National Cooperative Highway Research Program

NCHRP Synthesis 179

Latex-Modified Concretes and Mortars

A Synthesis of Highway Practice

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Synthesis of Highway Practice 179

Latex-Modified Concretes and Mortars

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Systematic, well-designed research provides the most effective approach to the solution of many problems facing highway administrators and engineers. Often, highway problems are of local interest and can best be studied by highway departments individually or in cooperation with their state universities and others. However, the accelerating growth of highway transportation develops increasingly complex problems of wide interest to highway authorities. These problems are best studied through a coordinated program of cooperative research.

In recognition of these needs, the highway administrators of the American Association of State Highway and Transportation Officials initiated in 1962 an objective national highway research program employing modern scientific techniques. This program is supported on a continuing basis by funds from participating member states of the Association and it receives the full cooperation and support of the Federal Highway Administration, United States Department of Transportation.

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The members of the technical committee selected to monitor this project and to review this report were chosen for recognized scholarly competence and with due consideration for the balance of disciplines appropriate to the project. The opinions and conclusions expressed or implied are those of the research agency that performed the research, and, while they have been accepted as appropriate by the technical committee, they are not necessarily those of the Transportation Research Board, the National Research Council, the American Association of State Highway and Transportation Officials, or the Federal Highway Administration of the U.S. Department of Transportation.

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PREFACE

A vast storehouse of information exists on nearly every subject of concern to highway administrators and engineers. Much of this information has resulted from both research and the successful application of solutions to the problems faced by practitioners in their daily work. Because previously there has been no systematic means for compiling such useful information and making it available to the entire highway community, the American Association of State Highway and Transportation Officials has, through the mechanism of the National Cooperative Highway Research Program, authorized the Transportation Research Board to undertake a continuing project to search out and synthesize useful knowledge from all available sources and to prepare documented reports on current practices in the subject areas of concern.

This synthesis series reports on various practices, making specific recommendations where appropriate but without the detailed directions usually found in handbooks or design manuals. Nonetheless, these documents can serve similar purposes, for each is a compendium of the best knowledge available on those measures found to be the most successful in resolving specific problems. The extent to which these reports are useful will be tempered by the user's knowledge and experience in the particular problem area.

FOREWORD

By Staff
Transportation Research Board

This synthesis will be of interest to materials engineers, construction engineers, maintenance engineers, pavement contractors, and others interested in the use of latex-modified mortars (LMM) and concretes (LMC). Information is provided on material properties of various LMM and LMC, as well as current construction practices used for LMM and LMC. Potential applications for LMM and LMC are also included.

Administrators, engineers, and researchers are continually faced with highway problems on which much information exists, either in the form of reports or in terms of undocumented experience and practice. Unfortunately, this information often is scattered and unevaluated, and, as a consequence, in seeking solutions, full information on what has been learned about a problem frequently is not assembled. Costly research findings may go unused, valuable experience may be overlooked, and full consideration may not be given to available practices for solving or alleviating the problem. In an effort to correct this situation, a continuing NCHRP project, carried out by the Transportation Research Board as the research agency, has the objective of reporting on common highway problems and synthesizing available information. The synthesis reports from this endeavor constitute an NCHRP publication series in which various forms of relevant information are assembled into single, concise documents pertaining to specific highway problems or sets of closely related problems.

The use of innovative modified portland cement mortars and concretes for construction and maintenance applications is growing. This report of the Transportation Research Board describes the current state of the practice with respect to the use of latex-modified portland cement concretes and mortars. The extent of use of each material (including case histories), based on results of surveys of state highway agencies and a review of the literature, is summarized.

To develop this synthesis in a comprehensive manner and to ensure inclusion of significant knowledge, the Board analyzed available information assembled from numerous sources, including a large number of state highway and transportation departments. A topic panel of experts in the subject area was established to guide the researcher in organizing and evaluating the collected data, and to review the final synthesis report.

This synthesis is an immediately useful document that records practices that were acceptable within the limitations of the knowledge available at the time of its preparation. As the processes of advancement continue, new knowledge can be expected to be added to that now at hand.

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Information on current practice was provided by many highway and transportation agencies. Their cooperation and assistance were most helpful.

LATEX-MODIFIED CONCRETES AND MORTARS

SUMMARY

Latex modification of portland cement has been in use for more than five decades. However, it has been only in the past 20 years that widespread use of synthetically produced latexes has been accepted for both concrete and mortar applications.

Latex-modified mortars (LMM) and concretes (LMC) were developed to minimize or to completely eliminate the weaknesses of portland cement mortars and concretes. These weaknesses include low tensile strength, low ductility, volume instability, low strength-to-weight ratio, and greater than desired permeability. Portland cement mortars and concretes are sometimes modified with polymer admixtures, such as latexes, powdered emulsions, water soluble polymers, liquid resins, and monomers. These modified concretes and mortars may have higher strengths, improved bonding to concrete materials, increased flexibility and impact resistance, increased resistance to penetration by water and chemicals, improved resistance to frost action, and decreased permeability. Because of this improved performance, latex-modified mortars and concretes are being used increasingly in bridge-deck overlays, in repair and rehabilitation work, and in the construction of new pavements, garages, marine facilities, and tunnel and pipe linings. LMM and LMC are more widely used than all other polymer concrete systems due to their less complicated production method and lower cost. Basic information about their characterization, past applications and performances, and prospective new applications are presented in this synthesis. A separate document, "Latex-Modified Concretes and Mortars-A Partially Annotated Bibliography of Their Performance Characteristics and Applications" is available from the Publications Office, Transportation Research Board, 2101 Constitution Avenue, Washington, D.C.

The properties of LMM and LMC depend on the type of latex used; within each type of latex there are many variations that result in different properties in the modified mortars and concretes. The types of latexes, their classification, latex manufacturing techniques, properties of latexes and their tests, and the mechanisms of latex modification are described in Chapter Two.

The materials used and the mixing procedure for LMC and LMM are almost the same as those for conventional portland cement mortar and concrete. Latexes, in dispersion form, are used in larger quantities in comparison to other chemical admixtures. The materials used, the mixture proportions for mortars and concretes, and a rational mixture proportioning procedure are presented in Chapter Three. Improvements that could be achieved in fresh and hardened concrete and mortar properties depend on the type and quality of materials used, such as latexes, cements, and aggregates, as well as such characteristics as latex/cement ratio, water/cement ratio, binder/void ratio, air content, placement and curing procedures, and environmental conditions

during placement and service life. The property enhancements achieved, and the various factors that tend to interact with each other are fully described in Chapter Four.

LMC and LMM are used mainly in applications where conventional cement mortar and concretes previously could not be used effectively. Current LMC and LMM applications, including some special applications, are listed in Chapter Five. New avenues for efficiently and profitably using these materials are being found. These new and potential applications include the addition of latexes to fiber-reinforced concrete, conventional shotcrete, fiber-reinforced shotcrete, roller-compacted concrete and light-weight foam concrete, for controlling or eliminating the alkali-aggregate and long term alkali-silica reactions, to improve skid resistance, and to enhance the properties of silica fume and fly ash concretes. Suggested new applications also include foundations and structures subjected to dynamic loads, marine and offshore structures, mass production of large noncorroding structural elements and weatherproof roof decks.

Currently, there are no standard American Society for Testing and Materials (ASTM), American Association of State Highway and Transportation Officials (AASHTO), or American Concrete Institute (ACI) specifications for quality control or application of LMM and LMC; however, ACI will be publishing a standard specification for bridge-deck overlay construction using styrene-butadiene rubber (SBR) latex. The prevailing procedures and construction practices are described in Chapter Six, and the limitations and problem areas are pointed out in Chapter Seven.

Recent nationwide surveys have shown that LMC is the favorite among the various advanced materials available for bridge-deck overlays. SBR latex-modified concrete is being used exclusively for this purpose. Various state evaluations and condition surveys have shown that the field performance of these decks has been satisfactory to excellent. The cost of the latex is a small portion of the total cost of the project and it is cost-effective when the benefits of low permeability of LMC are needed. These topics are discussed in Chapter Eight.

Based on an intensive and careful review of more than 450 published papers and reports, and personal discussions with researchers and users, it is concluded that LMM and LMC, particularly SBR latex-modified concrete for bridge-deck overlays, are safe, durable, beneficial, and economical. However, there is a need for education and training of the contractors and construction engineers in quality control procedures and in strict adherence to specifications and guidelines to ensure optimal results are obtained in LMM and LMC applications. There is also an urgent need to develop standards, specifications, and guides for the use of LMM and LMC in various applications. Chapter Nine lists further observations and recommendations.

CHAPTER ONE

INTRODUCTION

POLYMERS IN CONCRETE

Portland cement concrete is one of the most popular and widely used construction materials in the world, despite its low tensile strength, low ductility, volume instability, low strength-to-weight ratio, and greater than desired permeability. Ever since the introduction of portland cement concrete and mortar, attempts have been made to minimize or to completely eliminate these weaknesses. One such attempt was the development of latex-modified mortars (LMM) and concretes (LMC), more commonly known as polymer-modified concretes (PMC) or polymer portland cement concretes (PPCC).

The American Concrete Institute (ACI) Committee 548 has defined LMC as portland cement and fine and coarse aggregate combined at the time of mixing with organic polymers that are dispersed or redispersed in water. This organic polymer dispersion in water is called a latex. When the coarse aggregate is omitted, it is known as latex-modified mortar (LMM). Depending on the type of latex used, these modified mortars and concretes can have increased workability and strength, improved bonding to concrete substrates, increased flexibility and impact resistance, increased resistance to penetration by water and chemicals, improved resistance to frost action, and decreased permeability.

Polymer-modified portland cement concretes and mortars are widely used in construction due to their uncomplicated production method and lower cost compared to other polymer concrete systems such as polymer-impregnated concrete (PIC) and polymer concrete (PC).

HISTORICAL BACKGROUND

The first reference to latex was in the 16th century when Spanish explorers reported that some South American Indians were using rubber latex obtained from the tree *Hevea brasilienis* to make footwear. However, the first patent for latex use in mortars and concretes was obtained in Britain by Cresson on January 12, 1923 (*1*). This historically important patent was issued for using cement as a filler to paving materials with natural rubber latexes. Another patent was issued to Lefebure in 1924 (*2*). He was the first person who intended to produce latex-modified mortars and concrete using the present concept of a mixture proportioning method. Using a similar idea, Kirkpatrick obtained a patent in 1925 (*3*). The patent for suggesting the use of synthetic rubber in latex-modified systems was first issued to Bond in 1932 (*4*) and in 1933 a patent was issued to Rodwell in Germany to apply synthetic resin latexes, including polyvinyl acetate latexes, to modified systems (*5*). In the 1940s, some patents on latex-modified systems with synthetic latexes such as polychloroprene rubber (neoprene) latexes (*6*) and polyacrylic ester latexes (*7*) were issued. Polyvinyl acetates were also used for modifying mortars and concretes that found some practical applications. Griffiths (*8*) and Stevens (*9*) conducted feasibility studies on the application of natural rubber-modified systems in the United Kingdom. The use of synthetic latexes in latex-modified systems was also studied. Geist, et al. (*10*) conducted a basic study on polyvinyl acetate modified mortar and laid the foundation for valuable research on latex-modified mortar and concrete. Until the early 20th century, the only available latex was natural rubber latex. Since World War II, there has been a tremendous increase in the availability of other types of polymers in the market and there has been extensive research and development in latex-modified concrete systems. The initial investigation of styrene-butadiene latex-modified portland cement was conducted in 1956 by the Dow Chemical Company in Michigan. A cooperative effort between Dow Chemical Company and the Michigan Highway Department resulted in field trials in 1958 (*11*).

Since the 1960s, styrene-butadiene rubber (*12*), polyacrylic ester, and polyvinylidene chloride-vinyl chloride (*13*) modified mortars and concretes have been used increasingly in practical applications. Research and development activities in polymer-modified mortar and concrete have been conducted in various countries, including the U.S., the former Soviet Union, Germany, Japan, and the U.K. In Japan, several standards for quality and testing methods of latex-type cement modifiers and latex-modified mortars have been issued as Japanese Industrial Standards (JIS). A bibliography, "Latex-Modified Concretes and Mortars — A Partially Annotated Bibliography of Their Performance Characteristics and Applications," is available as a separate document from the Publications Office, Transportation Research Board, 2101 Constitution Avenue, Washington, D.C.

Due to improved performance in tensile, flexural, and bond strength, shock resistance, abrasion resistance, water proofing, and chemical resistance, latex-modified mortars and concretes have been used in many applications, such as deck coverings for ships, overlays for new bridge decks, repair of old bridge decks, highway and airport pavements, parking garages, new floors, floor toppings, steel coatings, adhesives, tile adhesives, grout, stucco work, patch applications, and anticorrosive applications. Many researchers have reported satisfactory results when latex-modified systems were used in surface coatings, pavement toppings and patching of damaged concrete. Styrene-butadiene rubber latex has been primarily used for bridge-deck overlays, floors, and parking garages, whereas acrylic polymers were mainly used as tile adhesive, grout, floor toppings, stucco, spray coats, terrazzo floor, and patching of damaged concrete (*14*). It has been reported by Shafer (*15*) that a half-inch section of latex-modified system placed on a badly scaled and spalled Michigan bridge in 1957 performed well until 1970. Steel and Judy (*16*) have reported that 18 bridge decks (where chloride ion penetration from application of deicing salts was the major problem) that received a thin overlay of 1 to 2 in. of latex-modified concrete or mortar in West Virginia have given encouraging results, particularly against chloride penetration.

It was estimated that each year in the U.S., 1.5 million yd^2 ($1.25 \times 106\ m^2$) of bridge decks receive overlays of PMC, mostly of styrene-butadiene latex-modified concrete (*16*). Marusin (*17*) described repair techniques using acrylic modified cast-in-place portland cement concrete in repairs of concrete columns, spandrels, and balconies on a high-rise housing complex in Chicago.

CHAPTER TWO

LATEXES AND THEIR PROPERTIES

CEMENT MODIFIERS

In recent years, various polymer dispersions have been developed and commercialized as cement modifiers. The polymers and monomers commonly used as cement modifiers are shown in Figure 1. Using these cement modifiers, several types of polymer-modified mortars and concretes, such as latex, powdered emulsion, water-soluble polymer, liquid resin, and monomer-modified mortars and concretes are produced. The discussion in this synthesis is limited only to LMM and LMC, the most widely used among the PMC (*18*).

What Is a Latex?

A latex is a stable dispersion of organic polymer particles in an aqueous surfactant solution giving a milky fluid that is generally white to off-white in color. On drying, these particles coalesce to form a continuous film. An organic polymer is a substance composed of giant molecules formed by the union of a number of simple molecules known as monomers (*18*). Polymers can be divided into two groups: homopolymers and copolymers. When a polymer is made by the polymerization of one type of monomer, it is called a homopolymer; if it is made by the polymerization of different monomers, it is called a copolymer (*19*). Natural rubber latex (NR) is a dispersion of polyisoprene (a homopolymer) that is polymerized by the tree.

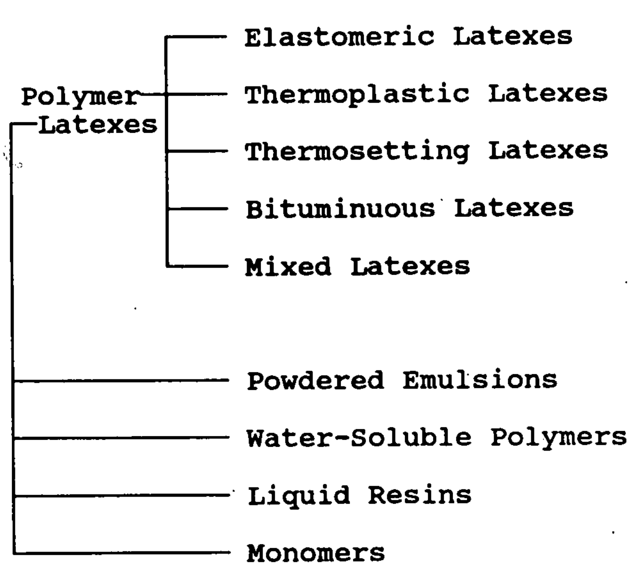


FIGURE 1 Polymers and monomers used as cement modifiers (*18*).

Latex Types

Latexes are classified as two types in ASTM C 1042-85. Type I, reemulsifiable latexes, should be used only in applications that are not subjected to immersion in water or high humidity. Type II, non-reemulsifiable latexes, can be used where water immersion or high humidity is expected.

Commonly Used Latexes

Many types and formulations of latexes are manufactured; however, only those specifically developed for use in hydraulic cement are used in mortar and concrete applications. Various latexes that have been used before and those that are currently used for modification of hydraulic cement mixtures are listed below with their common abbreviations.

Elastomeric:
- Natural Rubber (NR)
- Styrene-Butadiene (SB)
- Styrene-Butadiene Rubber (SBR)
- Polychloroprene (CR) (Neoprene)
- Acrylonitrile-Butadiene Rubber (NBR)

Thermoplastic:
- Polyacrylic Ester (PAE)
- Styrene-Acrylic (SA)
- Ethylene Vinyl Acetate (EVA)*
- Vinyl Acetate-Ethylene (VAE)
- Polyvinyl Acetate (PVAC)
- Polyvinylidene Chloride (PVDC)
- Vinyl Acetate-acrylic Copolymer (VAC)
- Polyvinyl Propionate
- Polypropylene
- Pure acrylics (e.g., ethyl acrylate/methyl methacrylate)

*Generally in the U.S., the name Vinyl Acetate - Ethylene copolymer (VAE) is used. The same latex is referred to as Ethylene Vinyl Acetate (EVA) in Japan and elsewhere.

Polyvinylidene chloride (PVDC) had been used earlier in the United States and Japan, primarily as a mortar additive and as a concrete admixture. Currently, PVDC is not generally used in the U.S. and Japan because there is a possibility of corrosion of embedded steel in PVDC mortars and concretes (Private communication from Y. Ohama, September, 1991). Polyvinyl acetates (PVAC) are not generally recommended for use in wet environments and outer exposure because some types may hydrolyze or break down chemically.

Mixed Latexes

Occasionally, blends of different types of latex, such as an elastomeric latex with a thermoplastic one, are used. These are known as mixed latexes.

LATEX MANUFACTURING TECHNIQUES

Latexes are mainly produced through a process called emulsion polymerization. Based on this production method, latexes are sometimes referred to as emulsions; however, epoxy resin latexes constitute an exception to this process. An emulsion process involves mixing monomers with water, stabilizers, and an initiator. The initiator generates a free radical that causes the monomers to polymerize by chain addition. The data in Table 1 typify the mix proportions for emulsion polymerization (*19*).

The usual method of polymerization is to charge the water, stabilizers, other ingredients and part of the monomers to a reactor under agitation. The temperature is increased to a desired point, then the initiator system is fed to the reactor followed by the remainder of the monomers. By controlling the temperature and adding other chemicals, the conversion can be 90 to 99 percent completed. Using a stripping process, the excess monomers can be reduced to a desired level. The resultant latex may be concentrated or diluted and a small amount of preservatives and stabilizers may be added. Other ingredients are also used in polymerization to control various properties such as pH, particle size, and molecular weight (*19*).

The characteristic properties of a latex are generally influenced by the conditions of polymerization, such as variations in catalytic level, reaction time, temperature and monomer concentration. It is possible to obtain latexes of different properties with the same monomers. The particles of polymer produced by emulsion polymerization are spherical and typically between 0.05 to 0.20 microns in diameter. A cubic millimeter of dried film will normally contain at least 125 billion particles.

Preservatives added to the latex after polymerization provide protection against bacterial contamination and give improved aging resistance. Stabilizers may be added to provide more stability. Antifoaming or defoaming agents can be added to reduce air entrainment when latex is mixed with aggregate and cement.

CLASSIFICATION OF LATEXES

Latexes can be classified by the three possible types of electrical charge on the particle. The electrical charge on the particle is determined by the type of stabilizer. Latex classifications include cationic (positively charged), anionic (negatively charged), and nonionic (not charged). Due to a lack of required stability, positively and negatively charged latexes are not suitable for use with hydraulic cement. Thus the latexes used most often are stabilized with surfactants that are nonionic. Typical chemical compositions for some of the latexes used with portland cement are given in Tables 2, 3, and 4 (*19*).

TABLE 1
TYPICAL MIXTURE FOR EMULSION POLYMERIZATION (*19*)

Substance	Parts by weight
Monomers	100.0
Stabilizer	1.0 - 10.0
Initiator	0.1 - 2.0
Water	80.0 - 150.0
Other ingredients	0.0 - 10.0

PROPERTIES OF LATEXES AND THEIR TESTS

The properties of modified hydraulic cement mixtures depend on the type of latex used. Within each type of latex, there are many variations that result in different properties of the modified mortar and concretes. The following variables in latex manufacture control the performance of latex-modified mortars and concretes in their fresh and hardened states.

Polymer Composition

Walters (*19*) has reported that portland cement concrete modified with a vinyl acetate homopolymer latex usually has poorer

TABLE 2
MIXTURE OF A POLYVINYL ACETATE LATEX (*19*)

Substance	Parts by weight
Vinyl acetate	100.0
Partially hydrolyzed polyvinyl alcohol	6.0
Sodium bicarbonate	0.3
Hydrogen peroxide, 35 %	0.7
Sodium formaldehyde sulfoxylate	0.5
Water	80.0

TABLE 3
MIXTURE OF AN ACRYLIC COPOLYMER LATEX (*19*)

Substance	Parts by weight
Ethyl acrylate	98.0
A vinyl carboxylic acid	2.0
Nonionic surfactant	6.0+
Anionic surfactant	0.3*
Sodium formaldehyde sulfoxylate	0.1
Caustic soda	0.2
Peroxide	0.1
Water	100.0

+ The nonionic surfactants may be nonyl phenols reacted with 20 to 40 molecules of ethylene oxide.
* The low levels of anionic surfactants are used to control the rate of polymerization.

