Table 4.8 shows that merely describing a polymer as acrylic without providing some additional specific information does not adequately describe the polymer. Properties can vary widely within the polymer family. Because most commercially available acrylic polymers are copolymers of several monomers, a wide range of strength and flexibility can be achieved.

4.2.2.1 Polymerization—Acrylic monomers are polymerized in bulk, by solution, suspension, or emulsion polymerization, to form a latex. The modification of portland cement mixtures primarily uses emulsion-polymerized acrylic copolymers. The basic fundamentals of emulsion polymers are discussed in detail in Chapter 3, but it is worthwhile to repeat that the properties of a polymer are greatly influenced by the conditions of polymerization, such as variations in polymerization initiator level, reaction time, temperature, and monomer concentration. All of these can be adjusted to alter the molecular structure of the polymer and, consequently, the polymer properties (Chern 2008).

4.2.2.2 Typical physical properties of acrylic latex—Table 4.9 lists some properties of acrylic latex used with portland cement. Although individual acrylic latexes from various chemical manufacturers may differ somewhat, they are generally characterized as relatively high solids latexes

Table 4.11—Formulation for a sprayable textured, acrylic latex-modified cement mortar by weight (lb)^{*} (Lavelle 1988)

Ingredient	Parts by mass
White portland cement	100.0
XO limestone cement [†]	100.0
Acrylic latex (47% solids)	21.0
Antifoam	0.1 to 0.2
Water	As required
Aggregate-cement ratio	1.0
Polymer-cement ratio	0.1

^{*}1 lb = 0.425 kg.

[†]XO limestone aggregate available from Georgia Marble Co., Tate, GA:

Specific gravity: 2.71.

Particle size distribution—

Percent retained on No. 16 (1.18 mm diameter) sieve: 10

Percent passing No. 40 (425 μm diameter) sieve: 15.

Table 4.12—Typical proportioning for an acrylic latex-modified cementitious coating by weight (lb)^{*} (Lavelle 1988)

Ingredient	Parts by mass
White portland cement	100.0
XO limestone cement [†]	100.0
Acrylic latex (47% solids)	42.6
Antifoam	0.2
Water	7.5
Aggregate-cement ratio	1.0
Polymer-cement ratio	0.2
w/cm	0.3

^{*}1 lb = 0.425 kg.

[†]XO limestone aggregate available from Georgia Marble Co., Tate, GA:

Specific gravity: 2.71.

Particle size distribution—

Percent retained on No. 16 (1.18 mm diameter) sieve: 10

Percent passing No. 40 (425 μm diameter) sieve: 15.

having film formation below room temperature. They are generally supplied without an antifoam agent (Amstock 2000).

4.2.3 Proportioning and properties—Depending on the particular application, a variety of mixture proportions is possible with acrylic latexes. The formulation in Table 4.10 is typical for a mortar containing a polymer-cement ratio by mass of 0.1. Special purpose formulations are shown in Tables 4.11 and 4.12.

Higher polymer-cement ratios by mass can be used depending on the properties desired. Performance properties as a function of polymer-cement ratio by mass are covered in a later section.

4.2.3.1 Variables affecting acrylic latex-modified mortar properties—The physical properties of a latex-modified cement mortar are affected to an extent by the same variables that affect unmodified portland-cement mortars and concrete. The type of aggregate, cement, and their proportions, and the amount of water, have effects similar to those observed in unmodified cement mortars.

Most of the practices used with normal portland-cement mortar apply to acrylic LMM, but there are at least two important differences. The first applies to mortar density, and the second to curing.

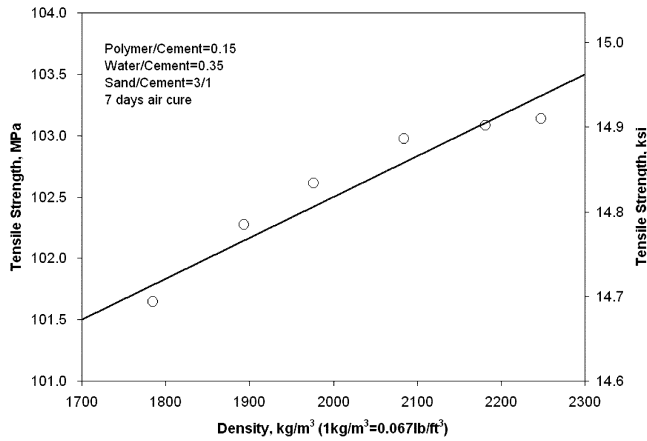


Fig. 4.32—Tensile strength versus density of acrylic latex-modified mortar.

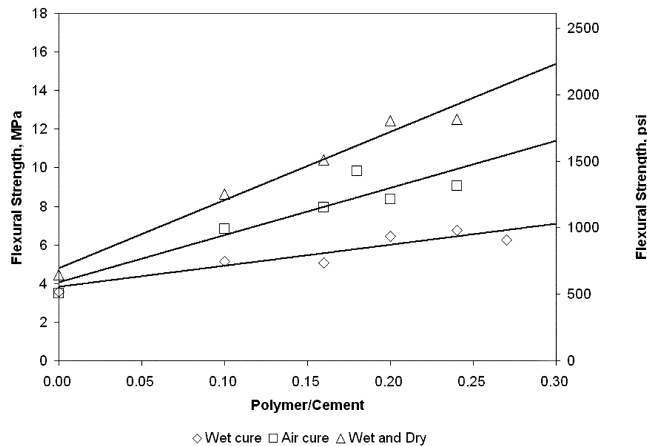


Fig. 4.33—Effect of curing conditions on flexural strength of acrylic latex-modified mortar. (Data from work by Lavelle [1988].)

4.2.3.2 Mortar density—For a given combination of materials, the maximum strength properties from a mortar are obtained by maximizing density. The use of acrylic latex entrains air and, consequently, lowers the density of the resulting mortar. An appropriate amount of antifoam agent is required to minimize air entrainment. Table 4.11 and Fig. 4.32 present the significance of mortar density on the mechanical properties of acrylic-modified mortar. It is therefore important to control the density of fresh LMM.

4.2.3.3 Curing conditions—To obtain most desirable physical properties, acrylic latex-modified mortars should be air cured. This procedure contrasts with that for unmodified mortar. The reason for this difference is that for the latex to beneficially modify the properties of the mixture, it must be allowed to coalesce and form a film. A detailed discussion of the film formation process is presented in Section 3.3. The removal of water is the key step in this film formation process. Figures 4.33 and 4.34 show flexural and tensile strength properties of acrylic LMM, wet cured (1 day at 95% RH plus 6 days immersion in water) versus air cured. The properties of the air-dried specimens are significantly higher. When latex-modified specimens that were wet-cured were

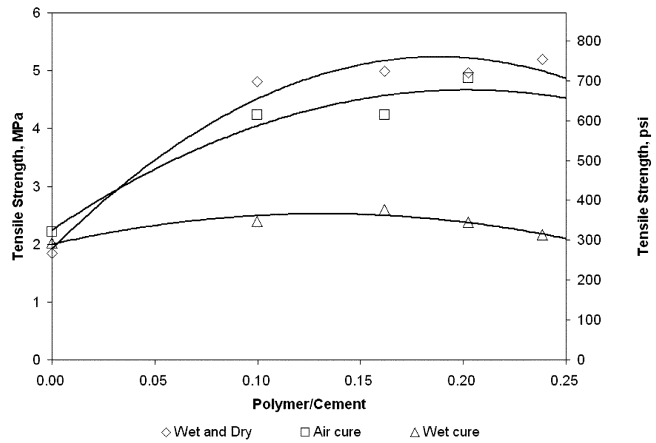


Fig. 4.34—Effect of curing conditions on tensile strength of acrylic latex-modified mortar. (Data from work by Lavelle [1988].)

eventually allowed to dry, the highest strength was achieved as illustrated in Fig. 4.33 and 4.34. As the latex is allowed to undergo proper film formation, the full potential of increasing the properties of the mortar is achieved. Subsequently, under moist curing, the strength generally increases as for conventional concrete and mortar.