TABLE 4
MIXTURE FOR A STYRENE BUTADIENE COPOLYMER LATEX (*19*)

Substance	Parts by weight
Styrene	64.0
Butadiene	35.0
A vinyl carboxylic acid	1.0
Nonionic surfactant	7.0+
Anionic surfactant	0.1*
Ammonium persulfate	0.2
Water	105.0

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

* The low levels of anionic surfactants are used to control the rate of polymerization.

water resistance than that of a similar unmodified concrete, but that a concrete modified with styrene-butadiene copolymer latex usually has better water resistance. A styrene-butadiene copolymer with a styrene-butadiene (SB) ratio of 30:70 will have a much lower compressive strength than a styrene-butadiene copolymer of similar molecular weight and an SB ratio of 70:30. This can be further complicated by differences in molecular weight. A latex-modified portland cement concrete using an SBR with lower molecular weight will not have the same strength, adhesion, and water resistance properties as that using a latex with higher molecular weight, even if the monomer composition and other ingredients are the same (*19*).

Adhesive properties of latex can be improved by the use of monomers that contain reactive groups such as unsaturated carboxylic acids, e.g., methacrylic and acrylic acid. There are also some reactive groups that have potential for retarding or accelerating hydration of cement.

Surfactant Type and Level

Surfactants are chemical compounds added during manufacture of latex that attach to the surface of latex particles. These are also known as stabilizers, soaps, and protective colloids. The type and concentration of surfactant influences stability and surface tension. Surfactants influence the interactions of the particles and the interactions of the particles with materials, such as portland cement, to which the latex is added. The main contribution of the surfactant is to increase the workability of portland cement mortar and concrete mixtures. Alternatively, for a given workability, a reduction in the water/cement ratio and hence, increased strength, can be achieved in the hardened latex-modified mortar and concretes. However, use of excessive quantities of surfactants can cause a reduction in water resistance and adhesion.

Particle size can be controlled by the amount of surfactant present at the start of polymerization. Large particles give latexes better workability (which leads to readily trowellable mortar mixtures), whereas small particles improve adhesion and penetration. Particle size distribution can also be important. A blend of small and large particles can give low viscosity at high solids concentration. The presence of extra large particles is undesirable as it encourages "creaming", the process by which large particles float to the top during storage. Film formation is encouraged by a wide distribution of particle sizes because there will be smaller inter-spaces between the particles. Natural rubber latex has a wide particle size distribution with a mean diameter of about one micron. SBRs and acrylics normally are about 0.15 micron in diameter. Styrene acrylics are available with a particle size below 0.1 micron (*20*).

Compounding Ingredients

The compounding process typically involves raising the pH to about 10.5, adjusting the solids content, and introducing other compounding ingredients. It may involve adding one or more of the following: plasticizer, coalescent, antifoaming agent, alkali, antioxidant, bactericide, water, thickener, dispersant, pigment, vulcanizing agent, filler, tackifier, anti-skinning agent, ultraviolet (UV) ray protection, additional cement admixtures such as accelerator/retarder, freeze-thaw stabilizer, antifreeze, fire retardant, odor-masking agent, and additional surfactant.

Some materials are added after the polymerization is completed to improve the product. Bactericides are added to provide protection against bacterial contamination. Antioxidants and UV protectors are added to provide protection against aging and light attack. Concentrations of these added materials are relatively low, ranging from a few parts per million (ppm) for bactericides up to 7 percent for surfactants. Defoaming or antifoaming agents, when they are not added by the manufacturer, are often added later to avoid high air content in the hydraulic cement concrete mixture.

Initiator

Persulphates are commonly used to generate the requisite free radicals. Higher concentrations of initiator yield lower latex molecular weights.

Minimum Film Forming Temperature

The lowest temperature at which the polymer particles of latex have sufficient mobility and flexibility to coalesce into a continuous film is controlled by the type and concentration of monomers used. This minimum film forming temperature (MFFT) may be reduced by the addition of plasticizers (*21*). The minimum film forming temperature should be lower than 40°F for successful application to latex-modified hydraulic cement mixtures (*23*). Satisfactory performance has been obtained with latex-modified hydraulic cement systems which were applied at temperatures below the MFFT of that particular latex. It has been postulated that the cement reduces the effective MFFT of the latex (*19*). Lowering the reaction temperature usually leads to an improvement in the properties of the dried film, including higher tensile strength.

Non-Volatile or Total Solids Content

The non-volatile or total solids content is the polymer content of latex together with any ingredients that are non-volatile at the temperature at which a volatility test is run. It is a very important property because it determines the properties of the latex-modified concrete and the cost of the product.

pH Value

The pH is the measure of the H^+ concentration of the system; thus, the pH is a measure of alkalinity (or acidity) of the latex. The recommended pH value for latexes to be mixed in concrete is 10; the pH value for concrete varies between 11 and 13.

Coagulum

Coagulum is the quantity of polymer that is retained after passing a known amount of latex through a certain size of screen or mesh. Usually, the mesh sizes are No. 100, No. 200, or No. 325, with the number indicating the number of spaces per linear inch. This test is a measure of the quantity of polymer that has particles larger than intended, which usually are formed by particle agglomeration or skin formation.

Viscosity

Viscosity is the internal resistance to flow exhibited by a fluid. Most latexes used with hydraulic cements are very fluid, having viscosities less than 100 cp, which is approximately the viscosity of milk. For comparison, water's viscosity is 0.894 cp at 25°C (77°F). Surfactants, particle size, and solids content have the greatest effect on viscosity. They influence the workability of latex-modified concrete mixtures.

Stability

Stability is a measure of resistance to change when subjected to some kind of force or shock. There are three forms of basic stability: mechanical, chemical, and thermal.

- *Mechanical Stability* generally is determined by subjecting latex to some mechanical motion, usually high speed agitation, for a specific period of time and then measuring the amount of coagulum that is formed (Refer to ASTM D 1417).
- *Chemical Stability* can be determined by the amount of chemical required to cause complete coagulation, or by adding a certain level of chemical and then determining the degree of mechanical stability.
- *Thermal Stability* is generally determined by subjecting latex to specified temperatures for a specific period of time and determining the effect of that temperature exposure on another property. In Federal Highway Administration (FHWA) Report 78-35 (*23*), there is a freeze-thaw stability test in which the amount of coagulum formed after subjecting latex to two freeze-thaw cycles is determined.

Surfactant use has the most effect in determining the total stability a latex will exhibit. Mechanical, chemical, and thermal stability are important for latexes used with hydraulic cements. This is because latex is often subjected to high shear in metering and transfer pumps, exposed to the extremely active chemical environment provided by hydraulic cements, and subjected to wide variations in temperature encountered in transportation related construction.

Weight per Gallon

Weight per gallon is a way to measure the density or specific gravity of a latex. It is determined by weighing a specific volume of latex under specified conditions. It is important because, along with the solids or nonvolatile content, it determines how much polymer is being used. A gallon of SBR latex is about 8.45 lbs (1kg/l), while that of an acrylic is about 8.9 lbs. If both contain the same amount of solids, around 47 percent of the SBR latex is made up of about 3.97 lbs of polymer solids per gallon while the acrylic contains 4.18 lbs (*22*).

Particle Size

Particle size is a measure of the size of the polymer particles dispersed in water. It will vary between 0.05 and 5 microns, which is much smaller than the particle size of cement or aggregates. Particle size can be measured using instruments such as electron microscopes, centrifuges, and photo spectrometers, although each method may yield different results (*19*). Surfactant use is a determining factor in effective particle size and thus, has an effect on latex-modified mortar or concrete.

Surface Tension

Surface tension relates to the ability of a material to wet, or not to wet, a surface, and can be determined with a tensiometer. The test procedure to determine latex surface tension has been described in FHWA report RD 78-35 (*23*). The lower the value of surface tension, the higher capacity for wetting by latex. Surface tension also affects the workability and finishability of a latex-modified mixture and is strongly dependent on the amount and type of surfactants.

Durability of Latexes

Latexes used for cement coating applications and as admixtures for LMC mortars for repair and rehabilitation of old concrete should be durable. Acrylic latexes are used extensively in such construction and they have excellent durability properties (*24*). Acrylics resist discoloration when exposed to elevated temperatures and are not attacked easily by acids and bases. Acrylics are chemically inert and are transparent in the spectral region between 350 and 300 nanometers (nm), which is the most photo-chemically active region of the solar spectrum (*24*). Since acrylics are largely transparent to natural sunlight and do not absorb UV radiation, they are durable outdoors. However, modification of acrylics with other polymers that absorb UV radiation will reduce the durability of acrylic systems for exterior applications.

OTHER LATEX TESTS

Many tests are used to characterize latex properties (*20*) such as appearance, odor, specific gravity, coagulum, total solids, pH, viscosity, stability, particle size distribution, surface tension, foamability, free monomers, minimum film forming temperature, alkali content, tendency of latex to promote or retard steel corrosion, electrical conductivity, and residual initiator. Other tests specific to natural rubber latex also exist. Due to aging effects, there is a possibility of changes in properties being measured over the latex service life. A number of organizations, including the American Society for Testing and Materials (ASTM), FHWA, British Standards Institute (BSI), German Industrial Standards (DIN) and International Standards Organization (ISO), have formulated test methods covering the above mentioned properties. Manufacturers also use their own test procedures for characterizing the material. One should be aware of the variations in test results possible by using different test methods.

Solids Content

Several test methods are accepted for determining the total solids content of nonvolatile material. A proposed ASTM method is given in ASTM D 1076. Total solids content is determined by weighing a representative sample of latex, drying it under specified conditions, and weighing the residue. The total solids content is expressed as a percentage of the original weight. Table 5 gives the nonvolatile content determined on the same latex by three different methods (*19*). The results can vary by about 10 percent. The main differences in these methods are the temperatures and times used to dry the latex.

The measured viscosity can also vary depending on the method of testing. Viscometers made by Brookfield are most often used to test latex (ASTM D 1417). Various Brookfield viscometers are used at different spindle speeds and give different values. The temperature at which the test is conducted also affects the viscosity. Different combinations of these factors can change the measured viscosity considerably. Hence, it is important when reporting Brookfield viscosity values to report the model number, spindle number and speed, and the temperature used for the test.

Tests on Dried Film

The properties of dried film will also have an influence on the performance of latex-modified mortars and concretes. Identifiable properties of dried film include (*20*): swelling in water, whitening of the film in contact with water, extensibility, recovery, tensile and flexural strength, adhesion, water extractables content, gel content, thermal/mechanical behavior, monomer composition, glass transition temperature, clarity, color, glow, refractive index, resistance to alkaline hydrolysis, resistance to solvents and aggressive chemicals, Mooney viscosity, abrasion resistance, tack, and surface hardness. The age and curing conditions of dried film will have a considerable effect on film properties.

Films of two latexes were tested by Frondistou-Yannas and Shah (*25*) for tensile strength before and after immersion in saturated lime solution, and after drying subsequent to immersion in saturated lime solution. During the 20-day immersion, changes in weight of the films and pH value of the solutions were measured. Tensile strength of polyvinyl acetate film was significantly reduced during immersion. For SBR and PVAC latex films, drying subsequent to immersion increased their strength to about twice the preimmersion strength, as shown in Figure 2. Although styrene-butadiene latex films are less resistant to change when immersed in lime solution, their stiffness increases after drying. Immersion of polyvinyl acetate films resulted in significant film swelling and in a marked decrease in the alkalinity of the solutions. No such change was observed for styrene-butadiene rubber films (Figure 3) (*25*). This may be due to the polyvinyl acetate undergoing hydrolysis in the presence of water.

Ohama and Ibe (*26*) reported that, when the bound styrene content increases, the film's tensile strength increases for a given percent elongation, as shown in Figure 4. Latex films were made from the styrene-butadiene latexes with bound styrene content varying from 30 to 70 percent. Films were dried on glass plates at room temperature and tested.

Some typical physical properties of acrylic latexes used with portland cement are shown in Table 6 (*24*).

ADVANTAGES OF LATEXES

Latexes are becoming more important because of their health and safety advantages over solvent-based products. Some of these advantages include:

- Nontoxicity,
- Nonflammability,
- Reasonable viscosity at 60 percent solids compared to a 10 percent limit for solvent-based systems,
- Emulsion polymerization permits customization of properties (*20*).

TABLE 5
RESULTS OF THREE DIFFERENT TYPES OF TESTS FOR NONVOLATILE CONTENTS (*19*)

Test method temperature	70°C (158°F)	105°C (221°F)	125°C (257°F)
Drying time (hours)	16.0	0.75	0.50
Nonvolatile content (%)	62.7	61.3	58.3

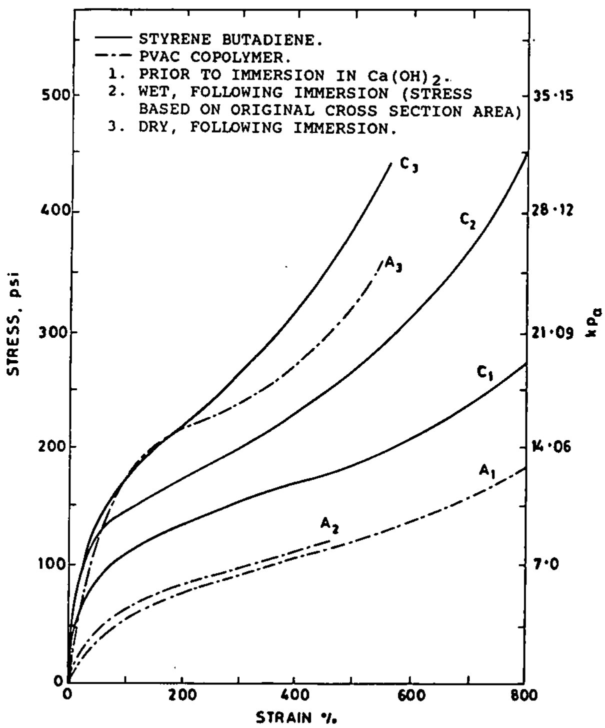


FIGURE 2 Tensile stress strain curves of polymer film (*27*).

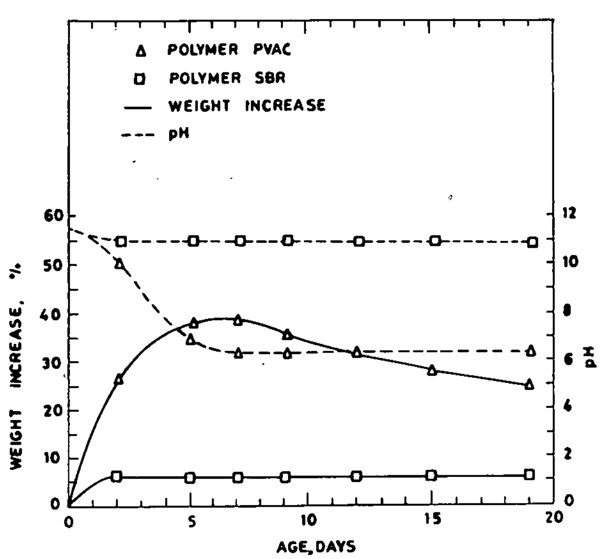


FIGURE 3 Effects of immersion in lime solution on polymer films (*27*).

CONCEPT OF LATEX MODIFICATION

Emulsion polymerization is of special interest in preparing polymers for modifying portland cement. An excellent hypothesis supported by electron microscope and other studies has been put forward by Ohama (*27*) to explain the latex modification process for SBR latexes. Latex modification happens in two processes: cement hydration and latex film formation. Normally the latex film formation occurs after the cement hydration. In surfaces where there is loss of water due to evaporation, the film formation will be faster than the cement hydration. When polymer latexes are mixed with fresh cement systems, the polymer particles are uniformly dispersed in the system. In an emulsion polymer system, as the water evaporates, the discrete polymer spheres approach each other and eventually touch and fuse into a continuous film. The hydrated cement phase and polymer phase interpenetrate, and aggregates are bound by this comatrix phase. The formation of a comatrix is shown in Figure 5 and the process of film formation on the cement hydrates is depicted in Figure 6.

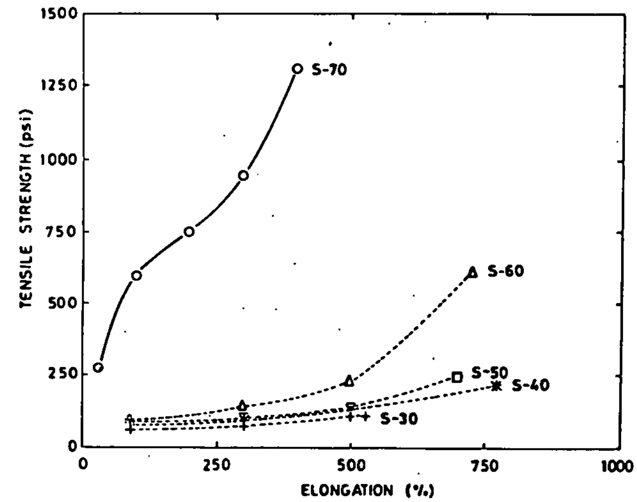


FIGURE 4 Tensile strength vs elongation of latex film (*28*).

TABLE 6
TYPICAL PHYSICAL PROPERTIES OF ACRYLIC LATEX FOR CEMENT (*22*)

Appearance	White, milky liquid
Solids content	47± 1.0%
pH when packed	8.8 to 10.0
Specific gravity	1.059
Pounds per gallon (kg/m^3)	8.8 (1,045)
Freeze-thaw stability	5 cycles
Minimum film formation temp (MFFT)	10° to 12°C (50° to 54°F)

In the cement latex system, the cement gel is gradually formed by hydration of cement. Water is saturated with calcium hydroxide formed during the hydration. It is possible that the $Ca(OH)_2$ in the water reacts with the silica surface of the aggregate and forms a calcium silicate layer. According to recent studies, the formation of $Ca(OH)_2$ and ettringite in the contact zone between cement hydrates and aggregates contributes to the bond between them (*28,29*).

With loss of water due to evaporation and cement hydration, polymer particles are gradually confined in capillary pores. As cement hydration proceeds, and the capillary water is reduced, the polymer particles coalesce to form a continuous close-packed layer on the surfaces of the cement gel and unhydrated cement

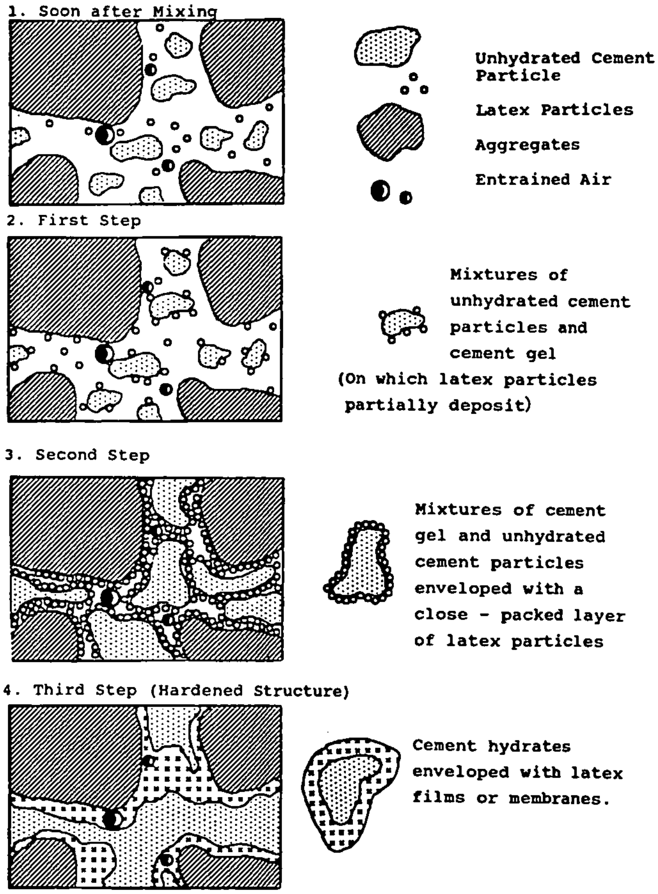


FIGURE 5 A simple model of latex-cement comatrix (*29*).

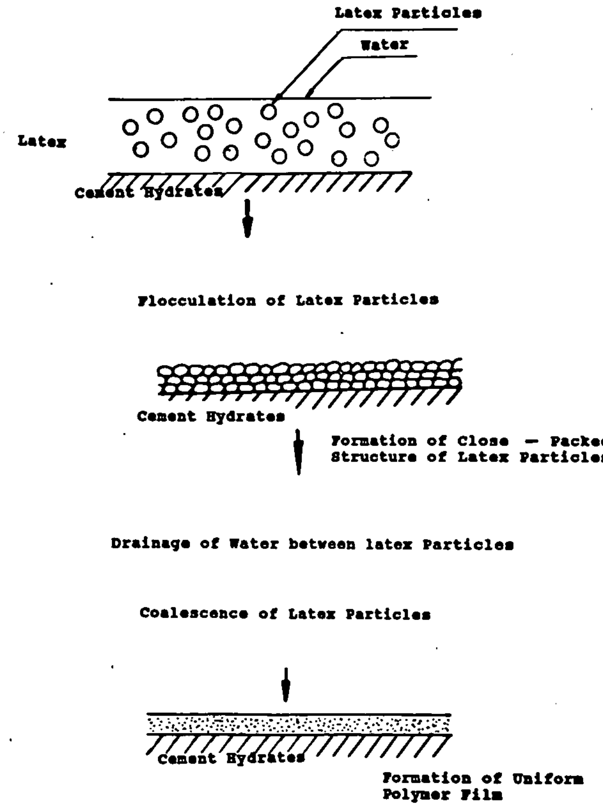


FIGURE 6 Simplified model of formation of latex film (*29*).

particle mixtures, and simultaneously adhere to the mixtures and the silicate layer over the aggregate surfaces. Latex particles are typically greater than 100 nm in diameter and therefore cannot penetrate the very small capillary pores in the cement paste. Hence, the permeability-reducing characteristics of latex can be more effective in the voids and larger capillaries.