While air curing is recommended for acrylic LMM, care should be taken to avoid rapid dehydration during the first 24 hours to avoid plastic-shrinkage cracking. When conditions causing high evaporation rates are experienced, appropriate measures should be taken to retard drying. Covering the mortar surface with wet burlap, straw, tarpaulin, or polyethylene helps to reduce evaporation. In cases with overlaying porous surfaces, sealing with a coat of diluted latex immediately before mortar application retards water loss from the mortar.

4.2.3.4 Strength properties—Mangat (1978) reported on the stress-strain and time-dependent acrylic LMC. Table 4.13 summarizes typical strength properties of acrylic LMM versus unmodified mortar. The data show that acrylic-latex modification improves abrasion resistance, adhesion, flexural strength, impact strength, and tensile strength (Rohm and Haas 1989). The data also show that w/cm is reduced with increasing polymer-cement ratio by mass, but Walters (1992) found that property improvement was due not only to the reduced w/cm but also to the incorporation of a polymer. Su et al. (1991) showed that the use of acrylic latex enhanced the microstructure of LMC. The ability of acrylic film to bridge concrete microcracks was shown to enhance fracture properties of LMC incorporating acrylic latex. Cao and Chung (2001) showed the ability of acrylic emulsion to improve carbon fiber dispersion in polymer-modified mortar. Chew et al. (2004) showed the significant enhancement in adhesion strength of polymer-modified mortar including styrene-acrylic copolymer. Almeida and Sichiari (2005) reported the superior adhesion strength of styrene-acrylic latex-modified mortar with porcelain stoneware tiles.

4.2.3.5 Durability—Acrylic polymers are recognized for their durability. They resist discoloration when exposed to elevated temperatures and attack by acids or bases. The backbone of the polymer is composed entirely of carbon-

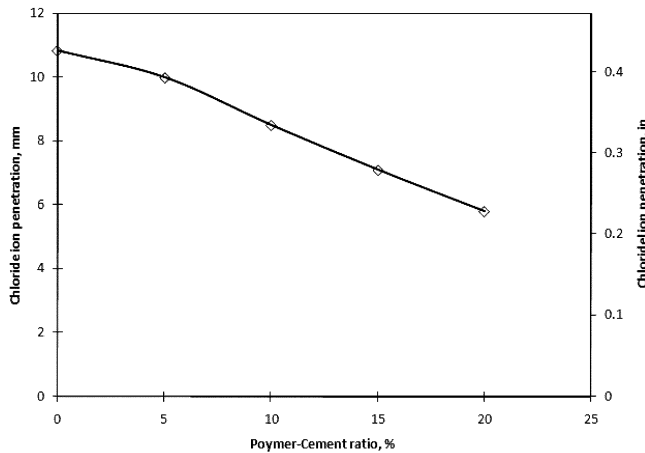


Fig. 4.35—Chloride ion penetration of acrylic latex-modified concretes at different polymer-cement ratio (Aggarwal et al. 2007).

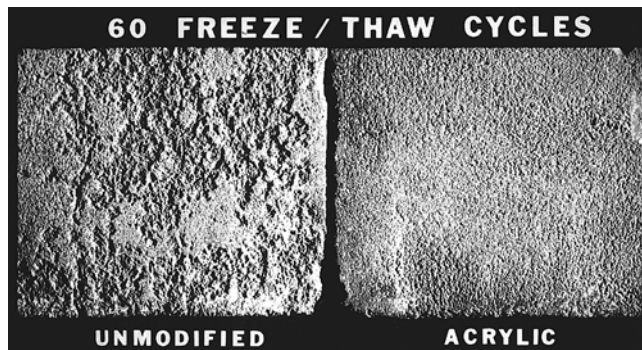


Fig. 4.36—Durability of unmodified and acrylic latex-modified portland-cement concretes exposed to freezing and thawing (Lavelle 1988).

carbon single bonds that are not susceptible to hydrolysis. Even though the ester side chains can be hydrolyzed, such action does not result in the breakdown of the polymer backbone. The rate of hydrolysis of these ester side chains is significantly less than that of an acetate group in PVA.

Cementitious mortars that require long-term durability under wet conditions can be obtained with acrylic latexes. The acrylic polymer imparts a significant degree of water resistance when exposed to wet conditions in the presence of the high alkalinity approximately pH 12) of portland cement paste. The strength and adhesion properties of acrylic latex-modified cement mortar, both dry and after total immersion in water, are summarized in Table 4.13. Studies have shown that thin cementitious coatings modified with acrylic latex maintain adhesion over many years of exposure to sunlight, rain, and snow, resulting in resistance to surface degradation, blistering, and cracking (Lavelle 1988).

Figure 4.35 shows the resistance of acrylic LMC to penetration by chloride ions as reported by Aggarwal et al. (2007). Experiments by Monteny et al. (2001) showed the superior resistance of styrene-acrylic latex-modified mortar to aggressive chemical environments. Furthermore, Bader (2003) also reported enhanced durability characteristics of LMC incorporating acrylic latex.

Table 4.13—Typical physical strength properties of portland-cement mortar versus acrylic latex-modified mortars (Lavelle 1988)

Acrylic polymer-cement ratio by mass	0.00	0.10	0.15	0.20
w/cm by mass	0.48	0.40	0.37	0.35
Wet density, lb*/U.S. gal.†	16.7	16.7	16.7	16.7
Tensile strength, psi‡ (ASTM C190)				
28 days air cure	235	530	615	855
28 days wet cure	535	—	—	—
28 days air cure + 7 days water soak	310	330	350	490
Compressive strength, psi‡ (ASTM C109/C109M)				
28 days air cure	2390	5450	5715	5690
28 days wet cure	5795	—	—	—
28 days air cure + 7 days water soak	4420	4700	5125	5460
Flexural strength, psi‡ (ASTM C348)				
28 days air cure	610	1355	1585	5690
28 days wet cure	1070	—	—	—
28 days air cure + 7 days water soak	735	950	1020	1050
Shear bond adhesion, psi‡ (Rohm and Haas 1989)				
28 days air cure	45 (A)	>500 (C)	>650 (C)	>550 (C)
28 days wet cure	185 (A)	—	—	—
28 days air cure + 7 days water soak	140 (A)	290 (C)	300 (C)	330 (C)
Impact strength, lbf-in.§ (Rohm and Haas 1989)				
28 days air cure	6	12	16	22
28 days wet cure	7	—	—	—
28 days air cure + 7 days water soak	9	11	13	18
Abrasion resistance, percent weight loss (Rohm and Haas 1989)				
28 days air cure	23.8	1.70	1.15	1.57
28 days wet cure	5.07	—	—	—

*1 lb = 0.453 kg.
 †1 U.S. gal = 0.00379 m³.
 ‡1 psi = 0.0069 MPa.
 §1 lbf-in. = 0.1128 N-m.
 Note: A = adhesive surface failure at surface of patch interface; and C = cohesive failure in substrate of test patch.

Figure 4.36 shows the surfaces of concrete blocks after 60 cycles of freezing and thawing using the ASTM C291 test method as modified by the Illinois Department of Transportation using rock salt. The acrylic LMM block (polymer-cement ratio by mass of 0.10) was marginally spalled, whereas the unmodified control block was severely pitted and eroded. These results suggest low penetration of water and salt into the acrylic LMM (Lavelle 1988).

4.2.3.6 Tensile capacity—Modification of cement mixtures with latex, as described in Table 4.9, results in increased tensile capacity of the hardened mortar and concrete. Figure 4.37 shows the flexural modulus (ASTM D790) of LMM (3/1 sand/cement after 28 days of curing) as a function of the polymer-cement ratio by mass. Figure 4.38 shows the increase in strain with respect to polymer-cement ratio by mass.

4.2.3.7 Resistance to weathering—Acrylic polymers resist discoloration because they do not absorb ultraviolet

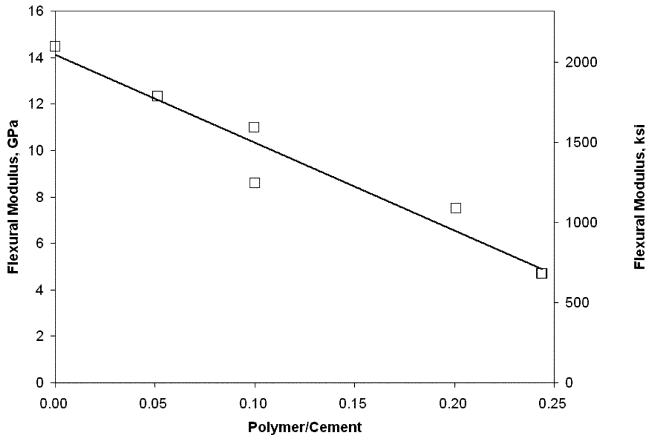


Fig. 4.37—Flexural modulus versus acrylic polymer-cement ratio of portland-cement mortars. (Data from work by Lavelle [1988].)

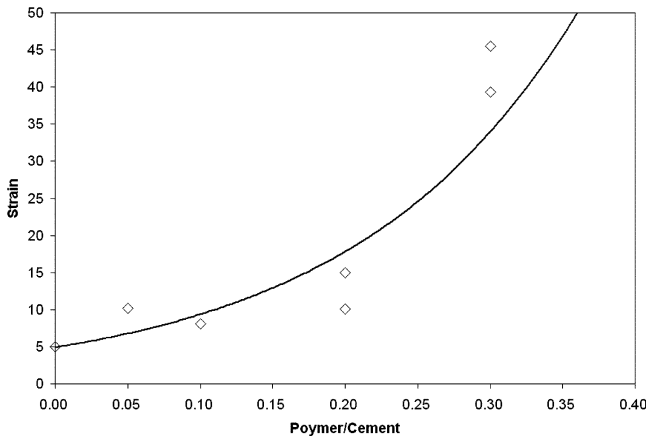


Fig. 4.38—Strain versus acrylic polymer-cement ratio of portland-cement mortars. (Data from work by Lavelle [1988].)

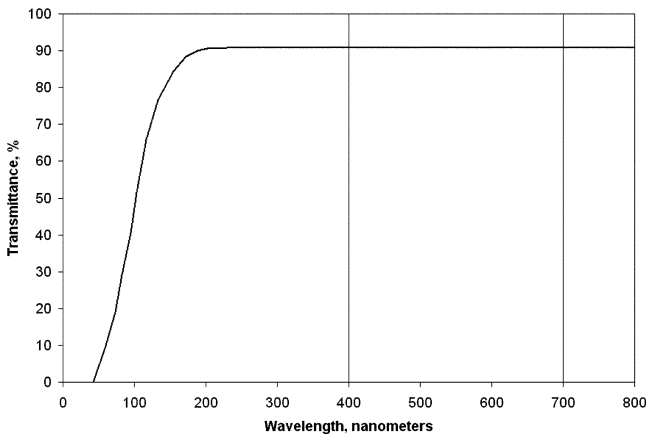


Fig. 4.39—Transmittance versus wavelength for acrylic polymer-cement mortars. (Data from work by Lavelle [1988].)

(UV) radiation and are transparent in the spectral region between 350 to 300 nanometers, the most photochemically active region of the solar spectrum. Consequently, modification of acrylics with other comonomers or polymers that absorb

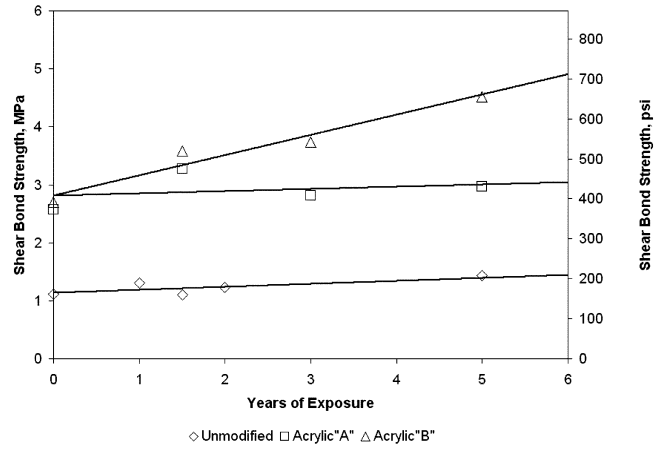


Fig. 4.40—Adhesion versus years of exposure of unmodified and acrylic latex-modified cement mortars. (Data from work by Lavelle [1988].)

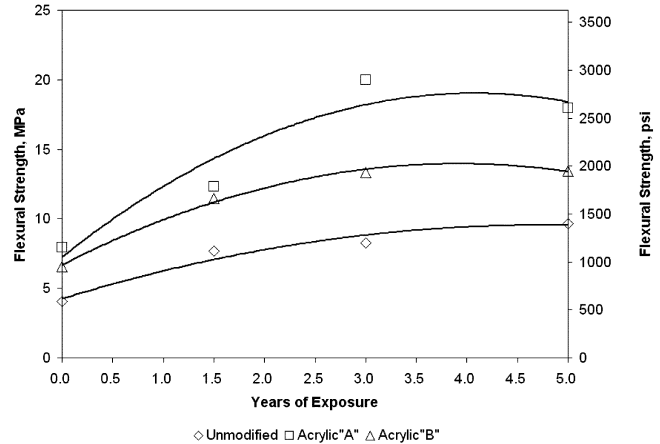


Fig. 4.41—Flexural strength versus years of exposure of unmodified and acrylic latex-modified cement mortars. (Data from work by Lavelle [1988].)

UV radiation invariably reduces the exterior durability of acrylic systems. Figure 4.39 shows that polymethyl methacrylate is essentially transparent to UV light down to the 300 nanometer wavelength range. These durability features of acrylic polymers are carried over to acrylic latex-modified cement mixtures.

A field study (Lavelle 1988) was conducted on the adhesion and flexural strength of portland-cement mortars modified with two different acrylic polymers and exposed outdoors for 5 years. These exposures were carried out in the northeastern part of the U.S. The specimens were subjected to at least 70 cycles of freezing and thawing per year and 1270 mm (50 in.) of rain per year. The results, shown in Fig. 4.40 and 4.41, indicate that adhesion and flexural strength were not degraded by exposure and actually showed some increase. In Fig. 4.41, Latexes A and B differ in monomer composition, but have similar glass-transition temperatures. All adhesion tests showed cohesive failure (failed in the concrete substrate), but adhesive failure (failed at bond line) for the unmodified mixture.

Table 4.14—Tensile strength (ASTM C190) changes of acrylic latex-modified and unmodified mortars with exposure (Lavelle 1988)

Exposure time	26 days	1 year	2 years	3 years	4 years
Polymer-cement ratio	Tensile strength, psi*				
0.00	310	655	654	643	780
0.10	665	789	780	736	867
0.15	820	1027	1092	913	1172
0.20	980	1332	1311	1122	1523

*1 psi = 0.0069 MPa.