Some chemical reactions may take place between calcium and other metallic ions (e.g., magnesium) in the cement and particle surfaces of the reactive polymer to improve the bond between the cement hydrates and aggregates. These reactions may also improve the inter-particle bonds, improving as well the strength and toughness of the hardened latex-modified mortar and concretes.

It was also observed that shrinkage stress-induced microcracks in latex-modified mortar and concrete are bridged by the formation of polymer films or membranes and prevent crack propagation. The latex particles also reduce the rate and extent of moisture movement by blocking the water passages and reducing evaporation of excess mixing water (which would otherwise result in drying shrinkage). This results in increased tensile strength and fracture toughness. During the initial stages, latex-modified concrete and mortar are more sensitive to plastic shrinkage cracking than plain mortar or concrete because of the water reducing influence of latex in the mixture. Water evaporation takes place at the surface of the mixture. When the latex solids coalesce before adequate cement hydration occurs, the cement paste may shrink before sufficient tensile strength develops to restrain crack formation. Therefore, surface evaporation should be prevented or minimized by adequate curing systems.

The polymer film sealing effect provides increased waterproofness or watertightness, resistance to moisture, air, and chloride ion permeation, increased chemical resistance and freeze-thaw durability.

All improvements increase with an increase in the polymer content or polymer/cement ratio. The optimum degree of polymer modification is usually achieved at 10 to 20 percent latex solids by weight of cement in the mixture. Excess use of latex solids is not economical and can cause excessive air entrainment and film formation on concrete surfaces. This also may cause discontinuities in the formed monolithic network structure and reduced strength.

The latex/cement ratio and the type of latex used will also affect the pore structure. The porosity, pore volume, pore distribution, and pore shape in latex-modified mortar are different from unmodified mortar. The former has a lower number of pores with a radius greater than 200 nm, but significantly more with a radius of 25 nm or less (*30*). The total porosity or pore volume tends to decrease with increasing polymer/cement ratios, resulting in decreased permeability, reduced carbonation, and increased frost-resistance. Wagner's experiments (*31*) have shown that although latex-modification can either accelerate or retard the initial setting time, it has little or no effect on the final cement hydration rate. The unmodified hardened cement paste generally is considered predominantly an agglomerated structure of calcium silicate hydrates and calcium hydroxide bound together by the relatively weak Van der Waal's forces that are present in this ionic environment. Microcracks occur easily under stress in such a paste, resulting in low tensile strength and fracture toughness. In latex-modified mortar and concrete, it appears that the microcracks are held together by the latex films or membranes that reduce crack propagation. This also gives a strong cement hydrate-aggregate bond (*27*).

CHAPTER THREE

MATERIALS AND MIXTURE PROPORTIONS

The materials and mixing procedures for latex-modified mortars and concretes are much the same as those for conventional portland cement mortars and concretes. Latexes in a dispersed form are simply used in larger quantities than other common chemical admixtures, such as air-entraining agents, water-reducing agents or superplasticizers.

Commercially Used Latexes

In Japan, the quality of latex-type cement modifiers is controlled by Japanese Industrial Standard (JIS) A6203. Table 7 shows the quality requirements for cement modifiers. In the U.S., the most commonly used latex for concrete overlays on bridge decks is styrene-butadiene and it has been evaluated for such overlays by the Federal Highway Administration (FHWA)(*23*). Other latexes in concrete are used for repair and rehabilitation work, and in mortar applications such as patching, floor leveling, tile grout and adhesive, stucco, basement waterproofing, and decorative and functional cement coatings. The choice of a particular latex depends on the specific application.

Cements

Portland cement Types I and II are commonly used; however, when early strength is required, Type III may be used. When colored mortars or concretes are required, white cement is recommended in conjunction with tinted acrylic or vinyl-acetate latexes. According to their applications, ultrahigh-early-strength portland cement, sulfate resisting portland cement, moderate heat portland cement, blended cement and high alumina cement are also used. However, air-entraining cements should not be used in latex mixtures.

Admixtures

Air-entraining admixtures should not be used because of inherent air entrainment due to latex addition. Water reducers usually are not needed for latex-modified mortars and concretes. However, workability additives, such as methyl cellulose, are used for some mortar applications.

Aggregates

The aggregates used for latex-modified mortars and concretes are similar to those used for conventional mortar and concrete mixtures. Fine and coarse aggregates such as river sands, gravels, crushed sands and stones, silica sands and artificial lightweight aggregates are also used for latex-modified mortars and concretes. Silica sands and siliceous crushed stones are sometimes recommended for corrosion resistant structures. The aggregates should be clean, sound, and properly graded. In some situations, such as when exposed aggregate surfaces are needed, gap-graded aggregates can be used efficiently. Selection of aggregate size and type normally depends on the thickness of the application, as well as type and density of reinforcement.

TABLE 7
QUALITY REQUIREMENTS FOR LATEXES SPECIFIED IN JIS A 6203

Type of test	Evaluation	Requirement
Latex test	Appearence	Exclusive of coarse particles, foreign substances and coagulants
	Total solids	Not less than 35.0% and within ±1.0% of the value marked by the manufacturer
Polymer-Modified Mortar Test	Flexural strength	Not less than 562 psi (3.9Mpa)
	Compressive strength	Not less than 1420 psi (9.8Mpa)
	Adhesion	Not less than 142 psi (0.98Mpa)
	Water absorption	Not more than 15%
	Amount of water permeation	Not more than 0.066 lb (300g)
	Length change	0 to 0.150%

MIXTURE PROPORTIONING-GENERAL

The mixture proportioning of latex-modified concrete and mortar is done in a way similar to that of portland cement mortar and concrete because the same variables influence the physical properties of both unmodified and modified mortars and concretes. The effect of type and quantity of fine aggregate, coarse aggregate, and cement, as well as the quantity of water, is similar in both portland cement and latex-modified mortars and concretes. However, as a general rule, the least amount of water should be used to achieve a suitable, workable consistency required for the end use. Including latex in portland cement replaces some of the water required to achieve necessary workability because latex acts as a dispersant of the portland cement and thus increases flowability. In proportioning the mixture, the water in the latex should be taken into consideration. Usually, there will be about a 50 percent water reduction if latex is used.

The mixture proportioning for latex-modified mortar and concrete should recognize its improved properties, such as tensile and flexural strengths, extensibility, adhesion, durability, and watertightness, over conventional mortar and concrete. These properties are controlled by the polymer/cement ratio rather than the water/cement ratio. Therefore, based on the end use, the polymer/cement ratio is specified.

Mortar Proportions

In latex-modified mortars, the cement/fine aggregate ratios range from 0.2 to 0.5 (by weight) depending on the end use; the water/cement ratios range from 0.3 to a maximum of 0.6, including water in the latex. Latex/cement ratios of 5 to 20 percent are used, with 15 percent the most frequently used value.

ACI Committee 548A recommended mortar proportions (*22*) are given in Table 8. In the U.S., proportions recommended by the product manufacturer generally are used. For acrylic latex-modified portland cement mortar, the proportions suggested by Lavelle (*24*) are given in Table 9. Ohama (*18*) has reported standard mixture proportions for latex-modified mortars used for various applications (Table 10).

Concrete Proportions

In latex-modified concrete mixtures, there is usually more fine aggregate than coarse aggregate because overlays (the typical end use) require texturizing for skid resistance. The overlays must be placed on scarified surfaces and the extra sand helps to prevent segregation on higher slopes. Higher sand content also reduces bleeding. Water/cement ratios less than 0.40, with slumps of 4 to 7 in. (102 to 178 mm), are typical for SBR latex-modified concretes. The maximum air entrainment is limited to 6.5 percent. A typical mixture proportion using SBR latex recommended by ACI Committee 548A (*22*) is given in Table 11. By using Type III cement and increasing the cement content, new mixture proportions have been developed recently to produce high-early-strength latex-modified concrete to speed up overlay construction (*34,35*). These overlays have been subjected to traffic in less than a day. Table 12 gives the mixture proportions for high-early-strength latex-modified concrete used by Sprinkel (*32*) for installation of an LMC overlay on a bridge on Route 340 in Virginia. A comparison of the chosen proportions with typical proportions used for standard latex-modified concrete and typical unmodified bridge-deck concrete is also presented in Table 12.

TABLE 8
TYPICAL PROPORTIONS FOR SBR LATEX-MODIFIED MORTAR MIXTURES (*22*)

Cement	100 lb (45.4kg)
Sand	290 lb (131.5 kg)
Latex*	3.7 gal (14.1 litres)
Water	2.6 gal (10.0 litres)

* assumed 48% solids, 52% water by weight

TABLE 9
PROPORTIONS FOR ACRYLIC-MODIFIED CEMENT MORTARS TYPICAL FORMULATION (*24*)

Ratio of polymer solids to cement 0.10

Material	Weight lb (kg)
Sand	300.0 (136)
Portland cement (Type 1)	100.0 (45)
Acrylic latex (47% solids)	21 (9.5)
Defoamer	0.1 (0.045)
Water	29 (13.15)
Water-cement ratio	0.4
Sand-cement ratio	3.0

A Rational Mixture Proportioning Method

A rational mixture proportioning method for polymer-modified concretes was proposed by Ohama (*34,35*). Based on extensive test results using SBR latex, he developed relationships

TABLE 11
TYPICAL PROPORTIONS FOR SBR LATEX-MODIFIED CONCRETE MIXTURES ACI COMMITTEE 548A (*22*)

Cement	685 lb (311 kg)
Sand	1710 lb (776 kg)
Coarse aggregate	1140 lb (517 kg)
Latex*	24.5 gal (92.8 litres)
Water	19.0 gal (72.0 litres)

* assumed 48% solids, 52% water by weight

TABLE 10
MIXTURE PROPORTIONS FOR LATEX-MODIFIED MORTARS (*18*)

Type	Applications	Standard mixture proportion cement:sand:latex by weight	Thickness of trowelling or coating inch(mm)
Paving materials	Floors for houses, warehouses, offices, shops, toilet floors	1 : 3 : 0.2-0.3	0.2-0.4 (5-10)
Floorings	Passages, stairs, chemical plants, railway platforms, roads, garages	1 : 3 : 0.3-0.5	0.4-0.6 (10-15)
Waterproofing materials	Concrete roof decks, mortar and concrete block walls, water tanks, swimming pools, septic tanks, silos	1 : 2-3 : 0.3-0.5	0.2-0.8 (5-20)
Adhesives	Bonding flooring, walling, and heat insulating materials to concrete walls and floors	1 : 0-3 : 0.2-0.5	
	Jointing new concrete to old concrete and new mortar to old mortar	1 : 0-1 over 0.2	
Anticorrosive	Effluent drains, linings chemical factory floors, grouting for acid-proof tile, septic tanks, foundations for machinery plants, floors for chemical labs, pharmaceutical warehouses, etc.	1 : 2-3 : 0.4-0.6	0.4-0.6 (10-15)
Deck coverings	Internal and external ship decks, bridge decks-undercoat	1 : 2-3 : 0.9-1.0	.04-.08 (1-2)
	Train or car floors-midcoat	1 : 3 : 0.4-0.6	0.2-0.24 (5-6)
	Foot bridge decks-topcoats.	1 : 3 : 0.5-0.6	.12-.16 (3-4)

between slump, "slump control factor (τ)", binder-void ratio (α), and compressive strength (f'_c).

The slump control factor is defined as

$$\tau = V_p + V_w \quad (1)$$

and the binder/void ratio is defined as

$$\alpha = V_c + V_p/V_a + V_w \quad (2)$$

where

Vp = Volume of polymer per unit volume of polymer-modified concrete

Vw = Volume of water per unit volume of polymer-modified concrete

Vc = Volume of cement per unit volume of polymer-modified concrete

Va = Volume of air per unit volume of concrete

Based on experimental results, it was concluded (*34*) that for latex-modified concrete, slump can be accurately predicted for each latex type and each fine to coarse aggregate ratio by the equation

$$S = A\tau - B(1 - F_p) \quad (3)$$

and the compressive strength can be predicted for various polymer cement ratios by the equation

$$f'_c = C\alpha + D \quad (4)$$

where, F_p is the fine aggregate percent by volume (fine/coarse aggregate ratio), and A,B,C, and D are empirical constants evaluated from experimental results. Using these equations, some nomographs were prepared (*34*).

1. Slump vs Slump control factor τ. Figure 7 shows that as the sand/aggregate ratio decreases, the slump increases for a given slump control factor.
2. Cement content vs binder/void ratio α. Figure 8 shows that more cement must be used as latex solids/cement ratio decreases for a given binder/void ratio.
3. Water/cement ratio vs binder/void ratio α (Figure 9).
4. Compressive strength vs binder/void ratio α (Figure 10).

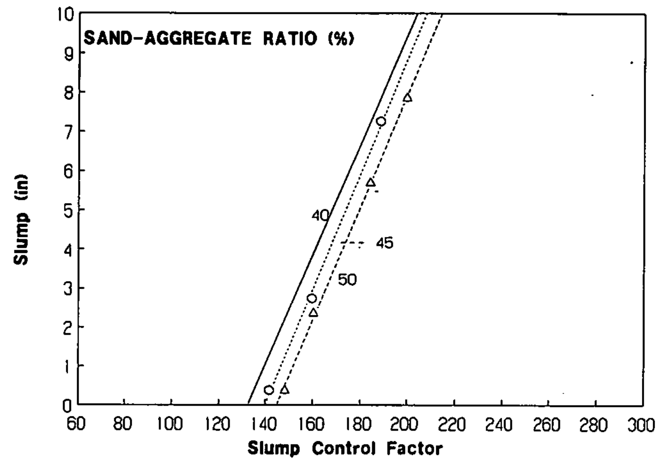


FIGURE 7 Slump vs slump control factor (from *36*).

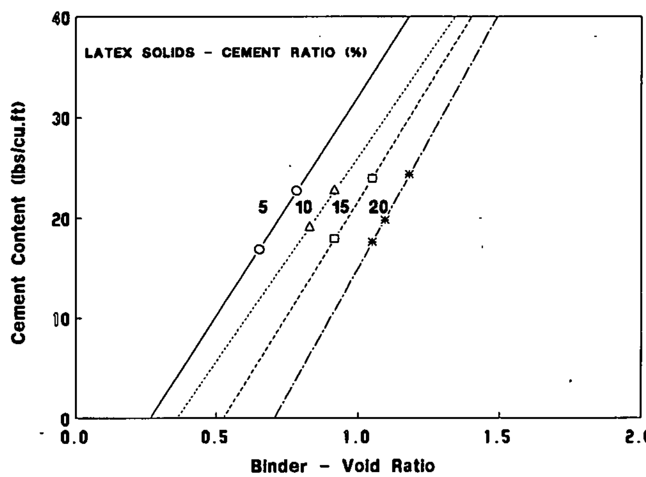


FIGURE 8 Cement content vs binder/void ratio (from *36*).

A flow chart (Figure 11) illustrates the procedure to be used in selecting the mixture proportions for SBR latex-modified concretes.

TABLE 12
COMPARISON OF MIXTURE PROPORTIONS FOR HIGH-EARLY-STRENGTH LATEX-MODIFIED CONCRETE OVERLAY AND OTHER BRIDGE-DECK CONCRETES USED IN VIRGINIA (*32*)

Material	Conventional concrete	LMC	LMC - HE
Cement, lb/yd^3	635	658	815
Water-cement ratio	0.45	0.37	0.34
Latex, gal/bag	0	3.5	3.0
Air, %	5 - 8	3 - 7	3 - 7
Fine aggregate lb/yd^3	1,178	1,571	1,402
Coarse aggregate lb/yd^3	1,809	1,234	1,142

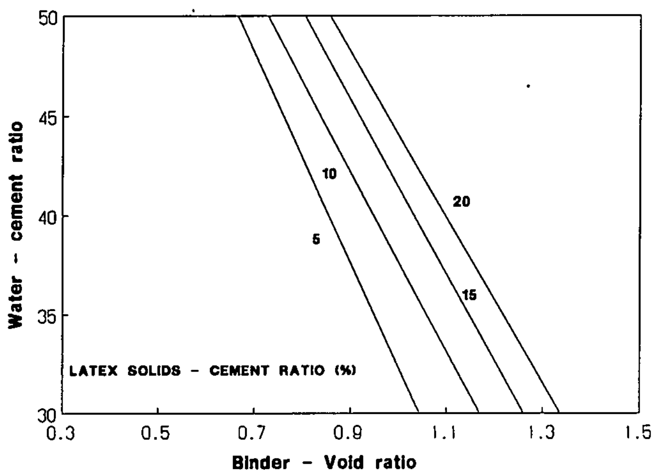


FIGURE 9 Water/cement ratio vs binder/void ratio (from *36*).

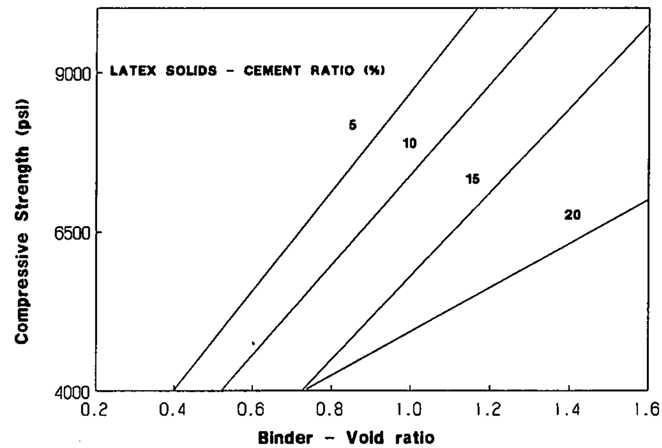


FIGURE 10 Compressive strength vs binder/void ratio (from *36*).

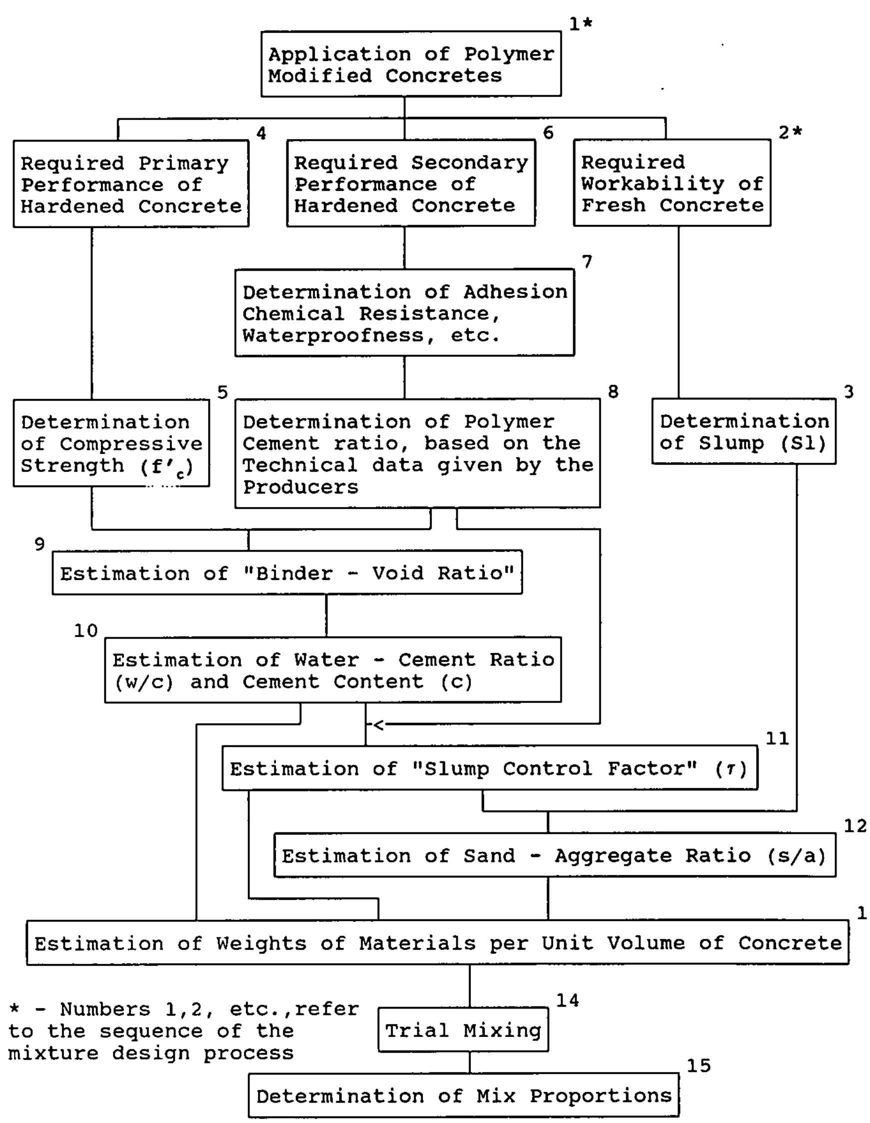


FIGURE 11 Flowchart for selecting mixture proportions for latex-modified concrete (*36*).

CHAPTER FOUR

PROPERTIES OF LATEX-MODIFIED MORTARS AND CONCRETES

In general, the properties of fresh and hardened latex-modified mortars and concretes show improvement over those of unmodified mortars and concretes as discussed below. However, these improvements are influenced by various factors that tend to interact with each other. The main factors are type and quantity of materials used (such as latexes, cements, and aggregates), polymer/cement ratio, water/cement ratio, binder/void ratio, air content, placement and curing procedures, testing methods, and environmental conditions during placement and during service.