Similar exposure studies (Mirza et al. 2002) showed that substantial improvements in tensile strength are achieved by acrylic latex modification of portland-cement mortars (Table 4.14). Mirza et al. (2002) reported satisfactory field performance of acrylic-based latex-modified mortar after 6 years in service on two operating spillways of a dam in a severe cold climate. Figure 4.42 shows an acrylic latex-modified cement coating (using white portland cement) applied to cement asbestos board and subjected to 18 years of exterior weathering in the northeastern U.S. This panel was oriented so as to face south at a 45-degree angle to the perpendicular (typical coating exposure condition), and was still intact after 18 years of weathering (Lavelle 1988). Unmodified control specimens within the series failed in the first 3 months. When the surface dirt was washed off, the coating showed no color loss and no cracking or spalling.

Pindado et al. (1999) investigated the fatigue strength of acrylic LMC using 150 x 300 mm (6 x 12 in.) cylinders loaded in compression. It was reported that the addition of acrylic polymers significantly enhanced the fatigue behavior. The test results are presented in Fig. 4.43.

4.2.4 Uses—Proper application practices should always be followed when using an acrylic LMM or LMC. For example, as in any unmodified concrete or mortar installation, the substrate should be sound. An unsound substrate continues to deteriorate regardless of the quality of the repair materials. The substrate should be prepared by removing all loose and disintegrated material. Oil, grease, or other chemicals should be removed with a detergent, and the detergent should be removed by several washings with water or mechanical means.

4.2.4.1 Flooring—Acrylic LMC and LMM are used for the repair of industrial and commercial floors that are subject to deterioration from abrasion, vibration, spillage, and aggressive conditions. The bond strength and abrasion resistance of acrylic latex-modified cement mortars produce better performance than unmodified overlays when the floors are subjected to these conditions.

4.2.4.2 Marine decks—Coatings of acrylic latex-modified portland cement mixtures have been applied to decks of ships to provide a skid-resistant and protective surface to the steel. The superior adhesion of these mixtures to steel makes them particularly applicable for this use.

4.2.4.3 Spray coatings—Cementitious coatings modified with acrylic latex have been formulated (Table 4.11) to be spray-applied over a variety of surfaces. Wood, concrete,

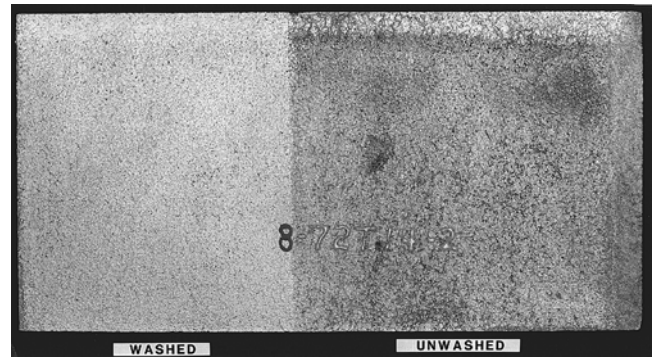


Fig. 4.42—Durability of acrylic latex-modified cement coatings (Lavelle 1988).

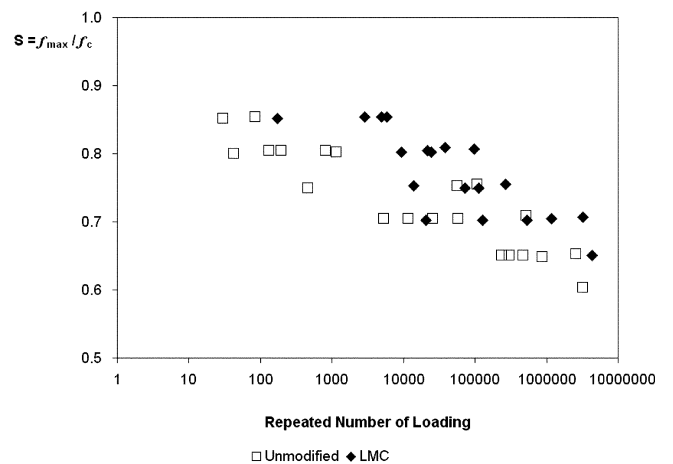


Fig. 4.43—Compressive strength after repeated load for latex-modified concrete and conventional concrete. (Data from work by Pindado et al. [1999].)

and masonry surfaces have been coated with these materials to improve appearance and performance. Because of the high adhesion property of the acrylic latex, these coatings can be relatively thin (approximately 3 mm [1/8 in.]) and still provide weather resistance and long-term performance. Figure 4.44 shows a building that was reconditioned with an exterior coating of this material while retaining the original architectural integrity.

4.2.4.4 Finish systems for exterior insulation—Acrylic latex-modified cement mixtures can also be used for exterior insulation finish systems. In this application, insulating materials, such as expanded polystyrene foam, are attached to the outside walls of buildings. The insulating material may be attached to the substrate with an acrylic latex-modified cement mixture. The insulating foam is then covered with an acrylic latex-modified cementitious layer reinforced with fiberglass scrim to provide the foam with integrity and protection from the moisture and sunlight. This base coat is normally covered with an acrylic latex-modified decorative finish. These systems offer the combined benefits of energy efficiency and enhanced appearance.

4.2.4.5 Patching—The increased strength and adhesion contributed to cement mixtures by acrylic latex modification are particularly beneficial in concrete patching applications.

Figure 4.45 shows where spalled concrete was restored with an acrylic latex-modified cement patching compound that had a 0.1 polymer-cement ratio by mass. First and second coats were brushed and then floated to a sand finish. The entire area was top-coated with a pigmented acrylic latex-modified cement mixture for top finishing. More information on LMC placement and patching can be found in ACI 548.4.

4.2.4.6 Basement waterproofing—Basement waterproofing represents another application for acrylic latex-cement coatings. Acrylic latex-cement coatings (Table 4.12)



Fig. 4.44—Sprayed acrylic latex-modified cement coatings.

offer important features such as ease of application (brush or spray) and cleanup, low odor, and nonflammability.

In a laboratory procedure used to test the waterproofing properties of latex/cement paints, two coats of the material are applied to a specified hollow concrete block that, after curing 7 days, is filled with water. An external pressure of 0.3 MPa (43 psi) is applied to the water in the block (equals approximate hydrostatic pressure on a basement wall 2 m (6.7 ft) below ground level) and maintained for a fixed time, then loss of adhesion, softening of the coating, and pressure drop are recorded. The apparatus is shown in Fig. 4.46. A comparison of an unmodified commercial coating versus an acrylic latex-modified coating for resistance to hydrostatic pressure is presented in Table 4.15.

4.3—Epoxy polymer modifiers

4.3.1 Background—The production of PMC using epoxy resins differs from other types of polymer-modified mixtures in that the polymer is formed after the components of the epoxy are added to the hydraulic-cement mixture. Polymerization occurs concurrently with the hydration of the cement. As mentioned in Chapter 1, the first use of epoxy resins to modify hydraulic cement was reported by Lezy and Paillere (1967).

The incorporation of the epoxy components does not require significant changes in the process technology. The advantages of epoxy modification are similar to those of other polymers, including increases in flexural strength,

Table 4.15—Summary of performance properties of an acrylic latex-modified cementitious waterproofing paint*

Sample identification	Weight, lb/gal.†	Coverage, ft ² /gal.‡	Coating properties	Water resistance§
Commercial waterproof cement paint	11.7	130	Chalky; surface cracking upon curing	Fail
Acrylic latex-modified cementitious waterproof paint	17.5	75	No defects	Pass

*Versus commercial basement waterproofing coatings (Lavelle 1988).

†1 lb/gal. = 0.112 kg/L.

‡1 ft²/gal. = 0.028 m²/L.

§Federal Specification TTP-00141.



Fig. 4.45—Spalled concrete restored with an acrylic latex-modified patching mortar.

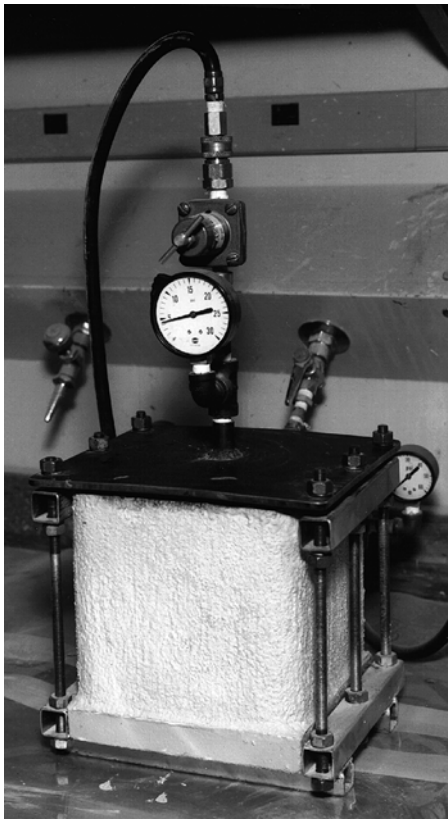


Fig. 4.46—Acrylic latex-modified cement coating resistance to hydrostatic pressure (Lavelle 1988).

tensile strength, and adhesion, with reductions in modulus of elasticity and permeability compared with unmodified hydraulic cement concretes and mortars (ACI Committee 548 1973, 1978, 1985, 1987; Schulz 1984).

4.3.2 Properties of epoxies

4.3.2.1 Characteristics of epoxy modifiers—Epoxies used to modify hydraulic cement are formulated to polymerize between 10 °C and 30 °C (50 °F and 86 °F) in a highly alkaline environment. The components have the following characteristics:

- Dispersible in water;
- Reduce the degree of hydration of cement;
- Available as liquids with no volatile solvents;
- Do not generate by-products during curing;
- Have low shrinkage after curing; and
- Resistant to weathering, moisture, common organic acids, and alkalis after curing.

Epoxy-resin systems for cement modification contain dispersing agents, and are used in emulsified form or are capable of forming emulsions when mixed with water. The modifier is supplied as a two-part system—one containing the epoxy resin, and the other containing the hardener or curing agent. Typical properties of uncured epoxies are presented in Table 4.16. When the two parts are mixed, the resin combines with the hardener to form the polymer (Popovics 1993).

4.3.2.2 Chemistry of epoxy resins—Most epoxy resins are synthesized by combining one molecule of bisphenol (derived from acetone and phenol) with two molecules of epichlorohydrin. This process forms the epoxy resin

Table 4.16—Typical properties of uncured epoxy (Celanese Coatings Co. 1972)

Property	Component A (resin)	Component B (hardener)	Mixed system*
Viscosity at 77 °F (25 °C), ASTM D445, cps [†]	3600	700	2000
Weight per gal., ASTM D1475, lb [‡]	9.65	8.20	9.20
Specific gravity	1.15	0.98	1.10
Color (Gardner Holt), ASTM D1544	3	12	10
Molecular weight per epoxide	200	—	—
Amine content [§]	—	500 to 550	—
Storage stability, year	>1	>1	

*Combined in ratio of 100 parts A and 35 parts B by mass.

[†]1 cps = 0.001 Pa·s.

[‡]1 lb = 0.425 kg.

[§]Milligrams (1 mg = 2.2 × 10⁻⁶ lb) of potassium hydroxide equivalent in 1 g (2.206 × 10⁻³ lb) of hardener.

Table 4.17—Typical properties* of undiluted cured epoxy

Tensile strength, psi (MPa)	9200 (63.5)
Tensile elongation, %	4
Flexural strength, psi (MPa)	14,100 (97.3)
Flexural modulus, psi (MPa)	0.46 × 10 ⁶ (3174)
Izod impact strength, ft-lb/in. notch	0.51
Compressive yield strength, psi (MPa)	12,600 (87)
Percent mass change	
24 hours in water	0.20
24 hours in 5% aqueous acetic acid	0.81

*Properties determined on 1/8 in. (3.2 mm)-thick casting cured for 2 weeks at 77 °F (25 °C).

component, which contains both epoxide and hydroxyl functional groups. In polymerization, the resin molecules chemically react with a hardener to form the polymer. The hardener commonly contains amine groups that react with the epoxide group (Petrie 2005).

When the epoxy and hardener are combined in optimum proportions (usually stoichiometric amounts), the cured epoxy will have a high softening point with a heat deflection temperature of greater than 100 °C (212 °F), using ASTM D648, and a balance of strength properties. Epoxy curing or polymerization is irreversible. The polymer is thermosetting, and will soften when heated above 90 °C (194 °F), but will not liquefy. The properties of a polymerized epoxy are largely dependent on the functionality of the monomer molecule, that is, the density of its crosslinking sites, and the degree of polymerization (Fried 2003).

4.3.2.3 Properties of epoxy resins—Methods for measuring the general properties of an epoxy resin have been specified in standards (Schutz 1982; Okada and Ohama 1984). Viscosities and suggested mixing rates vary with the manufacture of the epoxy resin. Typical properties of the cured epoxy resins are summarized in Table 4.17.

4.3.3 Principle of epoxy modification—The principle of epoxy modification of a hydraulic-cement mixture is similar to, although not identical to, that described in Section 3.3.

Table 4.18—Typical mixture proportioning of epoxy-modified concrete by weight in lb*

Ingredient	Parts by mass
Portland cement	100.0
Fine aggregate	275.0
Coarse aggregate	200.0
Water	42.0
Epoxy resin (Part A)	17.4
Epoxy hardener (Part B)	2.6

*1 lb = 0.453 kg.

Two processes are involved that occur simultaneously: cement hydration and polymerization of the epoxy system.

The two-part system contains a surfactant, such as a salt of abietic acid, which disperses the epoxy-resin throughout the cement mixture, and an antifoam agent to prevent excessive entrainment of air.

The epoxy-resin system is added to the fresh concrete in liquid form, either premixed or as separate components, near the end of the mixing of the concrete. As the epoxy polymerizes, the small spherical particles that form in the hardening cement paste are interconnected with thin epoxy layers, giving an irregular but coherent three-dimensional network interwoven throughout the cement paste, as can be seen in scanning electron microscope pictures (Conrad 1984; Schwarz 1984). This network acts as a secondary cementing mechanism and contributes to the increased flexural strength, tensile strength, abrasion resistance, and decreased permeability of the modified system. It also coats the surfaces of the interstitial voids (Boue and Kwasny 1984). The internal structure is similar to that of a styrene-butadiene LMC (Fig. 3.2).

Popovics and Tamas (1978) have shown that the addition of epoxy to portland cement mixtures produces a decrease in the degree of hydration of the cement, probably due to coating the cement particles and reducing their contact with water. There is no indication of a chemical reaction between the epoxy-resin system and components of the portland cement, although the cement may influence the cure of the epoxy. A method for checking the effect of the epoxy system on the hydration of portland cement is silylation (Popovics and Tamas 1978). Investigations by Ohama et al. (2004) on using epoxy resin without a hardener to modify portland-cement mortars showed the ability of the hydrations products to harden the unhardened epoxy resin when microcracks in the mortar take place. It was suggested that epoxy resin without a hardener might be used for applications requiring enhanced fracture toughness while prone to microcracking.