FRESH MORTARS AND CONCRETES

Air Entrainment

The surfactants included as emulsifiers and stabilizers in polymer latexes cause excessive air entrainment in latex-modified mortars and concretes compared to unmodified concretes and mortars. Air entrainment causes a reduction in strength (approximately a 5 percent reduction in compressive strength for every 1 percent increase in the air content)(*36*). Therefore, excessive air entrainment is controlled by the addition of an antifoaming agent such as silicone. The antifoaming agent is usually added by the latex manufacturer. Figure 12 shows the effect of a silicone emulsion-type antifoaming agent on the air content of latex-modified mortars (*37*). As shown in the figure, the relationship between antifoaming agent content and air content depends on the type of latex used; however, the trend is always the same. In addition, the composition of the cement and the type of aggregate can affect the air content. It is difficult to entrain more air when larger size aggregates are used. Therefore, it is important to evaluate the actual mixture proportions before using them in the field. The air content of most latex-modified mortars ranges from 5 to 20 percent, and that of most latex-modified concretes is less than 2 percent (*18*). The relationship between the polymer/cement ratio and the air content for latex-modified mortars is shown in Figure 13 (*37*) and the same for latex (SBR) modified concrete is shown in Figure 14 (*38*). For an increase in polymer/cement ratio, variation of the air content in the latex-modified mortar is considerably higher than that in the latex-modified concrete. The addition of an air-entraining agent is not required for resistance to freezing and thawing since the latex itself apparently provides this protection. Therefore, it is recommended that LMC should include a maximum air content of 6.5 percent, and not a minimum (*22*).

Workability

The addition of latex to portland cement mortar and concrete increases their workability. This is caused by the ball bearing action of polymer particles and entrained air and by the dispersing effect of the surfactants in the latexes (*18*). The effect of water/cement ratio and latex content on workability, measured as the flow using the ASTM C 230 test procedure, is shown in Figure 15 (*37*) for latex-modified mortars. All types of latexes tested at various water/cement ratios improved workability. A

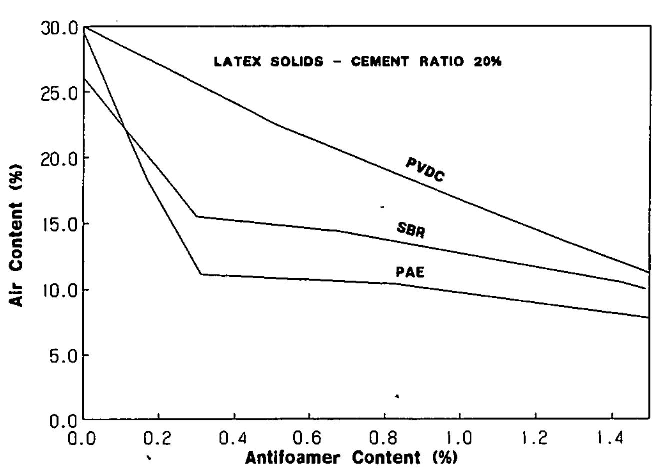


FIGURE 12 Antifoamer agent vs air content of mortars (from *37*).

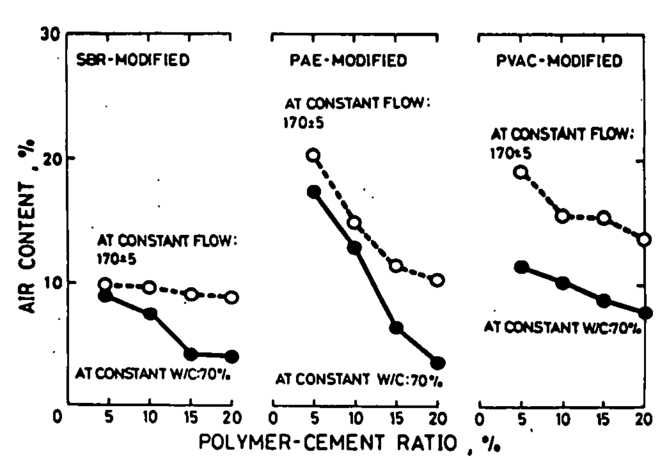


FIGURE 13 Polymer/cement ratio vs air content of latex-modified mortars (*37*).

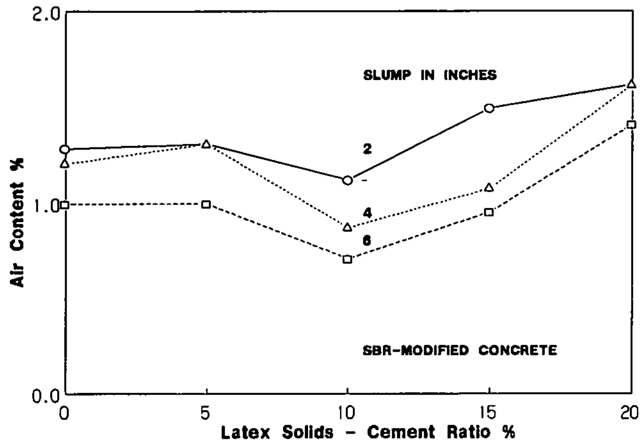


FIGURE 14 Latex solids/cement ratio vs air content for SBR latex-modified concretes (from *37*).

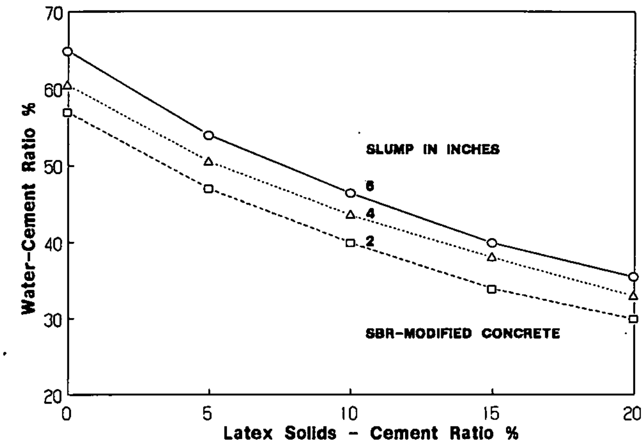


FIGURE 16 Relation between latex solids/cement ratio and water/cement ratio for constant slumps (from *18*).

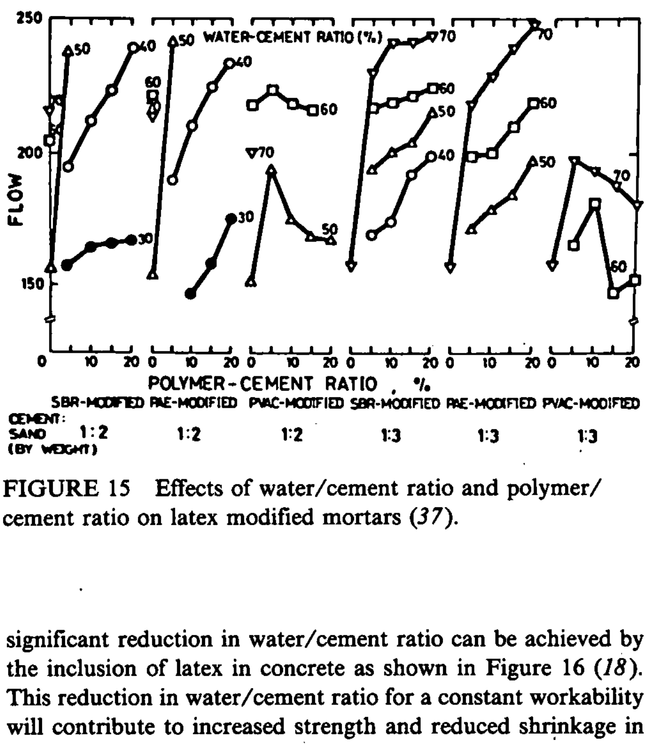


FIGURE 15 Effects of water/cement ratio and polymer/cement ratio on latex modified mortars (*37*).

significant reduction in water/cement ratio can be achieved by the inclusion of latex in concrete as shown in Figure 16 (*18*). This reduction in water/cement ratio for a constant workability will contribute to increased strength and reduced shrinkage in the hardened mortar and concrete. Experimental results reported by Ohama and Kan (*39*) have shown that for the same workability, a considerably reduced water/cement ratio can be achieved with the addition of latex (Table 13).

As in the case of conventional concretes, there is a loss of slump over time in latex-modified concretes. A study by the FHWA (*23*) reports that slump loss was similar for both conventional concretes and latex-modified concretes.

In a recent study, Kuhlman and Foor have demonstrated that with the addition of SBR latex (latex solids/cement ratio of 0.15) workable concretes with low water/cement ratios can be produced using Michigan and Maryland aggregates (*40*). Both mixtures had a fine to coarse aggregate ratio of 1.20:1.04, and a cement content of 658 lbs/yd^3 (390 kg/m^3). A slump of 8 in. (203 mm) was obtained with a water/cement ratio of 0.33 for the Michigan aggregate and a slump of 6 in. (152 mm) was achieved with a water/cement ratio of 0.37 for the Maryland aggregate.

Setting Time

It takes slightly more time for latex-modified mortars and concretes to set than for conventional portland cement mortars and concretes. The time difference depends on the latex type and the quantity used. The setting behavior of mortars for various latexes is compared with that of a corresponding unmodified mortar in Figure 17 (*41*). The setting behavior of SBR latex-modified concrete for various latex contents is shown in Figure 18 (*38*). Similar results were also reported by Smutzer and Hockett (*42*). The setting time increases with an increase in the latex/cement ratio. Natural rubber latex causes the maximum delay in setting time. The delay in setting time is due, in part, to the fact that surfactants contained in latexes inhibit the hydration of cement (*37*). Studies by Zivica (*43*) showed that in the case of PVAC-modified concrete, the hydration of cement is inhibited by the absorption of the surfactants on the binder surface. Setting time is a function of the hydration of cement and hence a delay in the hydration process is reflected in increased setting time.

Working Time

Working time, which is different from setting time, is the time available to place, work, and finish the mortar or concrete surface. It depends on the drying of the surface. During the drying process, a "crust" forms that hinders proper finishing of the surface. Air temperature, humidity, and wind speed influence the "crust" formation and determine working time. The working time is about 15 to 30 min after mixing latex in the mortar or concrete and exposing it to air. The maximum mixing time recommended is 5 min, so the use of transit mixers is not feasible (*22*).

TABLE 13
MIX PROPORTIONS OF LATEX-MODIFIED CONCRETES FOR CONSTANT WORKABILITY (*39*)

Type of concrete	Cement content lb/yd^3 (kg/m^3)	Latex solids-cement ratio (%)	Water-cement ratio	Sand-aggregate ratio	Slump inch (mm)
Unmodified	507 (300)	0	.675	.45	6.3 (160)
SBR modified	507 (300)	5	.583	.45	6.3 (160)
		10	.503	.45	6.1 (155)
		20	.410	.45	6.3 (160)
EVA modified	507 (300)	5	.587	.45	6.1 (155)
		10	.523	.45	6.1 (155)
		20	.443	.45	6.1 (155)

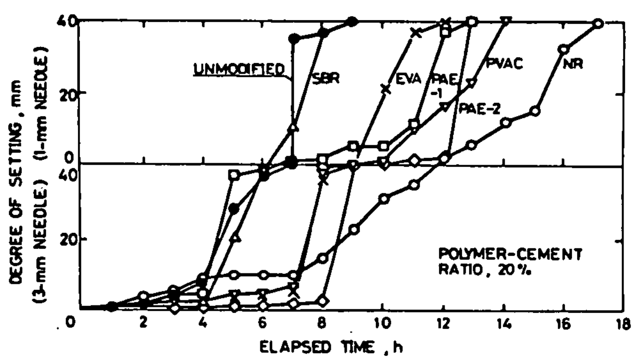


FIGURE 17 Elapsed time vs degree of setting of latex-modified mortars (*41*).

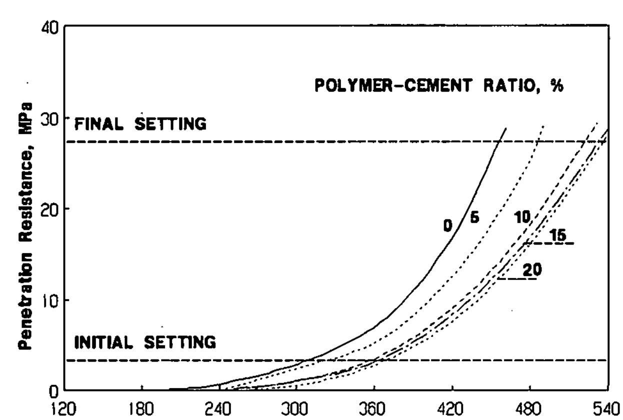


FIGURE 18 Elapsed time vs penetration resistance of SBR-modified concrete (from *38*).

Bleeding and Segregation

There is considerably less bleeding and segregation in latex-modified mortars and concretes when they have high workability. This is due to the hydrophobic colloidal properties of latexes. The air-entraining and water-reducing effects of surfactants will also contribute to the reduction in bleeding and segregation, resulting in increased strength and watertightness in the hardened products.

Finishability

The finishing characteristics of latex-modified mortars and concretes are different from those of unmodified mortars and concretes; LMM and LMC have increased drag and stickiness on finishing tools. A thin crust of approximately 0.07 in. (2 mm) forms if the surface is allowed to dry. Formation of this crust depends on environmental conditions such as temperature, wind speed, and humidity. Therefore, it becomes difficult to finish when there is a delay in the finishing operation. After mixing and exposure to air, the finishing time available is generally 15 to 30 min (*22*).

Water Retention

Latex-modified mortars and concretes exhibit excellent water retention due to hydrophobic and colloidal properties of the latexes, resulting in reduced water evaporation. Latex particles fill and seal voids, form an impermeable latex film, and retain a sufficient amount of water for cement hydration. Therefore, a dry cure is preferred rather than a wet cure or water cure for latex-modified systems. The water retention properties also help in preventing the "dry-out" phenomenon (the lack of cement hydration due to water loss in the mortar or concrete) in thin latex linings and coatings on highly water-absorbable substrates such as dried cement mortars and ceramic tiles (*18*).

The water retention of latex-modified mortars was measured by Ohama (*37*) according to ASTM C 91 (Standard Specification for Masonary Cement) and JIS A6908 (Finish Coatings and Wall Coverings for Decorative Use) and is given in Figure 19. Water retention generally increases with increasing latex/cement ratio, and becomes nearly constant at latex/cement ratios between 5 and 10 percent (*37*).

HARDENED MORTARS AND CONCRETES

Effects of Curing Conditions on Strength

The type and duration of curing have significant influence on strength and rate of strength development. To obtain maximum

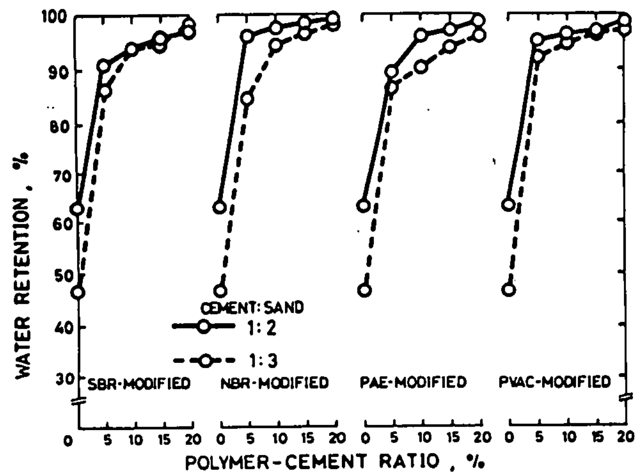


FIGURE 19 Polymer/cement ratio vs water retention of latex-modified mortars (*37*).

strength, latex-modified mortars and concretes are often cured in 100 percent relative humidity for the first 24 to 48 hrs and then dry cured at ambient temperature and humidity. This is unlike unmodified mortars and concretes where higher strength is achieved by wet curing alone. Air curing of LMM and LMC allows any excess water to evaporate and allows formation of the latex film; this is desirable because latex film formation in the internal structure is the main reason for the improved properties in latex-modified mortars and concretes.

The effects of curing conditions on the compressive and flexural strengths of latex-modified mortars and concretes are reported by Lavelle (*24*) and Ohama (*27,44*) as shown in Figures 20 and 21. For the same latex/cement ratio, flexural strength of acrylic latex-modified mortar wet cured (one day at 95 percent relative humidity plus six days of immersion in water) is significantly lower than that of air cured mortar (Figure 20). If the latex-modified specimens that were wet cured are allowed to dry eventually, the strength is restored. This shows that the basic strength will be achieved once the latex is allowed to undergo

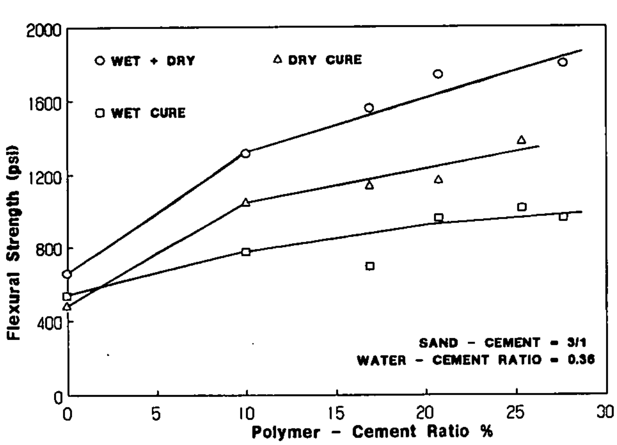


FIGURE 20 Effect of curing conditions on flexural strength of latex-modified mortars (from *39*).

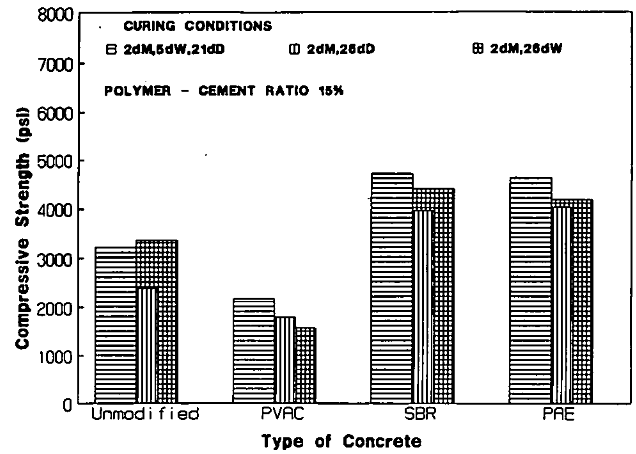


FIGURE 21 Effect of curing conditions on compressive strength of unmodified vs latex-modified concretes (from *44*).

film formation. After the film formation, standard moist curing will not adversely affect strength development. The strength increase will be similar to that of conventional mortar and concrete.

Figure 21 shows the effect of a 2-day moist, 5-day wet, and 21-day dry curing on the compressive strength of latex-modified concretes (*44*). This confirms the earlier statement that optimum strength in latex-modified concretes is achieved when a reasonable degree of cement hydration at early ages under wet conditions is allowed. This should be followed by dry conditions to promote latex film formation. Due to the smaller sizes of the test specimens, mortars are more sensitive to curing conditions than are concretes. Immersion in water after dry curing causes a sharp reduction in the strength of all latex-modified systems (*18*). However, the strength is recovered after subsequent drying (*37*).

Compressive Strength

Enhancement of compressive strength is not the main objective of adding latex to portland cement mortars and concretes. However, an increase in compressive strength may be achieved with the same workability because of the reduction in water/cement ratio achieved with the addition of latex. For the same durability requirements, a reduced air content is adequate in latex-modified mortars and concretes, which consequently increases the strength, as shown in Figure 22. An increase in the antifoaming agent content (consequently, a decrease in air content) thus increases the compressive strength (*37*).

For the same cement content, the 3-day, 7-day and 28-day compressive strengths of latex-modified concretes reported by various investigators (*23,45,46*) are given in Table 14 (*22*). For various water/cement ratios and polymer/cement ratios the 28-day strengths for acrylic latex-modified mortars reported by Lavelle (*24*) are given in Table 15. The influence of the type of curing on strength properties is also shown in Table 15. Two studies (*23,39*) were conducted on the effect of cylinder specimen size on measured compressive strength of LMC and both studies showed that the influence of specimen size on measured compressive strength was negligible (Figure 23).

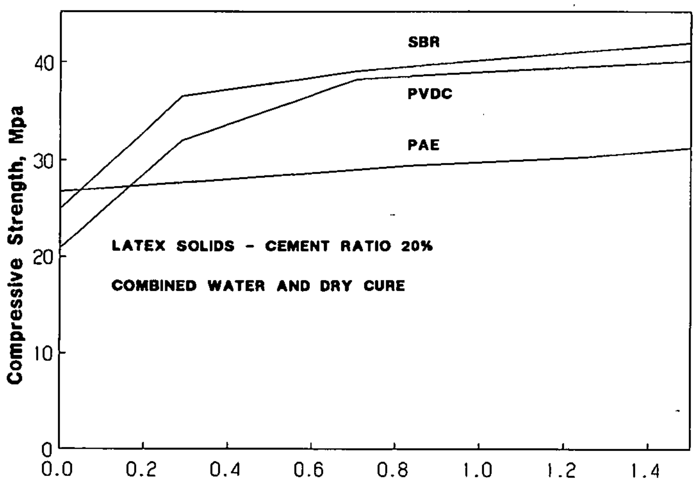


FIGURE 22 Silicone antifoamer agent vs compressive strength for latex-modified mortars (from *37*).