4.3.4 Mixture proportioning—The mixture proportioning of epoxy-modified concrete is similar to that of other polymer-modified concretes, and should be based on the requirements of the specific application. The usual dosage varies from ratios of 0.10 to 0.20 by mass. The use of higher levels is uneconomical for the benefits obtained. An epoxy-modified concrete mixture requires less mixing water for the same slump as a comparable unmodified mixture and is easier to consolidate. The amount of mixing water needed in

a given case should be determined by trial mixtures. It is important to note that, similar to polymer-modified concrete, air entrainment is not required to provide resistance to freezing and thawing for epoxy-modified concrete.

Epoxy-modified concrete may contain chemical admixtures or pozzolans. The use of such admixtures should be based on trial mixtures. The addition of fly ash and silica fume were reported to increase the strengths of epoxy-modified concrete (Popovics 1985). Generally, high cement contents are used in epoxy-modified concrete, with typical mixture proportioning given in Table 4.18. Curing of epoxy-modified concretes and mortars is similar to that of other polymer-modified materials (Section 4.1.5.5).

4.3.5 Properties of epoxy-modified concrete—There are no American standard methods for testing epoxy-modified concrete and mortar. ASTM International is in the process of creating such methods. Japan has standards for preparing specimens and measuring properties. These are usually modifications of standards for unmodified cement concrete and mortar. Therefore, most of the experiments reported below by different researchers are based on standards for unmodified concrete and mortar or polymer-modified concrete and mortar standards (for example, ASTM C1439).

4.3.5.1 Properties of fresh epoxy-modified mortar and concrete—Compared with unmodified conventional concrete mixtures, epoxy-modified concrete may be expected to increase workability and setting times, and to reduce segregation and bleeding.

4.3.5.2 Properties of hardened epoxy-modified mortar and concrete

4.3.5.2.1 Compressive strength—The compressive strength of epoxy-modified concrete is not significantly different from that of properly cured, unmodified concrete at a similar *w/cm*. It can be higher when the slump is kept constant due to the water-reduction effect of the surfactant that is in the epoxy system.

4.3.5.2.2 Flexural and tensile strengths—Epoxy modification increases flexural and tensile strengths compared with similar unmodified mixtures by as much as 100%. Typical values determined by Popovics (1974) are given in Table 4.19. Others have reported similar increases (Kreijger 1968; Popovics 1975; Conrad 1984).

4.3.5.2.3 Other properties—The modulus of elasticity of an epoxy-modified concrete is less than that of similar unmodified mixtures, even if the epoxy-modified concrete has higher strength (Table 4.19). The ductility of epoxy-modified systems is also higher (Raff and Austin 1973; Nawy et al. 1977; Rahal and El-Hawary 2002a). According to the results of test performed by Rahal and El-Hawary (2002b), the shear strength of epoxy-modified concrete is higher than conventional concrete at the same compressive strength.

Epoxy modification reduces permeability and chloride ion penetration (Conrad 1984; Marusin 1987; Perenchio and Marusin 1983; Pfeifer and Perenchio 1984).

Shrinkage is reduced by epoxy modification. Under air-drying conditions of 20 °C (68 °F) and 60% RH, shrinkage reduction of up to 40% was reported at the end of 28 days (Lezy and Paturel 1967; Valenta and Kucera 1970). Bader

(2003) reported the superior performance of epoxy-modified concrete compared with conventional concrete when used in aggressive environments with highly concentrated chloride and sulfate contents.

Resistance to freezing and thawing is increased by epoxy modification. Lezy and Pailere (1967) found that the strength of epoxy-modified mortars remained unchanged after 50 cycles of freezing and thawing, whereas the strength of the control specimens was reduced by 30 to 40%.

Table 4.19 shows that salt scaling resistance, acid resistance, and wear resistance of epoxy-modified concrete is superior to those of similar unmodified mixtures. Hinsche (1984) reported significant improvement in chemical resistance of epoxy-modified mortar.

4.3.6 Safety—The materials should be handled in accordance with guidelines provided by the supplier in Material Safety Data Sheets, ACI 506R, and other literature (Fowler et al. 1978). Users of epoxy systems have reported skin irritation and sensitization (ACI 548.1R).

4.3.7 Uses—Epoxy-modified mortar and concrete are used in applications where adhesion, low permeability, or both, are required. These applications include: grouts, stuccos, liners, protective coatings, skid-resistant coatings, and the repair of concrete structures including overlays for bridges and parking decks.

4.3.8 Construction techniques

4.3.8.1 Materials—Specifically formulated epoxy systems for cement modification should be used. Inexperienced contractors are advised not to attempt to make such formulations.

4.3.8.2 Surface preparation—The same techniques used to prepare concrete surfaces in Section 4.1.5.2 should be used for epoxy-modified concrete.

4.3.8.3 Mixing procedures—The recommended procedure is to mix the two parts of the epoxy system in a separate container to form the epoxy emulsion. The components should be stirred, preferably mechanically, until uniformly mixed, and set aside. Then the cement, aggregates, and half of the water should be loaded into the concrete mixer and blended. The premixed epoxy systems should be added along with the remainder of the mixture water and thoroughly mixed, which usually takes 2 to 5 minutes. Overmixing can cause excessive air entrapment, and should be avoided.

4.3.8.4 Placement, finishing, and curing—These procedures are similar to those described in Sections 4.1.5.3, 4.1.5.4, and 4.1.5.5, respectively.

4.3.8.5 Cleanup—Water will effectively clean mixers and tools unless the epoxy binder has partially reacted. All unreacted binder can usually be dissolved in glycol ether. Cleaning of the fully reacted epoxy is difficult, and procedures recommended by the manufacturer should be followed.

4.3.8.6 Quality control—Most common test procedures for quality control of concrete, such as slump, air content, and compressive strength, are applicable to epoxy-modified concrete after allowing for differences in mixing and curing.

4.4—Redispersible polymer powders

4.4.1 Background—This chapter discusses polymers in powder form that are used to modify hydraulic cement

Table 4.19—Comparison of strength properties of epoxy-modified and conventional concrete (Popovics 1974)

	Epoxy-modified [†]	Unmodified [†]
Tensile strength, psi (MPa)		
Dry	820 (5.66)	440 (30.36)
Wet [‡]	730 (5.03)	460 (3.17)
Flexural strength, psi (MPa)		
Dry	1650 (11.39)	850 (5.87)
Wet [‡]	1620 (11.18)	860 (5.93)
Compressive strength, psi (MPa)		
Dry	7500 (51.75)	5500 (37.95)
Wet [‡]	7000 (48.30)	6100 (42.09)
Modulus of elasticity, psi (MPa)	2.7×10^6 (18,630)	3.1×10^6 (21,390)
Coefficient of linear thermal expansion, in./in./°F (mm/mm/°C)	8.0×10^{-6} (14.4×10^{-6})	6.0×10^{-6} (10.8×10^{-6})
Salt scaling resistance		
20 cycles	Pass	Fail
50 cycles	Pass	N/A
Acid resistance, 15% hydrochloric	Some effervescence	Complete disintegration
Wear resistance, [§] passes for 3/8 in. (9.5 mm) of wear	7700	2400

^{*}Of similar w/cm, and fine and coarse aggregate-cement ratios.

[†]Epoxy-modified concrete cured for 28 days at 77 °F (25 °C) and 50% RH. Unmodified cured for 28 days at 77 °F (25 °C) and 95% RH.