Tensile and Flexural Strengths

Adding latex to portland cement mortars and concretes considerably increases the tensile and flexural strengths. This increase is due to improvement in the cement hydrate-aggregate bond and to the high tensile strength of latex film. Various factors, such as the type and quantity of latex, cement, aggregates, and the water/cement ratio, curing method, and testing procedures affect the measured flexural and tensile strengths. The density of the latex-modified mortar depends on latex/cement ratio and the amount of air-entrainment in the mortar. Figure 24 shows the effect of density on the tensile strength of acrylic latex-modified mortar (*24*). There seems to be a linear relationship between the density and tensile strength. An increase in latex/cement ratio increases the flexural strength (Figure 20).

The flexural strength of SBR latex-modified mortar depends on the tensile strength of the dried film when the latex/cement ratio is above 10 percent (*18*) as shown in Figure 25. The flexural strength is not significantly affected by the type of cement (*37*) as shown in Figure 26. However, high alumina cement could increase the strength to 1.5 to 2 times higher than that of mortars comprised of other cements. This is due to a difference in structure formation at the initial stage of setting (*18*). As with unmodified mortar, the flexural strength is increased with an increase in the size of the sand (increased fineness modulus) as indicated in Figure 27 (*37*).

Deformation Behavior and Modulus of Elasticity, Ductility, and Toughness

Adding latex in sufficient quantities will increase the ultimate strain capacity, ductility, and toughness of portland cement mortars and concretes. However, there can be a significant, often undesirable, change in modulus of elasticity in compression for PVAC and a small change for PAE and SBR latexes. The increase in ductility and strain capacity depends on the latex/cement ratio. This can be a very beneficial improvement when structures have to resist dynamic and impact loads, as in the case of earthquake- and blast-resistant structures and machine foundations. The tensile stress versus strain relationships for various polymer/cement ratios are shown in Figure 28. The tensile strain at failure is two to three times higher than that of unmodified concretes. The modulus of elasticity in tension decreases as the latex/cement ratio increases (*47*). It has also been reported by Ohama (*18*) that for latex-modified mortar with 20 percent polymer/cement ratio the maximum compressive strain had increased to two to three times more than that of unmodified mortar. The increased strain capacity is attributed to the polymer film, effectively halting the propagation of microcracks.

The modulus of elasticity in compression and the Poisson's ratio of latex-modified concretes are given in Table 16 (*48*). An increase in the polymer/cement ratio generally reduces the modulus of elasticity. The Poisson's ratios of PAE and SBR modified concretes are nearly equal to those of unmodified concrete regardless of the polymer/cement ratio. However, for the PVAC modified concrete the Poisson's ratio increases with an increase in polymer/cement ratio. Two other studies (*49,50*) also

TABLE 14
COMPRESSIVE STRENGTH OF LATEX-MODIFIED CONCRETES (AFTER *22*)

Reference	Cement factor bags/yd^3	Water-cement ratio	Air content (%)	Slump, inches (cm)	Compressive Strength psi (MPa) 3-day	7-day	28-day
44	7.0	0.31	2.1	3.5 (9)	NR	NR	5245 (36.18)
45	7.0	NR	3.9	4.7 (12)	3400 (23.94)	4100 (28.34)	5620 (38.74)
23	7.0	0.37	4.0	3.9 (10)	NR	4025 (27.75)	5005 (34.52)

NR - Not reported

TABLE 15
PHYSICAL AND STRENGTH PROPERTIES OF ACRYLIC LATEX-MODIFIED MORTARS (*24*)

Acrylic polymer solids-cement weight ratio	0	0.10	0.15	0.20
Water-cement ratio	0.48	0.40	0.37	0.35
Tensile strength, psi				
28-day air cure	235	530	615	855
28-day wet cure	535			
28-day air cure +7-day water soak	310	330	350	490
Compressive strength, psi				
28-day air cure	2390	5450	5715	5690
28-day wet cure	5795			
28-day air cure + 7-day water soak	4420	4700	5125	5460
Flexural strength, psi				
28-day air cure	610	1355	1585	1835
28-day wet cure	1070			
28-day air cure + 7-day water soak	735	950	1020	1050
Shear bond adhesion, psi				
28-day air cure	45 (A)	>500 (C)	>650 (C)	>550 (C)
28-day wet cure	185 (A)			
28-day air cure + 7-day water soak	140 (A)	290 (C)	300 (C)	330 (C)
Impact strength, inches/lb				
28-day air cure	6	12	16	22
28-day wet cure	7			
28-day air cure + 7-day water soak	9	11	13	18
Abrasion resistance, % weight loss				
28-day air cure	23.80	1.70	1.15	1.57
28-day wet cure	5.07			

1psi=0.007MPa; 1 inch-lb=0.113Nm

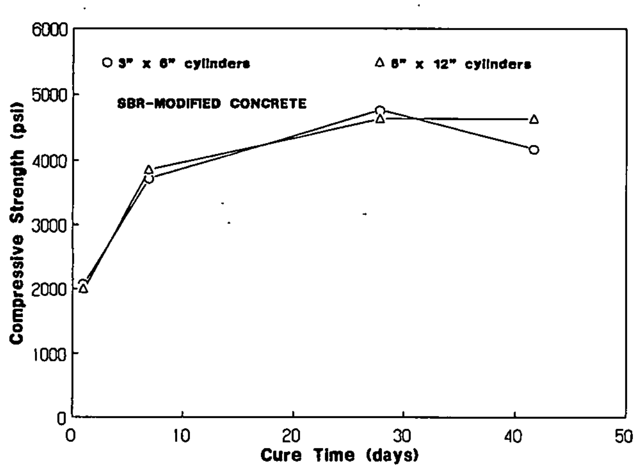


FIGURE 23 Effect of cylinder specimen size on compressive strength of latex-modified concretes (from *39*).

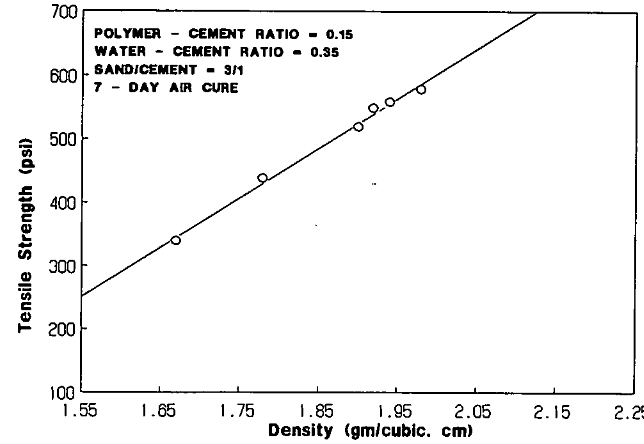


FIGURE 24 Tensile strength vs density for acrylic latex-modified mortars (from *24*).

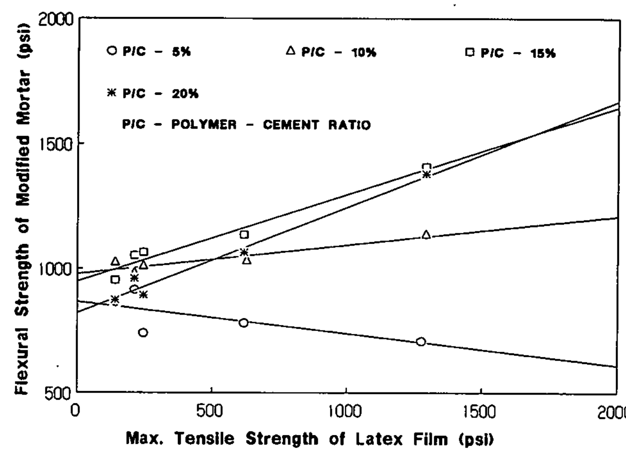


FIGURE 25 Tensile strength of SBR latex film vs flexural strength of mortar (from *18*).

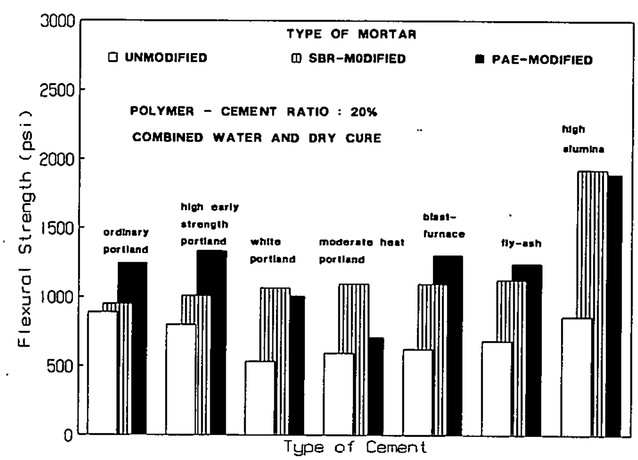


FIGURE 26 Influence of cement type on flexural strength of unmodified vs latex-modified mortars (from *37*).

reported similar findings. A significant reduction in modulus of elasticity was observed when the latex content exceeded 10 percent.

Shrinkage

Latex-modified mortars and concretes are more sensitive to initial plastic shrinkage if improperly cured. However, the drying

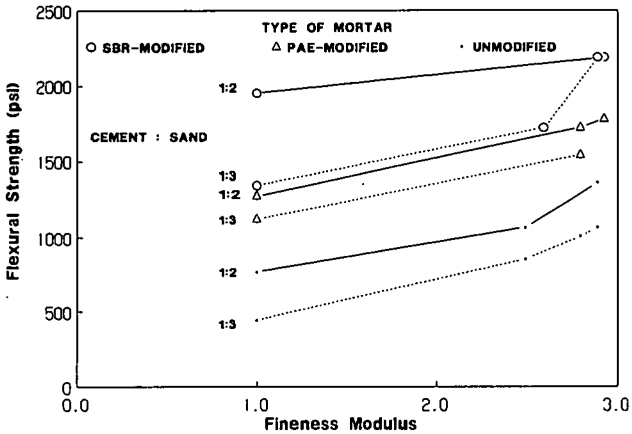


FIGURE 27 Effect of fineness modulus of fine aggregate on flexural strength for mortar (from *37*).

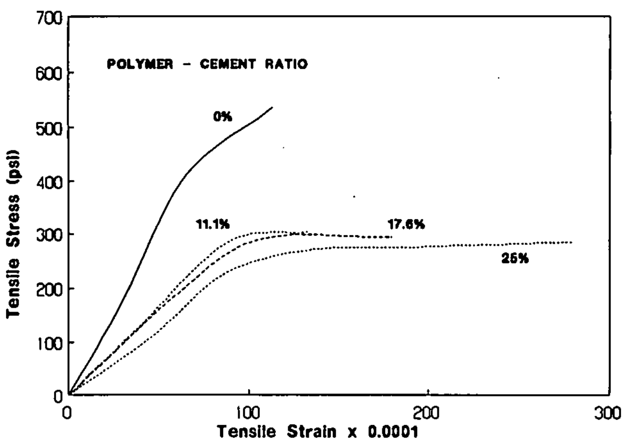


FIGURE 28 Tensile stress vs strain for SBR-modified concretes (from *47*).

TABLE 16
MODULUS OF ELASTICITY AND POISSON'S RATIO OF LATEX-MODIFIED CONCRETES (*48*)

Type of concrete	Polymer-cement (%)	Modulus of elasticity in compression ($X10^5$ kg/cm^2)	Poisson's ratio
Unmodified	0	2.11	0.17
PAE modified	5	2.27	0.16
	10	2.36	0.17
	15	2.30	0.17
	20	2.24	0.17
SBR modified	5	2.28	0.16
	10	2.43	0.18
	15	2.42	0.18
	20	2.02	0.18
PVAC modified	5	1.90	0.16
	10	1.79	0.19
	15	1.35	0.24
	20	1.00	0.29

1 kg/cm^2 = 0.0981 MPa

shrinkage depends on the type and quantity of latex addition. The drying shrinkage increases with additional dry curing period. After 28 days of dry curing, the shrinkage almost ceases for all latex types and quantitites. The 28-day drying shrinkage generally tends to decrease with increasing latex/cement ratio. Some latexes (PVAC, NR and CR) cause more shrinkage than that of unmodified mortars and concretes. The largest shrinkage occurs in PVAC latex-modified mortar. This is probably caused by evaporation of the large amount of water absorbed in the polymer phase due to the low water resistance of the polyvinyl acetate. Ohama (*37*) showed that this excessive shrinkage can be reduced by 75 percent with the addition of ethylene into the polymer formulation. Acrylonitrile-butadiene rubber (NBR) modified mortar has the least shrinkage. The drying shrinkage is less for concretes and mortars with higher latex/cement ratio because of higher water retention ability. It was reported by Kawano (*51*) that latex-modified mortars and concretes had less shrinkage than conventional mortars and concretes, mainly due to the effects of surfactants and antifoaming agents added to the latexes. As reported by Michalyshin (*52*), adding SBR latex to concretes does not increase the drying shrinkage. In this study, the drying shrinkage strains of latex-modified and conventional concretes with similar water/cement ratios were compared, as shown in Figure 29 (Table 17). In an earlier study (*39*), Ohama had obtained similar results. He investigated three latex/cement ratios, and three different sizes of concrete specimens were used. The same workability was maintained by adjusting the water/cement ratio as shown in Table 18. The measured shrinkage strains are given in Figures 30A and 30B. Ohama concluded that drying shrinkage does not depend on latex content, but rather depends mainly on water content. Comparing Figures 30A and 30B, one can see that the drying shrinkage of SBR and EVA latex-modified concretes decreased with an increase in specimen size. The effect of specimen size is almost the same for both unmodified concrete and latex-modified concrete.

Creep

There is not much published information on the creep behavior of latex-modified mortars and concretes. Two investigations

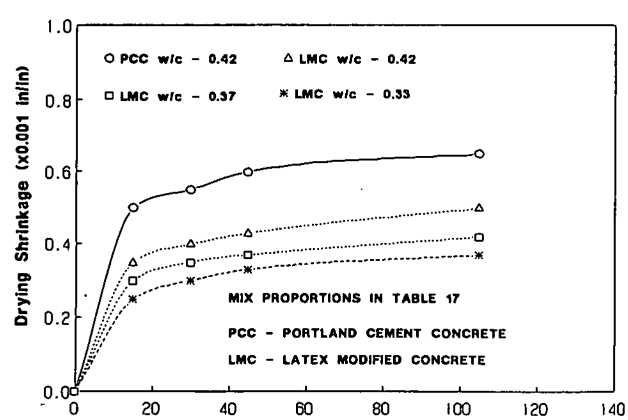


FIGURE 29 Drying shrinkage for unmodified vs latex-modified concretes (from *52*).

TABLE 17
MIXTURE PROPORTIONS FOR CONCRETE USED IN LINEAR SHRINKAGE STUDY (AFTER *22*)

Type	Cement	Slump, inch (cm)	WR (%)	AEA (%)	Air (%)	Water-cement ratio	Compressive strength at 28-day, psi (MPa)
LMC	I	5.5 (14)	-	-	5.0	0.33	6005 (41.4)
	I	7.9 (20)	-	-	4.7	0.37	5510 (38.0)
	I	9.8 (25)	-	-	3.7	0.42	5210 (35.9)
Conventional*	I	1.6 (4)	0.42	0.05	9.2	0.42	5170 (35.6)

* Conventional mixture contained a water reducer (WR) and air-entraining agent (AEA). Values given are by weight based on cement.

LMC - Latex-modified Concrete

All mixtures had fine/coarse aggregate of 1.5/1.0, and cement factor of 658 lb/yd^3. Latex solids/cement of latex-modified concretes was 0.15.

TABLE 18
MIXTURE PROPORTIONS OF CONCRETES USED IN SHRINKAGE STUDY (*22*)

Type of concrete	Cement content	Latex solids/cement ratio	Water/cement ratio	Fine coarse aggregate	Slump inches (cm)
Unmodified	505 (300)	0	0.67	0.45	6.3 (16.0)
Latex modified	505 (300)	0.05	0.58	0.45	6.3 (16.0)
		0.10	0.50	0.45	6.1 (15.5)
		0.20	0.41		6.3 (16.0)

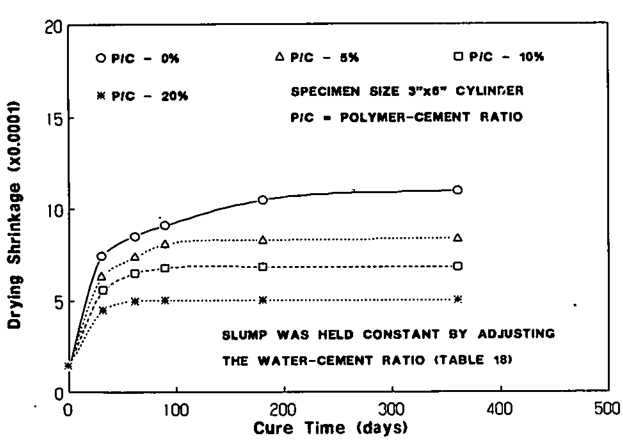


FIGURE 30A Drying shrinkage vs time for 3" x 6" concrete cylinders (from *39*).

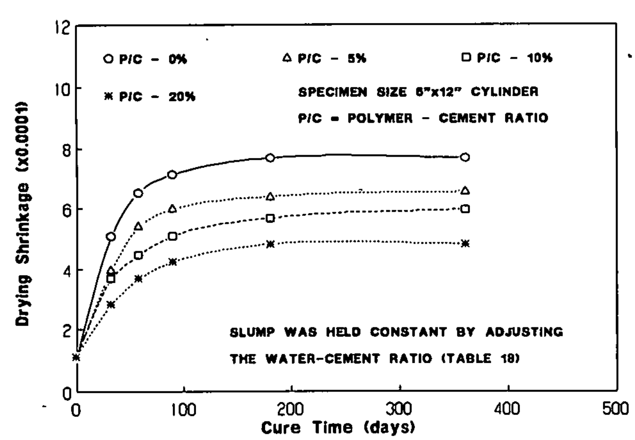


FIGURE 30B Drying shrinkage vs time for 6" x 12" concrete cylinders (from *39*).

conducted by Ohama, one on latex-modified mortars (*53*) and another on latex-modified concretes (*54*) showed that, for the same slump, creep strains are significantly lower for latex-modified mortars and concretes than for those of unmodified mortars and concretes. He also showed that the relationship between time (t) and creep strain (ϵ_c) or creep coefficient (ϕ) (creep strain/elastic strain ratio) for latex-modified concretes could be expressed by the same equation that is generally used for unmodified concretes (Figure 31):

$$\epsilon_c, \phi = \frac{t}{A + Bt} \tag{5}$$

where A and B are empirical constants evaluated from experimental results. He attributes the low creep in latex-modified mortars to the strengthening of the binders with polymers, and the long term strength development to improved water retention.

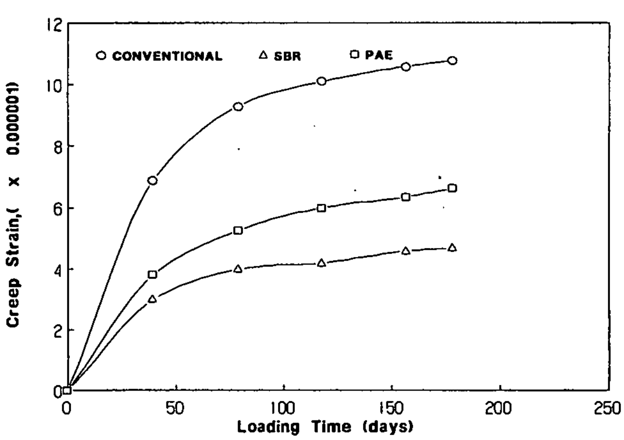


FIGURE 31A Creep strains of unmodified vs latex-modified concretes (from *54*).

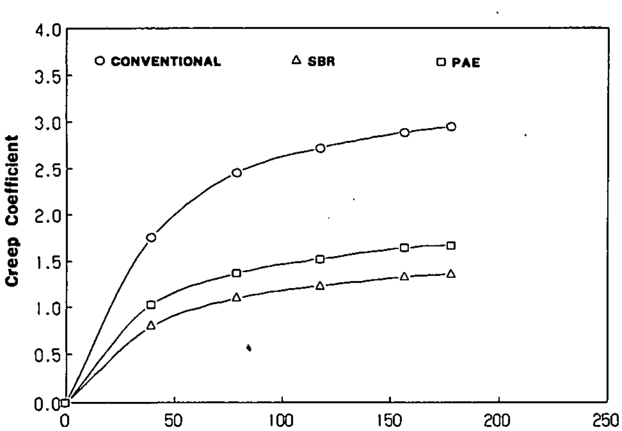


FIGURE 31B Creep coefficient vs loading time for unmodified and latex-modified concretes (from *54*).

Impact Strength

The impact strength increases with an increase in latex/cement ratios as shown in Table 15. Latex-modified mortars and concretes have higher impact strength than corresponding conventional mortars and concretes because of the high impact resistance of latexes. Similar results were reported earlier by Ohama (*37*). He observed that latex-modified mortars with elastomers are superior to mortars with thermoplastic resins. Mortars modified with NR and SBR latexes with a latex/cement ratio of 20 percent had impact resistances about 10 times greater than those of unmodified mortar.

Bond or Adhesion Strength

Incorporating latex in conventional mortars and concretes can dramatically improve the bond or adhesion to various substrates. This improvement depends on the type of latex and is attributed to the high adhesion property of latex. Most latexes, when added to mortar or concrete, develop excellent adhesion to substrates such as old concrete, stone, ceramic tile, brick, steel, and wood. The bond strength depends mainly on the latex/cement ratio, the latex type, surface texture, temperature and humidity during placing, and the condition of the substrates to which the latex-modified mortar and concrete are bonded. The observed bond strength also depends on the test method used to measure this property. The measured shear bond adhesion strengths of acrylic polymer modified mortars for various polymer/cement ratios are compared with those of conventional mortar adhesion strengths in Table 15. All latex-modified mortars had cohesion failures (C), whereas the unmodified mortars had adhesion failures (A) at the bonding surfaces. Adhesion tends to increase with an increase in latex/cement ratio. Similar results were reported by Ohama (*27*). Using the patched-beam method, he measured the adhesion in flexure of SBR, PAE, and PVDC latex-modified mortars to ordinary cement mortar as a substrate and found that the flexural adhesion increases with increased latex/cement ratio. However, there are optimum latex/cement ratios above which no increase in strength was observed.

The adhesion in tension for various latex-modified mortars, measured using tensile briquette specimens per ASTM C 190, is shown in Figure 32 (*45*). The briquettes were cut in half and the

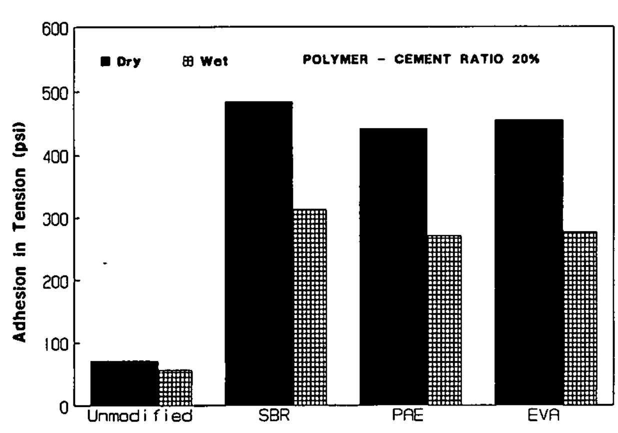


FIGURE 32 Adhesion in tension of unmodified vs latex-modified mortars (from *45*).

mortars being tested were cast against the cut face. The adhesion in flexure for the same latex-modified mortars is shown in Figure 33 (*45*). Both tensile and flexural bond strengths depend to a great extent on the moisture content of the mortar during testing. Adhesion is improved significantly in the dry state, while there is considerably less improvement in the wet state. This is a disadvantage of the latex-modified mortars and concretes in that, under wet service conditions, adhesion is reduced. However, the bond strengths of latex-modified mortars, after immersion in water, are greater than those of unmodified mortars.

As stated above, research conducted in ideal laboratory conditions has shown that adhesion is better when the substrate surface is dry. However, the recommended guidelines for bridge-deck overlay (*52*) require placement of the overlay only on a wet surface. The surface should be in a saturated condition but without pools of water collecting on the surface. There are several reasons for this practical recommendation. When a thin overlay is placed on a dry surface, the dry surface will quickly absorb water from the overlay concrete and may induce plastic shrinkage cracks. Also, the cooling effect due to the evaporation of water from a wet surface will have a beneficial effect on the overlay concrete; it will reduce any temperature difference between the substrate and the overlay concrete, particularly when the overlay is placed in the summer months, and thus avoid thermal stresses between the overlay and the base concrete.

Recently, a number of studies about adhesion of latex-modified mortars and concretes (*21,24,46,49,55-59*) have been conducted in the United States. Adhesion in tension of latex-modified concrete has been measured using the tensile splitting test with unmodified prior-split concrete cylinder halves as substrate material (*46*). The latex-modified concrete cylinder specimens containing 15 percent latex/cement ratio and cured for 28 days failed at an average of 525 psi (3.62 MPa) tensile splitting stress. For all six specimens the failure surface was through the aggregate and no failure took place at the bonded interface. The direct tensile test method (*21,57*) used to measure bond strength showed that bond of latex-modified concretes exceeds 262 psi (1.81 MPa) at 3 days and 334 psi (2.30 MPa) at 28 days (Table 19). The SBR latex-modified concretes had a significant increase

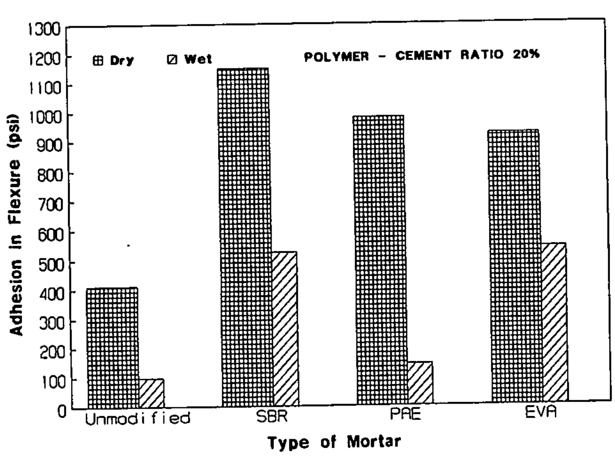


FIGURE 33 Adhesion in flexure of unmodified vs latex-modified mortars (from *45*).

TABLE 19
TENSILE BOND STRENGTH (*21*)

Cure days	Unmodified Psi (MPa)	Latex-modified Psi (MPa)
3	161 (1.11)	262 (1.81)
7	181 (1.25)	278 (1.92)
14	215 (1.48)	327 (2.26)
28	243 (1.68)	334 (2.30)
90	256 (1.77)	365 (2.52)

in direct tension bond strength compared to that of the unmodified concrete.

Tests conducted at the Dow Chemical Company laboratories over a number of years (*58*) showed that the 28-day shear bond strength of SBR latex-modified concrete is almost twice that of conventional concrete. However, the actual test results have not been reported (*58*). A guillotine-type device to shear a cap of latex-modified concrete off a cylinder of unmodified concrete was used in this test. The average values of bond strength for latex-modified concretes with 15 percent latex/cement ratio obtained from tests conducted over several years, were 256 psi (1.77 MPa) after a 7-day cure, and 469 psi (3.24 MPa) at 28 days.

The adhesion between reinforcing steel and the SBR latex-modified concrete has been found to be adequate to develop the yield strength of the steel (*59*). Epoxy-coated and uncoated steel bars, 18 in. (45.72 cm) long and 0.5 and 0.625 in. (13 and 16 mm) in diameter, were embedded 1.5 in. (3.75 cm) deep in a latex-modified concrete overlay that was 2 in. (5 cm) thick and the test bond (pull-out) loads achieved were 12,950 lbs (5,886 kg) and 19,870 lbs (9,031 kg) respectively for the 0.5 in. and 0.625 in. (13 and 16 mm) diameter bars. The yield strengths of these bars were 12,000 lbs (5,454 kg) and 18,600 lbs (8,454 kg). Using a newly developed test method to determine direct tension bond strength (*55*), Kuhlmann has shown that the bond of latex-modified concrete exceeds 70 psi (0.48 MPa) in one day of curing at room temperature, 340 psi (2.35 MPa) in 28 days and 450 psi (3.12 MPa) in 90 days.

Abrasion Resistance

Another improvement due to the addition of latexes to conventional mortars or concretes is the increase in abrasion resisting ability. Many investigators (*24,60,61,62*) have reported a tremendous increase in the abrasion resistance of latex-modified mortars and concretes for several types of latexes. For acrylic latex-modified mortars, the increase was more than three times (Table 15). Figure 34 shows the abrasion resistance of various latex-modified mortars (*60*). These were tested according to the Japanese standard JIS A 1453-Method of Abrasion Test for Building Materials. With a latex/cement ratio of 20 percent, the abrasion resistance had increased to more than 20 times that of unmodified mortar. Teichmann (*61*) reported an abrasion

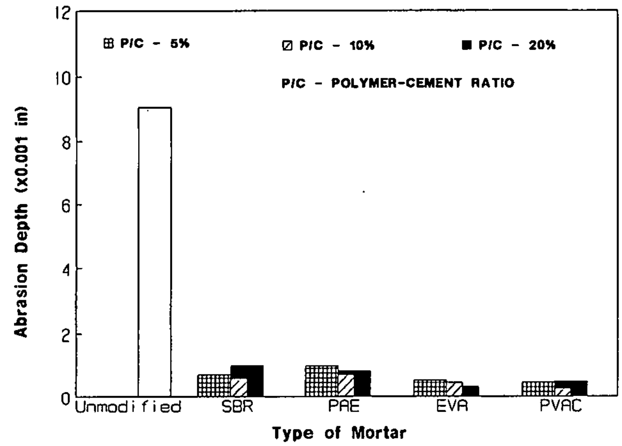


FIGURE 34 Abrasion resistance for unmodified vs latex-modified mortars (from *60*).

resistance 200 times higher than conventional mortar for PAE latex-modified mortar with 20 percent latex-cement ratio. Using a traffic simulator for abrasion testing, Gierloff (*62*) showed that various PAE latex-modified concretes with a high latex/cement ratio and a low water/cement ratio resisted traffic abrasion very well.

In general the abrasion resistance of latex-modified mortars and concretes is influenced by the type of latex used, latex/cement ratio, and wear conditions. An increase in latex/cement ratio increases the abrasion resistance; for SBR latex-modified mortars, the abrasion resistance is increased with an increase in bound styrene content (*26*).

Thermal Performance

Thermal expansion characteristics of latex-modified concretes and mortars are similar to those of unmodified mortars and concretes and are mainly influenced by the type of aggregates used (*63*). Most polymers undergo a rapid reduction in strength at elevated temperatures, particularly at temperatures higher than the glass transition temperature of the polymers (usually 176° to 212°F (80° to 100°C)) and with higher latex/cement ratios. Most latex-modified mortars lose 50 percent or more of their strength at temperatures above 122°F (50°C) (*18*).

The combustibility of latex-modified mortars and concretes depends on the type of latex used, latex content, and latex/cement ratio. All latex-modified concretes and mortars with less than 5 percent latex/cement ratio have very low combustibility. However, the combustibility increases with increasing latex/cement ratio.

Pore Structure and Permeability

The pore structure of cement paste has the greatest influence on permeability, and hence, on the durability of concrete. This indirectly affects the rate and amount of corrosion of reinforcement embedded in the concrete. Pore structure controls the rate of flow of chemical species, including chloride ions which increase the corrosion of steel in concrete. As explained in Chapter Two, pore structure is beneficially altered by the addition of latexes to cement paste. The micropores and voids normally occurring in portland cement systems are partially filled with the latex film that forms during curing. Filling of the pores depends on the types of latexes and the latex/cement ratios. Total porosity or pore volume is decreased with an increase in latex/cement ratio. Latex-modified mortars and concretes have fewer large-radius pores (0.2 μm or more) and more small-radius pores (75 nm or less) compared to unmodified mortars and concretes. This reduces the permeability and water absorption of latex-modified cement systems. Several tests, such as water vapor transmission, chloride permeability, water absorption, and carbonation resistance, measure the effect of pore structure modification.

Marusin (*63*), based on scanning electron microscopy investigations, observed that conventional concrete and concretes modified with latexes showed a different distribution and shape of pores. While the large pores were surrounded by a number of smaller pores in conventional portland cement concrete, latex-modified concretes (both acrylic and SB latexes) contained only single, mostly spherical, pores. She also reported the concrete weight changes due to immersion in a 15 percent NaCl water solution for 21 days and air drying in a climate-controlled room using 4 in. (10 cm) cubes. Weight gains and losses at 3, 7, 14 and 21 days during the 21-day soak in a salt solution and the 21-day drying period, are shown in Figure 35A. Conventional concrete with water/cement ratio of 0.4 was able to expel about 65 percent of absorbed water by vapor transmission. Acrylic latex-modified concrete lost all the absorbed water and SB latex-modified lost 66 percent of its absorbed water when allowed to dry.

Water absorption with respect to immersion period for different latex/cement ratios for SBR latex- modified mortar is shown in Figure 35B (*37*). Water absorption becomes nearly constant after 48 hours of immersion in water for a lower latex/cement ratio. As the latex content increases, water absorption decreases. Similar effects were observed with the water vapor transmission test (*37*) as shown in Figure 36. The water permeation of latex-modified mortars is considerably reduced with an increase in latex/cement ratio as shown in Figure 37. This 48-hour water

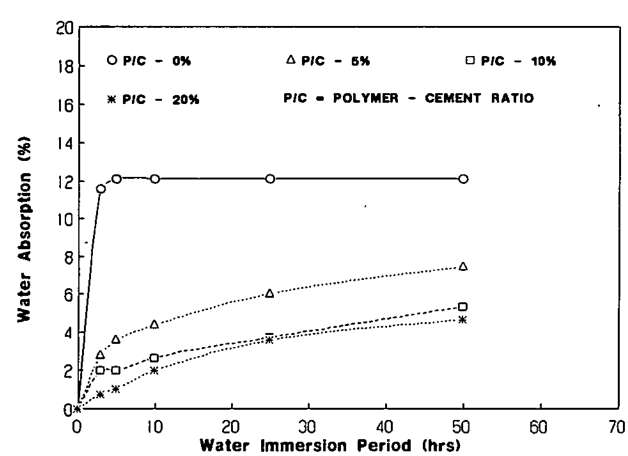


FIGURE 35A Weight gain and loss for latex-modified concretes (from *63*).

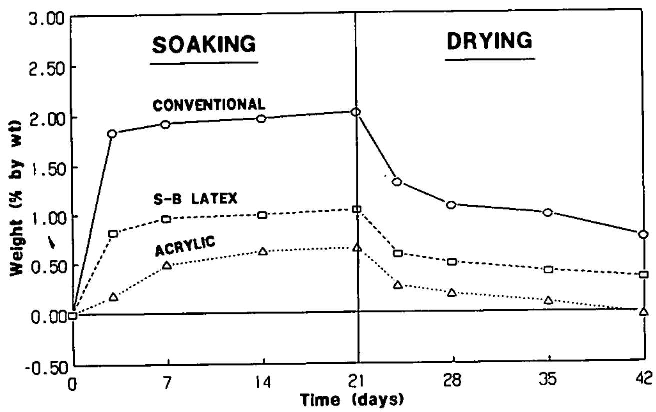


FIGURE 35B Water absorption vs water immersion period for SBR-modified mortar (from *37*).

permeation test was conducted under a pressure of 0.1 MPa (*41*). The PVAC latex-modified mortar behaves differently because it swells due to water absorption and it is partially hydrolyzed under alkaline conditions.

Several test methods have been devised to measure chloride permeability in concrete. The results of an FHWA study (*23*) to determine the chloride permeability from a 90-day ponding test are shown in Figure 38. Ohama (*64*) soaked cylinders in salt solutions for 28 and 91 days and measured the chloride penetration with an indicator solution on the concrete surface after the cylinders were split. The penetration decreased with an increase in latex content as shown in Figures 39 and 40. The apparent chloride-ion diffusion coefficients of the latex-modified mortars and concretes immersed in artificial sea water (sodium chloride content of 2.4 percent) are given in Table 20 (*65*).

For a quicker determination of the chloride-ion permeability, a rapid permeability test (AASHTO T 277) was developed (*66*). Using this test, several investigations have been conducted in the U.S. and Canada (*40,49,56,58,67,68*). In latex-modified concretes, even at higher air contents, air voids were small and well-

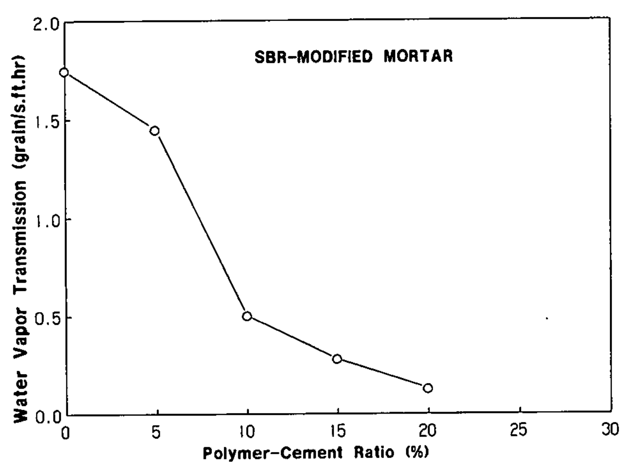


FIGURE 36 Water vapor transmission in mortar vs polymer content (from *37*).

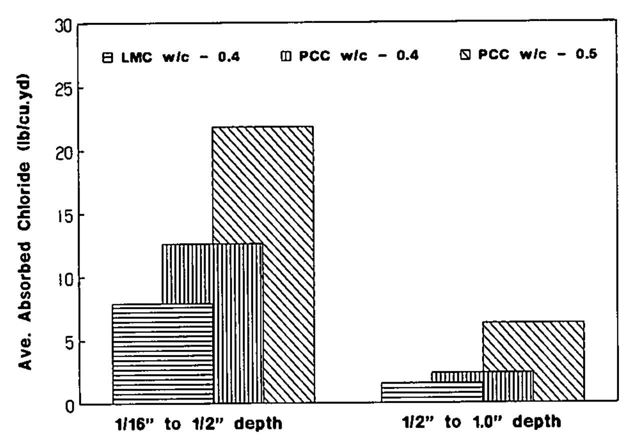


FIGURE 38 Chloride permeability by 90-day ponding test for unmodified vs SBR latex-modified concretes (from *23*).

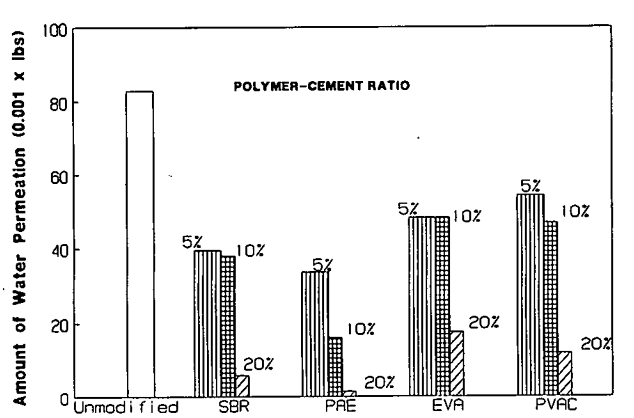


FIGURE 37 Amount of water permeation of unmodified vs latex-modified mortars (from *41*).

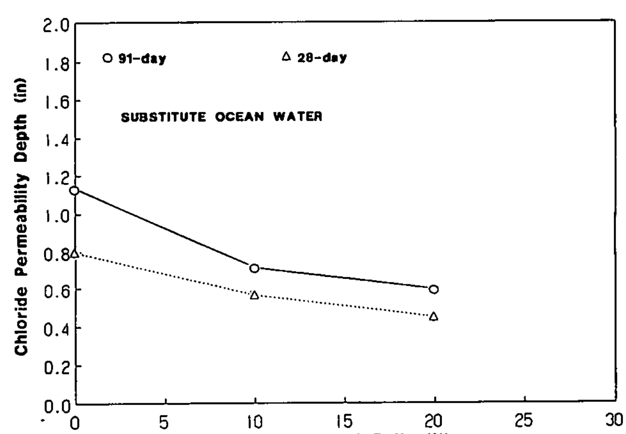


FIGURE 39 Chloride permeability depth vs polymer/cement ratio for concrete cylinder specimens (from *65*).

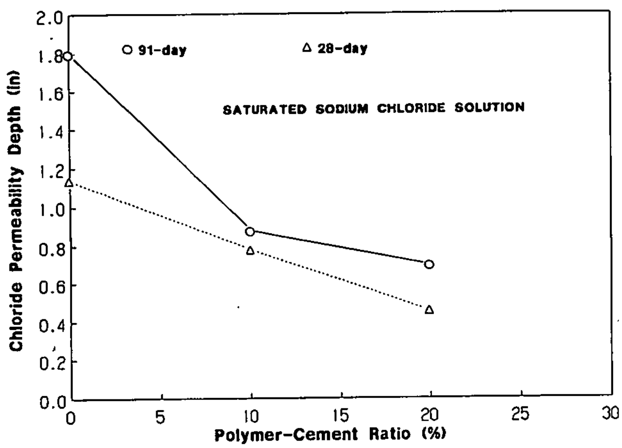


FIGURE 40 Chloride permeability vs polymer/cement ratio for concrete cylinder specimens (from *65*).

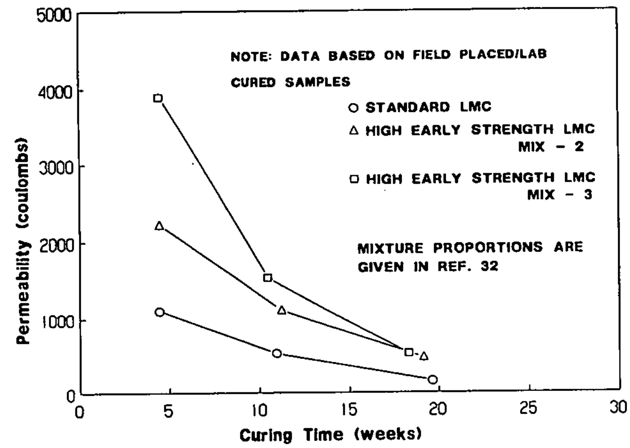


FIGURE 41 Effect of age on permeability for latex-modified concretes (from *49*).

distributed and the permeability did not increase (*40*), as shown in Table 21A, suggested ratings shown in Table 21B.

Permeability is significantly reduced with age beyond the normal 28-day period (*49,68*). Samples taken from field-placed latex-modified concretes at three different locations in the U.S., using different aggregates and cements, were cured in laboratory conditions (72° F and 50 percent relative humidity). The permeability results for these samples are shown in Figure 41. They all show low permeability at 90 days. The measured permeabilities for some field-placed and field-cured latex-modified concretes (*56*) are given in Table 22. In general, the latex-modified concretes are less permeable than unmodified concretes. Figure 42 (*58*) shows the influence of latex content on the permeability of SBR latex-modified concrete. It is evident that latex/cement ratios below 10 percent do not significantly reduce permeability and that increasing latex content more than 15 percent does not improve permeability significantly. Therefore, it seems that a latex/cement ratio of 10 to 15 percent is optimum with regard to permeability reduction in concretes.