[‡]After an additional 28 days in water at 77 °F (25 °C).

[§]A loaded 1-5/8 in. (40 mm)-wide steel wheel with total mass of 400 lb (181 kg).

mixtures. Such powders are referred to as redispersible in that they convert to latex on mixing with water.

Like latexes, these polymers are made by emulsion polymerization, and the resultant latex is converted to powder form, usually by a process known as spray drying. Currently, the commercially available redispersible powders are vinyl acetate homopolymers, vinyl acetate copolymers, and acrylic copolymers.

These powders impart similar properties to hydraulic-cement mixtures, and are used for similar applications as their latex counterparts (refer to Sections 4.2 and 4.5), but give the convenience and accuracy of premixing with the cement, aggregates, and other possible powder components.

4.4.2 Manufacture—Redispersible powders are manufactured by using two separate processes. The latex polymer is made by emulsion polymerization and is then spray-dried to obtain the powder. The emulsion polymerization is similar to that described in Chapter 3.

After polymerization, but before spray drying, the latex is formulated further by the addition of several ingredients such as bactericides, spray-drying aids, and application chemicals. The latter can include such materials as high-range water-reducing admixtures, anti-sag agents, and anti-foam agents that affect such parameters as workability or air content of the cement mixtures.

Walters (1992a) described spray drying of vinyl acetate-ethylene copolymers. Acrylic copolymers are made by a similar process. Anti-blocking aids are introduced into the powder during or shortly after spray drying. These aids are

Table 4.20—Comparison of polymer-modified mortars using VAE latex and powder (Walters 1992a)

Mortar	Latex	Powder
Parts by mass		
Mixture proportioning by weight in lb (kg)		
Portland cement	100 (45.3)	100 (45.3)
Graded silica sand	300 (136)	300 (136)
VAE latex (55% solids)	18 (8.15)	—
VAE powder (9% ash)	—	11 (5)
Water	39 (17.67)	49 (22.2)
Mortar properties		
<i>w/cm</i>	0.47	0.49
Flow, ASTM C230, 25 drops	110	110
Flexural strength, psi (MPa)	1590 (11)	1320 (9.1)
Compressive strength, psi (MPa)	5140 (35.5)	5040 (34.8)
Permeability, coulombs	1130	1370
Adhesion, psi (MPa)	300 (2.1)	260 (1.8)

incorporated to prevent caking of the powder during storage. Clay, silica, and calcium carbonate are used for this purpose. Application chemicals, such as water-reducing agents, may also be added during or after spray drying. The powders are packaged in bags (10 to 25 kg [24 or 60 lb]) or in bulk form in containers known as totes.

4.4.3 Powder properties—Redispersible powders are usually free-flowing white powders with ash contents of 5 to 15%. The ash content that primarily comes from the anti-blocking aid varies, depending on the type of material. Calcium carbonate and clay give lower ash contents than equivalent amounts of silica. The bulk density of the powder is quite low, being less than 25% of portland cement. The particle size of the powder averages approximately 0.08 mm (0.003 in.); however, these particles are agglomerates that break up on redispersing in water to give typical latex-particle sizes (1 to 5 μm). The glass transition temperature T_g of powders varies depending on the polymer makeup.

4.4.4 Mixture proportioning—Mixture proportioning of cement mixtures modified by redispersible powder polymers is similar to that of other polymer-modified systems, except that no water is contributed by the polymer. Where these powder-modified mixtures are primarily used for improvement in adhesion, the normal polymer-cement ratio by mass is about 0.10 (approximately 0.11 powder-cement ratio). In floor applications, the polymers are used to increase flexural and tensile strength and abrasion resistance. The polymer-cement ratio by mass depends on whether the application is an underlayment or a wearing surface, and varies between 0.05 and 0.20. If the powder does not contain an antifoam agent, one (as a powder) is normally incorporated into the mixture. Like latexes, these polymer powders act as water-reducing agents.

Mixture proportions and *w/cm* differ with the end use. Typical mixtures have been described by Walters (1992a). In proprietary materials, such as for self-leveling floors (Alexanderson 1990) and concrete repair mortars, the polymer powder represents an essential component of the formulation. Once the polymer is selected, balancing of the formulation is

required to achieve the desired performance (Lambe et al. 1990; Decter and Lambe 1992). Powder-polymer-modified mixtures rarely use aggregates larger than 6 mm (1/4 in.).

4.4.5 Properties of unhardened mortar—Unhardened properties of the powder-polymer-modified mortars are similar to those obtained with latexes of similar composition, except that a marginally higher *w/cm* is required to obtain similar flow.

4.4.6 Properties of hardened mortar—Properties of hardened powder-polymer-modified mortars are marginally reduced compared with those obtained with latexes of similar composition. Table 4.20 gives a comparison of the properties of PMMs using the same VAE copolymer in latex and powder form, respectively. The mortars were cured in the mold for 16 to 24 hours followed by storage in laboratory air (approximately 50% RH and 14 °C [58 °F]) for 27 days. Afridi et al. (1990) showed that redispersible PMMs exhibit resistance to freezing and thawing similar to that of LMMs.

In another study, Bright et al. (1992) compared the physical properties of various polymer types, including VAE, S-B, and PAE latexes and VAE redispersible copolymer powders, when used in cementitious patching compounds. It was concluded that the VAE redispersible copolymer powders appear to be at least equivalent to the latexes in formulations prepared at equivalent *w/cm*. Hackel et al. (1987) also concluded that the properties of mortars prepared with VA-VEOVA copolymer powders met the requirements for concrete restoration. Lambe et al. (1990) and Decter and Lambe (1992) describe the physical properties of concrete repair mortars containing redispersible polymer powders. These mortars show low diffusion properties to chloride ions, oxygen, and carbon dioxide (Lambe et al. 1990) and also low drying shrinkage (Decter and Lambe 1992).

4.4.7 Uses—The uses of powder PMCs are those where the convenience of prepackaged mixtures is paramount. Bright et al. (1992) stated that the use of redispersible polymer powder in prepackaged mixtures avoids the storage and transport of 5 gal. (22.7 L) buckets, which are normally used to contain the latex. The disposal of these buckets is increasingly becoming an environmental concern. Also, preblending of the polymer powder at the factory should ensure the correct polymer level in the final product.

The three major end uses are:

- Ceramic tile adhesives and grouts;
- Underlayments and industrial floor toppings; and
- Concrete repair and patching mortars.

As these end uses require some degree of water resistance, copolymers of VAE, VEOVA, or an acrylic ester are preferred to PVA (Walters 1990).

In addition, these powders are used to a limited degree in the exterior insulating finishing systems described in Section 4.2.4.4.

PMMs made using vinyl acetate copolymer redispersible powders are inferior in permeability to similar mortars using SBR latexes (Ohama 1995a). This indicates that the former should not be used where a high degree of water resistance is required (as on bridge decks).

4.4.7.1 Ceramic tile adhesives and grouts—Cement, sand, cellulosic thickener, and polymer powder are premixed and sold by formulators to contractors and homeowners. Such mixtures usually comply with the application requirements of the American National Standard Specifications for Properties of Latex-Portland Cement Mortar, A 118.4.

4.4.7.2 Underlayments and industrial floors—The largest application of powder-polymer-modified mortar is for underlayments and industrial floors. It has been described in some detail by Alexanderson (1990).

4.4.7.3 Prepackaged patching mortars—Polymer powders are used in prepackaged mortars that can be basic patching compounds or more sophisticated mortars for use as part of a system for the repair and protection of damaged reinforced concrete. These materials are proportioned and packaged by a formulator, and sold to contractors and homeowners. The user completes the proportioning by adding the amount of water required for a workable consistency.