Marusin (*63*) measured the absorbed chloride ion contents for

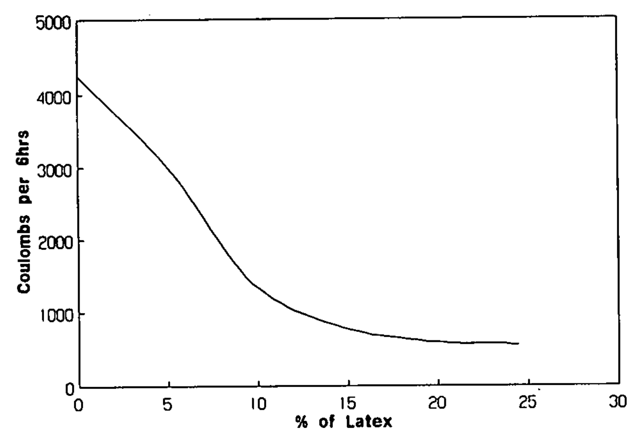


FIGURE 42 Effect of latex level on concrete permeability (from *68*).

TABLE 20
CHLORIDE ION DIFFUSION COEFFICIENT OF LATEX-MODIFIED MORTARS AND CONCRETES (*65*)

Type of mortar	Polymer-cement ratio (%)	Apparent chloride ion diffusion coefficient cm^2/s	Type of concrete	Polymer-cement ratio (%)	Apparent chloride ion diffusion coefficient cm^2/s
Unmodified	0	6.4×10^{-8}	Unmodified	0	2.2×10^{-8}
SBR-modified	10	6.4×10^{-8}	SBR-modified	10	1.9×10^{-8}
	20	3.9×10^{-8}		20	9.3×10^{-9}
EVA-modified	10	4.4×10^{-8}	EVA-modified	10	7.9×10^{-9}
	20	2.4×10^{-8}		20	1.0×10^{-8}
PAE-modified	10	3.8×10^{-8}	PAE-modified	10	6.2×10^{-9}
	20	4.4×10^{-8}		20	5.8×10^{-9}

TABLE 21A
TOTAL COULOMBS PASSED FOR LATEX-MODIFIED CONCRETE HAVING VARIOUS AIR CONTENTS (*40*)

Mix	Air content (%)	Age (days)	Total coulombs
1	3.0	63	650
		69	740
2	4.5	28	520
		35	455
		91	240
3	5.6	28	935
		29	870
4	7.5	16	1105
		24	835
		63	530
		70	780
5	12	41	760
		50	510
6	15	35	705
		37	650
		91	425

TABLE 21B
CHLORIDE PERMEABILITY RATINGS BASED ON COULOMBS (*40*)

Chloride Permeability	Coulombs
High	4,000
Moderate	2,000 to 4,000
Low	1,000 to 2,000
Very low	100 to 1,000
Negligible	Below 100

acrylic and SB latex-modified concretes using 4 in. (10 cm) cube specimens. The chloride ion content of the drilled powder from the same specimens was determined using an acid digestion, potentiometric titration procedure. Concretes with 25 percent latex and 2 to 4 percent air content contained about 0.02 and 0.03 percent chloride ion content in the depth interval of ½ to 1 in. (12 to 25 mm). The acrylic latex and SB latex showed similar profiles at all depths. The performance of both latex-modified concretes was similar in minimizing the ingress of chloride ions into these concretes and "both provided excellent performance" (*63*).

Carbonation Resistance

Carbonation resistance is an important property that influences the durability of concrete and corrosion of rebar. It has been reported (*69*) that latex-modified mortars and concretes have superior carbonation resisting ability compared to unmodified mortars and concretes. The carbonation resistance is increased with an increase in latex/cement ratio. Ohama investigated the latex-modified concretes exposed to carbon dioxide gas and carbon dioxide solution (carbonic acid), under a pressure of 0.1 to 0.6 MPa (1 to 6 kg/cm^2) up to a period of 6 months. After exposure, the samples were painted with phenolphthalein solution. The measured carbonation depths are shown in Figures 43 and 44. In both methods, carbonation is significantly reduced by the addition of a latex to the concrete.

DURABILITY

Freeze-Thaw Resistance

In general, latex-modified mortars and concretes have good freeze-thaw resistance, provided they have been properly cured allowing the formation of the latex film. It was reported (*27*) that the freeze-thaw durability of latex-modified mortars and concretes is improved even at a low polymer/cement ratio of 5

TABLE 22
PERMEABILITY OF FIELD-PLACED LATEX-MODIFIED CONCRETES (*56*)

Type of project	Location	Date of placement	Overlay thickness (inches)	Age	Permeability coulombs
Bridge	Indiana	11/83	1 3/8	5 mo	524
			1 3/4	5 mo	302
			1 7/8	5 mo	346
			1 3/8	5 mo	257
			1 1/2	5 mo	214
			1 1/4	5 mo	323
			1 1/2	5 mo	285
			1 3/4	5 mo	274
			1 1/2	5 mo	419
			1 1/2	5 mo	310
Bridge	Pennsylvania	1979	1 7/8	6 yr	243
			1 7/8	6 yr	215
			1 3/4	6 yr	366
			1 5/8	6 yr	160
			1 7/8	6 yr	249
			2	6 yr	104
			1 7/8	6 yr	269
Parking garage	Pennsylvania	1985	2	4 mo	619
			2	4 mo	538
Bridge	Washington	unknown	2	5 mo	260
			2	5 mo	260
Bridge	Illinois	1982	2	4 yr	287
			2	4 yr	277
Bridge	Illinois	1982	2	4 yr	433
			2	4 yr	441
Stadium	Illinois	1981	2	3 yr	48
			2	3 yr	65
			2	3 yr	43
			2	3 yr	65
			2	3 yr	26
Parking garage	North Dakota	unknown	2	2 yr	397
				2 yr	379

Note: Indiana specimens were tested by FHWA; all other specimens were tested by Dow Chemical Company. All samples were 2 inches thick, therefore some contained conventional deck concretes. See Table 21B for suggested ratings.

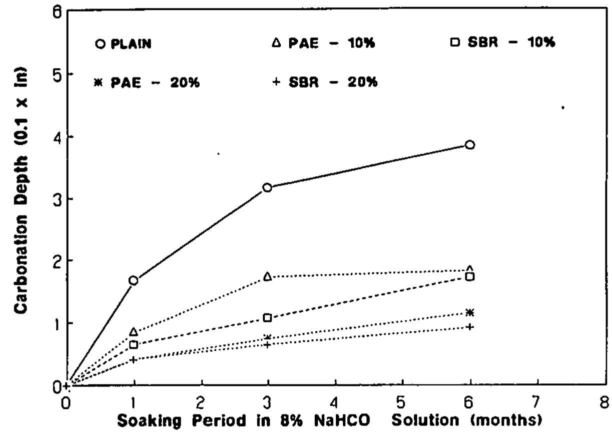


FIGURE 43 Carbonation depth vs soaking period for unmodified vs latex-modified concretes (from *69*).

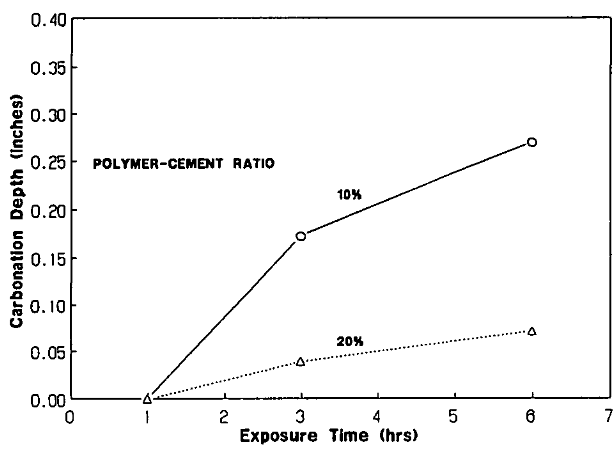


FIGURE 44 Carbonation depth of SBR latex-modified concrete vs exposure time (from *69*).

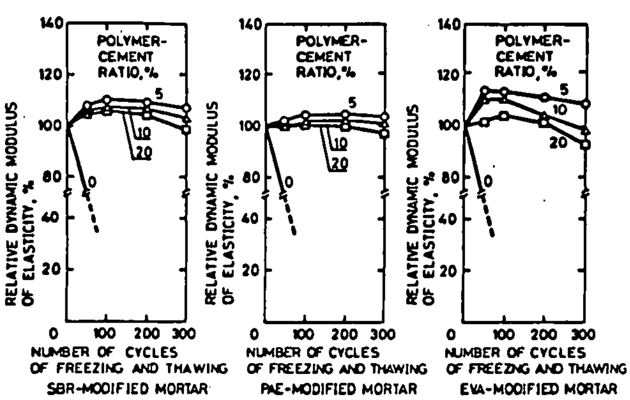


FIGURE 45 Freeze-thaw resistance of latex-modified mortars (*27*).

percent as compared to concrete that is not air-entrained. The freeze-thaw resistance is due to the combined effects of water impermeability and air-entrainment provided by latex. An increase in latex/cement ratio may not increase the freeze-thaw durability (*30*) as shown in Figure 45.

TABLE 23
FREEZE-THAW RESISTANCE OF LATEX-MODIFIED CONCRETES (*58*)

Air content (%)	Cure	Number of cycles	Durability factor
5.1	1-day wet 27-day dry	323	91
5.8	1-day wet 27-day dry	323	98
5.2	1-day wet	323	91

Both laboratory and field studies (*42,49,58,68,70,71*) conducted in the U.S. have shown that latex-modified concretes have excellent freeze-thaw resistance. In the field, in latex-modified concretes placed late in the construction season (when freezing temperatures occurred before 28 days of curing), no apparent damage had occurred. This is attributed to the relatively dry conditions of the cool weather since drying is part of the latex-modified concrete curing process (*22*).

Durability factors for some latex-modified concretes obtained using the ASTM C 666 freeze-thaw tests are given in Table 23 (*58*).

Resistance to Deicing Chemicals

The resistance of concrete surfaces to scaling when exposed to deicing chemicals and freeze-thaw cycles is another measure of their durability. The scaling resistances of latex-modified and unmodified concretes, measured by the Indiana State Highway Commission using ASTM Test Method C 672, are given in Table 24 (*42*).

Latex-modified concrete was given a rating of 0 in a rating scale of 0 to 5, indicating that no scaling had occured after 50 cycles of freezing and thawing.

Weatherability or Long-Term Exposure Effects

The effect of long-term exterior exposure (weathering) on latex-modified mortars and concretes has been reported (*24,27,72,73*). Outdoor exposure normally includes the effects of carbonation, salt contact, and freezing and thawing, and latex-

TABLE 24
SCALING SUSCEPTIBILITY OF LATEX-MODIFIED CONCRETES (*58*)

Type	Air content	Number of cycles	Rating
Latex	4.1	50	0
Conventional	4.9	50	2

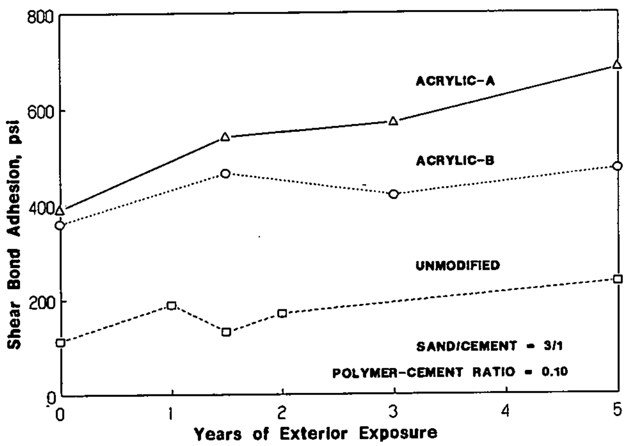


FIGURE 46 Effect of latex level on concrete permeability (from *68*).

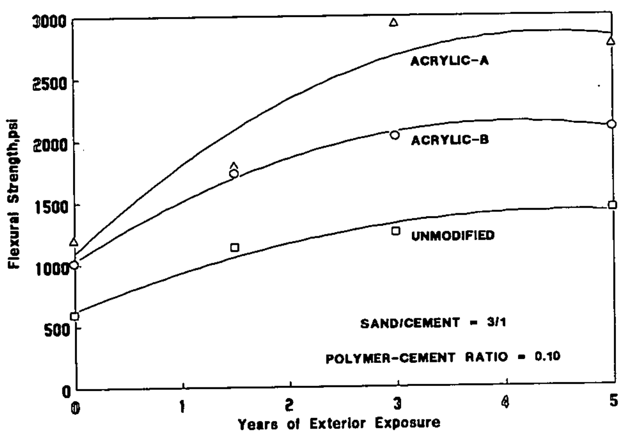


FIGURE 47 Carbonation depth vs soaking period for unmodified vs latex-modified concretes (from *69*).

modified mortars have shown excellent weatherability. The results of a study of the effects of weathering on adhesion and flexural strength of acrylic latex-modified mortars are shown respectively in Figures 46 and 47 (*24*). This five-year exposure study was carried out in the northeastern part of the United States, and the specimens were subjected to at least 70 freeze-thaw cycles per year and 50 in. (1,300 mm) of rain per year. Adhesion strength and flexural strength were not affected by the exposure. All adhesive tests showed cohesive failures for latex-modified mortar but adhesive failures for unmodified control specimens. Another eleven-year exposure study showed retention of initial bond strength during the exposure (*24*).

Ohama has reported the effects of weathering on flexural strength (Figure 48 (*72*)) and adhesion (Figure 49 (*73*)). This study was conducted for 10 years at the Building Research Institute's outdoor site in Japan. The latex-modified mortars had excellent durability compared to unmodified mortars.

Chemical Resistance

Generally, hydrated cement is not resistant to inorganic acids, organic acids, or sulfates. Most latex-modified mortars and con-

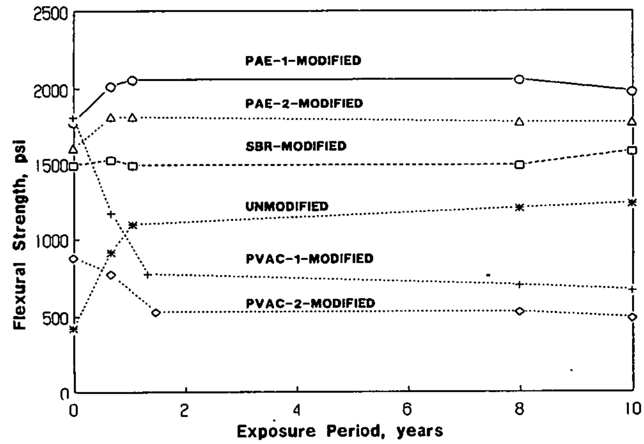


FIGURE 48 Weatherability of latex-modified mortars (from *72*).

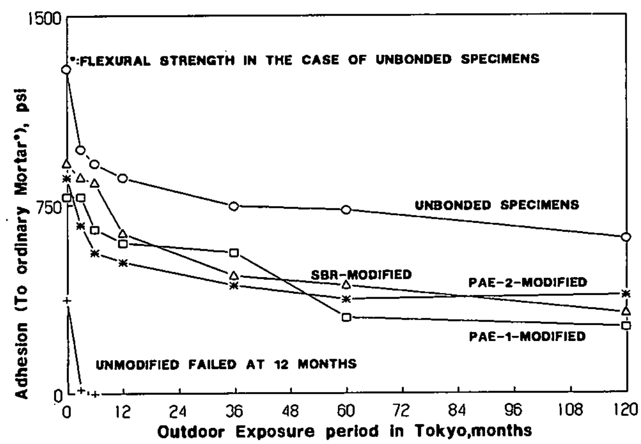


FIGURE 49 Adhesion durability of latex-modified mortars (from *73*).

cretes are damaged by these chemicals. However, they may resist alkalis, fats, oils, and various salts except sulfates. Organic solvents easily attack most latex-modified mortars and concretes. Table 25 shows the chemical resistance of mortars containing synthetic and natural rubber latexes (*74*). PVDC latex-modified mortar is reported (*75*) to have good resistance to alkalis and most organic solvents. PVAC latex-modified mortar does not resist acids and alkalis, but is stable in organic solvents such as mineral oils (*18*). PVAC is not recommended for outdoor use.

COMPARISON OF PROPERTIES OF DIFFERENT LATEX-MODIFIED MORTARS

Recently, the properties of latex-modified mortars made from five different commonly used latexes were compared by Walters (*76*), as shown in Table 26. In this laboratory investigation, the following five latexes were used:

- A plasticized polyvinyl acetate homopolymer (PVAC)
- A copolymer of vinyl acetate and ethylene (VAE)

TABLE 25
CHEMICAL RESISTANCE OF LATEX-MODIFIED MORTARS (*74*)

Type of chemicals	Concentration (%)	Weight change (%)				
		Unmodified	NBR-modified	CR-modified	NR-modified	SBR-modified
Sulfuric Acid	5	138.8	-62.6	-80.9	-86.1	-44.4
Hydrochloric Acid	5	-87.7	-76.7	-87.9	-82.9	-77.8
Chromic Acid	5	-59.5	-48.4	-46.4	-55.8	-52.8
Hydrofluoric Acid	5	-33.3	-27.0	-37.9	-57.0	-27.6
Sulfurous Acid	6	-61.0	-60.5	-58.9	-59.4	-25.4
Acetic Acid	5	-66.7	-	-56.1	-44.3	-42.1
Butyric Acid	5 10	- -52.5	- -42.5	- 46.7	- -55.2	-4.8 -
Lactic Acid	5 20	- -77.6	- -59.2	- -63.7	- -72.7	-23.8 -
Sodium Hydroxide	45	-13.0	-	-0.9	-3.9	-
Sodium Sulfate	10	10.9	1.6	2.4	6.9	-
Magnesium Sulfate	saturated	7.5	1.6	3.3	2.8	-
Ammonium Sulfate	saturated	-100.0	-100.0	-100.0	-100.0	-
Ammonium Nitrate	50	2.4	-1.6	-1.6	4.5	0.0
Sodium Hydrogencarbonate	10	11.0	3.1	5.6	8.9	-
Sodium Chloride	saturated	11.9	0.8	3.2	5.0	1.6
Benzene	100	7.4	2.4	0.8	48.5	-
Trichlorethylene	100	11.5	3.9	-100.0	101.8	-
Rapeseed Oil	-	-100.0	0.8	0.0	3.9	0.0
Gasoline	-	8.3	1.6	2.5	24.3	2.4
Kerosene	-	7.5	1.6	1.6	16.5	0.8
Heavy Oil	-	7.3	1.6	0.8	1.9	-
Cane Sugar	50	8.1	0.8	1.6	0.9	-

NBR - Acrylonitrile-Butadiene Rubber
NR - Natural Rubber

- A copolymer of vinyl acetate and ethylene (VAE)
- A carboxylated styrene-butyl acrylate copolymer (SA)
- A carboxylated butyl acrylate-methyl methacrylate copolymer (BAMM)
- A carboxylated styrene-butadiene copolymer (SB).

Based on the test results, Walters recommends that the PVAC latex should not be used as a hydraulic cement modifier for mortars that may be exposed to moisture. The properties of PVAC latex-modified mortars were generally significantly poorer than those of other latexes. They had high permeability due to latex hydrolyzation in the highly alkaline and moist conditions. Except in extremely environmentally hostile conditions, VAE latex-modified mortars showed very similar properties to those of other latex-modified mortars and had reasonable color and weathering resistance. Because VAE costs less, it could be considered for use in less demanding applications. The butyl acrylate-methyl methacrylate and SA latexes imparted similar properties to the latex-modified mortars, except that the former induced more carbonation than any other latex. These latexes could be used where brightness/whiteness is very important and also in environmentally hostile environments. The SB latex-modified mortars performed much better than the other latex-modified mortars, except in the brightness or whiteness test. Therefore, SB latex could be used in situations where adhesion and resistance to water and water-soluable chemicals are needed. SB latexes are good for use in bridge-deck and parking garage protective overlays.

TABLE 26
COMPARISON OF PROPERTIES OF LATEX-MODIFIED MORTARS (*76*)

Latex type	PVAC	VAE	S-A	BAMM*	S-B
Water/cement ratio	0.45	0.44	0.38	0.39	0.37
Density of LMM, lb/ft^3	131	133	135	138	136
Compressive strength ASTM C 109	4870	5580	6570	6600	5675
average psi, C.V. (%)	9.7	1.8	7.5	7.8	2.1
Adhesion, tensile bond	185	400	380	370	410
Average, psi C.V. (%)	3.8	6.0	6.6	6.8	8.3
Mode	bond	old	old	old	old
Carbonation, depth Average, mm	5	2	1	7	1
Acid resistance retention flexural strength					
Average, (%)	28	54	56	47	66
C.V. (%)	10.4	6.9	7.7	2.6	6.6
Permeability resistance AASHTO T-277					
Average, (%)	5,000	2,400	2,100	2,300	1,500
C.V. (%)	-	10.6	5.3	6.7	6.7
Freeze-thaw resistance Retention, flexural					
strength, Average, (%)	21.1	43.3	49.2	64.3	72.5
C.V. (%)	64.5	41.3	8.7	11.2	5.5
Weather resistance retention of flexural strength					
Average, (%)	91	89	90	103	101
C.V (%)	13.4	8.6	11.0	8.9	5.2
Weathering resistance Brightness:					
original	46.4	60.1	65.7	60.2	53.0
exposed	48.3	54.6	44.6	50.7	27.9
Rating:					
original	5	2	1	3	4
exposed	3	1	4	2	5

* Butyl acrylate methyl methacrylate copolymer
C.V. = Coefficient of variation
1lb/ft^3 = 0.62 kg/m^3; 1 psi = 0.007 MPa; 1mm = 0.039 in.