Basic patching mortar may only consist of sand, cement, and polymers. The concrete repair mortars may be required to meet more stringent requirements, such as low shrinkage and low permeability to chloride ions and carbon dioxide (Lambe et al. 1990; Decter and Lambe 1992). Meeting these requirements may necessitate the use of other additives. The adjustment of the levels of the various components in these formulations is necessary to meet performance specifications with a PMM.

4.5—Other polymers

4.5.1 General—The polymers most widely used for modification of hydraulic cements have been described in the previous chapters. Other polymers in latex or powder form are being used or have been used, but there is little published information on their performance.

This chapter deals with the latexes and powders not previously addressed in this report. They are not as widely used as those polymers described previously because of cost or performance deficiencies. These materials are primarily used in mortars rather than concrete.

4.5.2 Other latexes and polymers—A list of latex types used with hydraulic cements is presented in Table 3.1. Those not previously discussed include natural rubber latex, copolymers of butadiene and acrylonitrile, polymers and copolymers of chloroprene, polymers and copolymers of vinyl acetate, copolymers of vinylidene chloride, polymers and copolymers of vinyl esters and alcohol, and bituminous latexes.

The most widely used materials include natural rubber latex, polymers and copolymers of vinyl acetate, and copolymers of vinylidene chloride. Ohama (1995b) and Jenni et al. (2006) reported on these polymers.

4.5.3 Performance—The performance of these materials is similar in many respects to those described in previous chapters. Mixture proportioning, relationship between performance and polymer-cement ratio, and effect on mixture workability are similar.

4.5.3.1 Properties of unhardened mixtures—Water reduction is obtained with most of these materials that were designed for use with hydraulic cements. Butadiene-acrylonitrile

latexes have a greater water-reducing effect than polyvinyl acetate latexes.

Most of these materials increase setting times. The largest increases have been observed with chloroprene polymers. Vinyl acetate-ethylene (VAE) copolymers have moderate increases.

Entrained air contents of the polymer-cementitious mixtures are higher than similar unmodified mixtures, unless antifoam agents are used.

Water reduction, setting time, and entrained air content are all affected by the type and level of surfactant used to manufacture these polymers and latexes.

4.5.3.2 Properties of hardened mixtures—All of the aforementioned materials appear to exhibit similar-shaped performance curves versus polymer-cement ratios with respect to adhesion, abrasion resistance, and tensile and flexural strengths. The degree of change with polymer-cement ratio, however, can be significantly different depending on the polymer type; for example, copolymers of vinylidene chloride exhibit much higher flexural strength than those of bituminous latexes (Ohama 1995a). Drying shrinkage tends to decrease with an increasing polymer-cement ratio, but it varies significantly with polymer type, with polymers and copolymers of vinyl acetate having greater shrinkage than butadiene-acrylonitrile, and vinylidene chloride copolymers (Ohama 1995a).

Durability of these PMCs can be limited. The use of copolymers of vinylidene chloride has been virtually discontinued because of their tendency to release chloride ions, which can cause corrosion problems in steel reinforcement. Polyvinyl acetate latexes should not be used in cementitious mixtures that are liable to be exposed to moisture because this type of polymer is degraded by hydrolysis in wet, alkaline environments (Walters 1990).

Most of these polymers reduce water permeability of cementitious systems. Ohama (1995b) showed the relative performance of some latex-modified and unmodified mortars with respect to water absorption and water permeation.

As with most polymer-modified mixtures, these mortars show marked strength reduction between dry and wet test conditions (Jenni et al. 2006), but butadiene-acrylonitrile copolymers may be an exception (Ohama 1995a).

4.5.4 Uses—There is little published information on the use of hydraulic-cement mixtures using these other latexes and powders. Their increased adhesion over similar unmodified formulations is the most common reason for use of these polymer-modified mixtures. Repair and patching of plaster, stucco, mortar, and concrete appear to be the most common uses. Polymers and copolymers of vinyl acetate, however, are widely used as bonding agents between fresh and hardened hydraulic-cement admixtures, or for plastering over gypsum board.

CHAPTER 5—REFERENCES

5.1—Referenced standards and reports

The standards and reports listed below were the latest editions at the time this document was prepared. Because these documents are revised frequently, the reader is advised to check the proper sponsoring group if it is desired to refer to the latest version.

American Concrete Institute

- 305R Hot Weather Concreting
 306R Cold Weather Concreting
 506R Guide to Shotcrete
 548.1R Guide for the Use of Polymers in Concrete
 548.4 Standard Specification for Latex-Modified Concrete (LMC) Overlays

American National Standards Institute (ANSI)

- A 118.4 Specifications for Properties of Latex-Portland Cement Mortar

ASTM International

- C109/C109M Standard Test Method for Compressive Strength of Hydraulic Cement Mortars (Using 2-in. or [50-mm] Cube Specimens)
 C150 Standard Specification for Portland Cement
 C190 Method of Test for Tensile Strength of Hydraulic Cement Mortars (withdrawn 1990)
 C230/C230M Standard Specification for Flow Table for Use in Tests of Hydraulic Cement
 C291 Standard Test Method for Resistance of Concrete Specimens to Rapid Freezing in Air and Thawing in Water (withdrawn 1971)
 C348 Standard Test Method for Flexural Strength of Hydraulic-Cement Mortars
 C457 Standard Test Method for Microscopical Determination of Parameters of the Air-Void System in Hardened Concrete
 C666/C666M Standard Test Method for Resistance of Concrete to Rapid Freezing and Thawing
 C672/C672M Standard Test Method for Scaling Resistance of Concrete Surfaces Exposed to Deicing Chemicals
 C1202 Standard Test Method for Electrical Indication of Concrete's Ability to Resist Chloride Ion Penetration
 C1438 Standard Specification for Latex and Powder Polymer Modifiers for Hydraulic Cement Concrete and Mortar
 C1439 Standard Test Methods for Evaluating Polymer Modifiers in Mortar and Concrete
 D445 Standard Test Method for Kinematic Viscosity of Transparent and Opaque Liquids (and Calculation of Dynamic Viscosity)
 D648 Standard Test Method for Deflection Temperature of Plastics Under Flexural Load in the Edgewise Position
 D790 Standard Test Methods for Flexural Properties of Unreinforced and Reinforced Plastics and Electrical Insulating Materials
 D1076 Standard Specification for Rubber-Concentrated, Ammonia Preserved, Creamed, and Centrifuged Natural Latex
 D1417 Standard Test Methods for Rubber Latices-Synthetic

- D2354 Standard Test Method for Minimum Film Formation Temperature (MFFT) of Emulsion Vehicles

These publications may be obtained from these organizations:

American Concrete Institute
 38800 Country Club Drive
 Farmington Hills, MI 48331
 www.concrete.org

ANSI
 25 West 43rd Street
 4th Floor
 New York, NY 10036
 www.ansi.org

ASTM International
 100 Barr Harbor Dr.
 West Conshohocken, PA 19428-2959
 www.astm.org

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Afridi, M. U. K.; Ohama, Y.; Demura, K.; and Iqbal, M. Z., 2003, "Development of Polymer Films by the Coalescence of Polymer Particles in Powdered and Aqueous Polymer-Modified Mortars," *Cement and Concrete Research*, V. 33, pp. 1715-1721.

Aggarwal, L. K.; Thapliyal, P. C.; and Karadea, S. R., 2007, "Properties of Polymer-Modified Mortars Using Epoxy and Acrylic Emulsions," *Construction and Building Materials*, V. 21, No. 2, pp. 379-383.

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