CHAPTER FIVE

CURRENT USES AND POTENTIAL APPLICATIONS

The development of latex-modified mortars and concretes extended the use of these materials in applications where conventional cement mortars and concretes could not be used effectively. Compared to conventional mortars and concretes, latex-modified mortars and concretes can improve properties such as tensile and flexural strength, adhesion, water and air impermeability, abrasion resistance, toughness, and chemical resistance.

CURRENT MORTAR APPLICATIONS

Some current applications of latex-modified mortars include skid-resistant slurries for pavements, thin overlays for floors and pavements, tile grout and tile adhesive, swimming pool coatings, concrete repair and patch work, cementitious coatings, skid-resistant coatings for ship decks, floor leveling and floorings, stucco, and thin-layer terrazzo flooring, pipeline liners, waterproofing, anti-corrosive linings, and decorative and functional cement coatings.

Acrylic latexes are recommended for cement coating applications because of their excellent color stability and durability (*24,77*). They have other advantages as well, such as ease of application by brush or spray, low odor, nonflammability, excellent adhesion to wet substrates, and good weatherability.

Special Applications of Latex-Modified Mortars

Prefabricated latex-modified mortar panels for masonry curtain walls, about 9 x 14 ft, (3.0 x 4.6 m), were developed and used in a number of construction projects in the U.S. (*78*). In Canada, a repair system for concrete structures, known as the "tape process" was developed (*79*). This system used a lamination process of latex-modified mortar and glass or fine steel reinforcing cloth. A thin layer of latex-modified mortar is brushed or sprayed on a damaged concrete surface, and a layer of reinforcing cloth is rolled onto the coated surface. This process is repeated until a desired thickness of the coating is obtained.

Latex-modified mortar has been used as a vibration insulator or damper for railway bridges in Japan (*18*). In this process, a latex-modifed mortar is troweled on the steel girders of the bridge. Latex-modified mortars also have been used for oil well (*80*) and geothermal well (*81*) cementing operations.

CURRENT CONCRETE APPLICATIONS

Latex-modified concretes currently are used in the following applications: overlays for bridge decks, overlays for parking decks; repairs of buildings, stadiums and other structures; and pavement repair and patching.

The most important improvements in conventional concrete properties due to the addition of latex are reduced permeability to water and chloride ions, increased resistance to freeze-thaw action, and improved adhesion to old concrete substrates. Therefore, LMC is a good material for overlays on bridges, parking garages, and exposed stadiums where the degree of reduction of chloride penetration (and hence corrosion reduction) is directly related to the overall performance and life of the structure. The chloride ion penetration resistance provided by an acrylic latex-modified concrete is shown in Figure 50. These measurements were taken by ponding the surface with 3 percent sodium chloride solution for 60 days (*77*).

The current major use of latex-modified concrete has been as overlays—typically 1.25 to 2 in. (30 to 50 mm) thick—on bridge decks. These overlays have been applied to new construction as well as to old bridge repair and restoration, and are intended to provide a well-bonded, long-wearing riding surface and to act as a barrier to deicing salts. In the U.S., thousands of bridge decks and parking garages have been rehabilitated since 1957 (*11,15,17,23,32,46,49,57,70,71,79,80,83,84*). Some of the projects that have used SBR latex-modified concretes as protective overlays, both bridges and parking garages, new as well as repair projects, are listed in Tables 27 and 28 (*84*).

A notable application of latex-modified concrete is in the repair of Soldier Field Stadium in Chicago in 1981 (*84*). This 58-year-old concrete stadium was structurally restored by bonding reinforced latex-modified concrete to the existing concrete. The horizontal treads received 3 in. (76 mm) and the vertical risers received 6 in. (152 mm) of latex-modified concrete with a specified minimum strength of 4,000 psi (27.5 MPa) at 28 days. The actual compressive strengths averaged 6,000 psi (41.4 MPa).

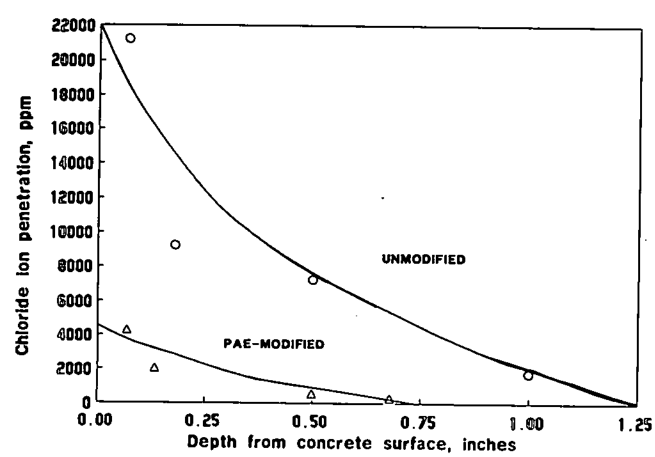


FIGURE 50 Comparison of chloride ion penetration of unmodified and acrylic latex-modified concrete (from *73*).

TABLE 27
BRIDGE PROJECTS USING LATEX-MODIFIED CONCRETE (*22*)

Overlay Installed	Project	Location
1973	Rip van Winkle Bridge over Hudson River	Catskill, New York
1972	University Avenue Bridge, I-676 over Schuylkill River	Philadelphia, Pennsylvania
1982-1985	Chicago Skyway	Chicago, Illinois
1975	Floating Bridge, Hwy 520 over Lake Washington	Seattle, Washington
1980	I-480 over Rocky River	Cleveland, Ohio
1980	Mile Long-Bensonville Street Bridge	Chicago, Illinois
1979	Clark's Summit Bridge, Pennsylvania Turnpike	Pennsylvania
1978	New River Gorge Bridge	West Virginia
1982-1988	Delaware Memorial Bridge, I-295 over Delaware River	Wilmington, Delaware
1984	Newburgh-Beacon Bridge, I-84 over Hudson River	New York
1985	Reedy Point Bridge over Chesapeake-Delaware Canal	Delaware
1982	Columbia River Bridge	Portland, Oregon
1983	Marquam Street Bridge	Portland, Oregon
1983	Wiscasset Bridge	Wiscasset, Maine
1980	Denny Creek Bridge	Snoqualmie Falls, Washington
1980	Sandusky Bay Bridge	Sandusky, Ohio
1978	O'Hare Departure Ramp	Chicago, Illinois
1987	Chesapeake Bay Bridge	Maryland

Another notable application of latex-modified concrete was reported by Howard (*85*); the Marquam Bridge in Portland, Oregon, after 17 years of service, was overlayed in 1983 with latex-modified concrete composed of Type III cement and has given satisfactory results.

The first application of high-early-strength latex-modified concrete overlays for the Virginia Department of Transportation was reported by Sprinkel (*32,33*). Mixture proportions used for this project are given in Chapter Two. The overlay was prepared with more cement (Type III) and less water than is used in conventional latex-modified concrete overlays. Traffic loading was allowed after 24 hours rather than the 4 to 7 days required for conventional latex-modified concrete. After 1 year of service, tests of the bond strength and penetration of chloride ions indicated that the overlay was performing satisfactorily. This application technique, if it continues to give satisfactory results in the future, will be a boon to highway repair and rehabilitation projects, as well as new construction. It could be used in situations in which it is desirable to accelerate construction, to reduce inconvenience to motorists, to allow for installation during off-peak traffic periods such as weekends, to provide a more rapid cure in cold weather, to provide low permeability, or to provide high strength at a very early age.

Some of the other high-early-strength latex-modified concrete overlays include a 150 ft-long section installed on the Delaware Memorial Bridge in 1987 (traffic was allowed on this overlay 24 hours after placement), northbound I-81 in Saltville, Virginia in 1985, and the Chicago Skyway (I-90) at 79th Street in Chicago in 1987. These overlays are all performing well.

Special Applications of Latex-Modified Concretes

In Japan, an experimental investigation was conducted to demonstrate the advantage of higher ductility of latex-modified concrete (*86*), compared to conventional concrete, to resist seismic loads. The experiments were conducted on ductile latex-modified concrete shear walls. Latex-modified systems have been used to produce foam lightweight concrete (*87*) that has higher strength, higher toughness and lower permeability than ordinary foam concrete.

TABLE 28
PARKING GARAGE PROJECTS USING LATEX-MODIFIED CONCRETE OVERLAYS

Overlay Installed	Project	Location
1979	Church Street Garage, University of Michigan	Ann Arbor, Michigan
1977-1980	City Council Building	Indianapolis, Indiana
1979	General Motors Executive Parking Garage	Detroit, Michigan
1979	Dayton Street Parking Garage	Madison, Wisconsin
1977	Gateway Shopping Center	Lincoln, Nebraska
1979	City of Saginaw Garage	Saginaw, Michigan
1976-1980	Grant Street Parking Garage, Purdue University	West Lafayette, Indiana
1981	City of Madison Garage	Madison, Wisconsin
1981	State Securities Building	Lincoln, Nebraska
1982	Larned St. Parking Garage	Detroit, Michigan
1982	Cobo Hall	Detroit, Michigan
1981	Grand Circus Parking	Detroit, Michigan
1980-1981	Crown Center	Kansas City, Kansas
June 1980	City Parking Garage	Des Plaines, Illinois
1979	New York City Bus Terminal ramps	New York, New York
1982	Center Street Parking Facility	Rochester, Minnesota
1983	Hinsdale Hospital	Hinsdale, Illinois
1983	City of Lansing, Mason Bldg	Lansing, Michigan
1983	Catherine Street, University of Michigan	Ann Arbor, Michigan
1983	U.S. Post Office	Grand Rapids, Michigan
1983	Wisconsin Natural Gas	Racine, Wisconsin
1983-1985	O'Hare Parking Garage spiral ramps	Chicago, Illinois
1984	U.S. Post Office	Detroit, Michigan
1985	Grant Park	Chicago, Illinois
1985	McCormick Place	Chicago, Illinois
1984	SouthWestern Bell Telephone	Kansas City, Missouri
1985	Polyclinic Medical Center	Harrisburg, Pennsylvania

POTENTIAL APPLICATIONS FOR LATEX-MODIFIED CONCRETES

Use in Fiber-Reinforced Concrete

Adding steel fibers to concrete considerably improves its flexural strength, impact strength, direct tensile strength, shock resistance, ductility, and post-crack load carrying capacity. It has been demonstrated that these improvements can be achieved without a reduction of workability and that this material is very suitable for bridge-deck overlays, new pavements, and for construction of other concrete structures (*88,89*). When latex is added to steel fiber-reinforced concrete, tremendous improvements may be achieved in the permeability reduction, freeze-thaw resistance, deformation characteristics, and elastic and mechanical properties (*90*). The presence of latex in the matrix of the concrete composite has a higher synergistic effect than for ordinary fiber-reinforced concrete. Reinforcing latex-modified mortars with steel fibers also markedly decreases the drying shrinkage and tremendously increases the impact strength (*90*). Steel, glass, polymers, and carbon fibers can be used to increase the toughness and flexural strength of latex-modified concrete, or latex may be added to fiber-reinforced concrete to improve workability, to reduce drying shrinkage, to improve durability and weatherability, to increase bond strength, and to increase resistance to carbonation and chloride ion and oxygen penetration. Carbon fiber-reinforced polymer-modified mortars have been developed (*91*) and employed in concrete repairs. The use of latex-modified mortar as a matrix for ferrocement was tried for the purpose of improving its durability (*92*). The presence of polymer latex in fiber-reinforced mortar could increase the strength values by a factor of four compared to plain cement mortar. Fiber reinforcement could induce changes in the load-deflection curves, making them smoother without discontinuities. There may be beneficial changes in the microcracking characteristics. Elastomeric latexes might perform better than thermoplastic latexes.

Thus, the marriage between fibers and the latex-modified concretes could produce a material well-suited for the rehabilitation of bridge decks and parking garages, repair and restoration of older structures, and new construction of earthquake and blast-resistant structures. There is a need for development of thin precast elements or slabs with fiber-reinforced latex-modified concretes for bridge-deck and parking garage overlays and for other repair work or new construction where durability and ductility are primary concerns.

The first reported (*93*) use of latex-modified steel fiber-reinforced concrete was in the deck repair of the Morrison Bridge in Portland, Oregon. This overlay reduced costs and overlay thickness for the bridge and also contributed significantly to the structural strength of the existing deck. The inclusion of latex reduced the water demand of the mixture, thus helping to control excessive shrinkage and to reduce permeability, and increasing resistance to penetration by deicing salts (*94*). Other advantages of latex inclusion were very fluid concrete mixtures and better bonding between the overlay and the existing deck. The overlay has been in place since 1980 with no deterioration of the deck surface.

The contractor who carried out the Morrison Bridge deck overlay also installed similar overlays on the Sandial-Sandy River Bridge in Troutdale, Oregon in 1982 and the Centralia, Washington Bridge in 1983. The former was a restoration project for a deteriorated bridge deck, the latter a new bridge where some structural problems apparently developed during construction (*95*). The Oregon Department of Transportation has subsequently approved similar overlays for three other bridge-deck repair projects on I-80 near Troutdale (*95*).

In 1981, Lankard (*94*) carried out a comparative evaluation of latex-modified and various steel fiber-reinforced latex-modified concrete mixtures intended for use in overlay applications in Ohio. As a result of successful performance of the latex-modified steel fiber-reinforced concrete, it was used for overlays on a bridge in Ohio on State Route 665. One year later it was reported to be in excellent condition (*95*).

Use in Conventional Shotcrete

Another area of potential application for latexes is conventional shotcrete. Many shotcrete applications need a protective membrane or matrix that is impermeable and will resist corrosion and freeze-thaw damage. Latexes added to shotcretes may achieve such a protection. In 1973, investigations of structures containing polymers were reported by Graham (*96*) and Bates (*97*). In 1984, Chynoweth (*98*) advocated the use of latex-modified shotcretes. In a few instances, latex-modified shotcretes have been used (*99*). Including latex in a shotcrete mixture results in the development of a latex binder throughout the shotcrete and this imparts increased bond, flexural and tensile strength, and improved ductility and toughness. As in the case of concrete, the bridging action of the polymer binder across microcracks in the cement paste, coupled with the continuous latex film throughout the shotcrete matrix, results in reduced permeability to water and corrosive solutions. Increased bonding and reduced shrinkage make latex-modified shotcrete, if properly used, a more compatible repair material than conventional shotcrete. Latex-modified shotcrete could be more appropriately used in repair of structures subjected to wet-dry cycles and high concentration of chlorides, such as bridges and waterfront structures, especially along coastal regions.

A failure of a latex-modified shotcrete application has caused some concern about the suitability of the material. The possibility of a special type of bond failure in styrene-butadiene latex-modified concrete was pointed out by Marusin (*99*). Polymer-rich films were noticed on the interface surfaces of shotcrete layers due to the latex migration "to form films that hardened on the surface of previously applied layers." It was concluded that extensive cracking of the latex-modified, dry-mixture shotcrete structures occurred as a result of both separation between the shotcrete layers and early shrinkage. "Applying new shotcrete layers over the hard surface of previously applied shotcrete that was partially covered with a smooth, dense, and nonabsorptive polymer-rich film caused by latex migration" caused the delamination of shotcrete layers, Marusin reported.

Another extensive study of the same failure, involving field tests and laboratory simulations of field failure mechanism, concluded that improper shotcreting procedures had created interfacial zones of high porosity and poor bond between successive shotcrete layers (private communication from R.D. Morgan, January, 1991). The layers of porous overspray, entrapped rebound, and hardened SBR latex film were not removed before applying another layer. It was believed that the drying shrinkage and curling stresses on layers of unreinforced shotcrete, which already had very weak interfacial bond, had precipitated the failure of the repaired shotcrete; it was not a failure of the latex-modified shotcrete as a material. Appropriate procedures and safety precautions may have averted this reported failure. Adequate training of construction personnel may be needed to expand the application of latex-modified shotcrete.

Use in Fiber-Reinforced Shotcrete

As stated for fiber-reinforced concrete, the addition of latex might produce a suitable and efficient material for the repair and rehabilitation of certain types of structures and for new construction of particular structures. Steel fiber-reinforced shotcrete was first introduced in the U.S. in the 1970s (*100*) and since then it has been used in numerous applications, mainly in new construction or for lining rock slopes and underground openings in mines and tunnels.

Latex-modified steel fiber shotcrete has the potential for excellent bond characteristics, very high flexural strength, toughness, impact strength, fatigue strength, lower shrinkage, and good durability. This innovative material may be very attractive as a rehabilitation material and may provide a viable alternative to conventional rehabilitation procedures. Potential applications where latex-modified fiber shotcrete may provide an economical and technically feasible alternative to conventional rehabilitation procedures include the following: repair of corroded or impact-damaged structures such as bridge deck soffits, girders, and abutments; marine structures such as surge breakers, jetties, sea walls, dolosse, and piles; and rehabilitation of deteriorated tank linings, drains, and trenches (*101*).

Use in Foundations and Structures Subjected to Dynamic Loads

Toughness, ductility, and high energy absorption capacity are essential requirements for structures likely to be subjected to suddenly applied loads such as earthquakes, blasts, tornados, and wind gusts. The same is true for structures subjected to repeatedly applied dynamic loads, such as machinery foundations. The required ductility can be induced in concrete by adding an appropriate quantity of latex. As stated in Chapter Four, latex-modified concretes have markedly improved deformation characteristics and ductility. However, this has to be achieved without drastically reducing its strength. Experimental investigation using concrete shear-wall structures has demonstrated this feasibility (*86*). A latex-modified concrete with a 25 percent polymer/cement ratio had nearly twice the toughness of unmodified concrete.

Researchers in India (*102*) have demonstrated that pronounced improvements in deformation characteristics could be achieved without sacrificing strength properties in natural rubber latex-modified concretes. This was done through proper combination of natural rubber latexes, chemical admixtures, and superplasticizers. The potential application of latex-modified concrete for structures subjected to dynamic loads (e.g., machine foundations) has been demonstrated (*103*). Experiments were conducted using ordinary concrete and latex-modified concrete footings of three different thicknesses for three loads at four excitation levels. Experimental results revealed that the amplitude of resonance was reduced considerably in latex-modified concrete foundations. It was also observed that the damping factor of the latex-foundation-soil system was considerably larger than that for ordinary concrete foundations. Therefore, it was stated that the use of latex-modified concrete in foundations could lead to more economical designs.

Use in Marine and Offshore Structures

Latex-modified concrete, with its tremendously reduced permeability to water and salt solutions, enhanced resistance to carbonation and corrosion, and increased flexural strength and ultimate strain capacity, is well-suited for use in marine structures and offshore structures.

At Florida Atlantic University, an investigation (*104*) was conducted to evaluate the suitability of latex-modified fiber-reinforced concretes for marine structural applications. Fiber- (steel, glass and polymer) and latex-modified concrete structural members were exposed for varying periods to marine environments. The structural integrity (the compressive, tensile, flexural, and impact strengths over an extended period of time) and long-term durability were studied with alternating exposure to sea water and oven drying. The findings from this limited study indicated the superior behavior of latex- and fiber-modified concretes in the marine environment. Polymer fibers were more stable in the marine environment than glass or steel. However, the addition of latex has improved the durability characteristics in all concretes. The investigation concluded that the latex fiber-modified concrete is the most suitable for long term applications in the marine environment.

Miscellaneous Potential Applications

Roller-compacted concrete is used in the construction of dams and it could be also used in highway and airport pavements and parking lots. Lack of adequate freeze-thaw durability is a major problem in the use of roller-compacted concrete (*105*). Adding a latex to roller-compacted concrete could improve its durability; however, cost may be a limiting criterion.

Latexes or latex-coated aggregates may be used in critical situations to control or eliminate the alkali-aggregate reactions and long term alkali-silica reactions of concretes (*106*).

Small amounts of latex could be added to conventional shotcrete to control dust and reduce the rebound rate during shotcreting (*107*). Artificial wood, with properties similar to natural wood, was developed without portland cement using calcium silicate, a polymer dispersion, and glass fibers (*108*).

Latexes may increasingly be used in the precast and prestressing industry. Mass production of large noncorroding structural elements and weather-proofed roof-decks could be economical and long lasting.

Use To Improve Skid Resistance

The loss of skid resistance from traffic due to the polishing of soft aggregates will severely restrict the useful life of a bridge deck. Such damaged bridge decks can be rehabilitated by using the bonding capabilities of latex-modification. Sprinkel has reported the application of a latex-modified portland cement slag slurry in Virginia in 1989 and 1990 to increase the skid resistance of pavements and decks constructed with insufficient microtexture and macrotexture (*109*). This technique had been used twice before, in Indiana in 1980 and in San Juan, Puerto Rico in 1986.

Two experimental applications, one a 300 ft (90 m) section of pavement in the travel lane (May 1989), and another a passing lane and travel lane of a bridge on I-81 in Rockbridge County (November 1969 and April 1990), were described. In two of the three cases, traffic was allowed after about 48 hours of cure. The initial cost of the latex-modified slag slurry was \$5.90 /yd^2, which is low compared to the \$35 /yd^2 cost of a 1.3 in. (33 mm) minimum thickness latex-modified concrete overlay. It was concluded that "the application of a latex-modified portland cement slag slurry is an economical technique for increasing the microtexture and macrotexture of hardened concrete surfaces constructed with polishing or nonpolishing aggregates. The technique also increases the cover over the rebar" (*109*).

Use of Silica Fume to Enhance the Properties of Latex-Modified Systems

Silica fume is being added to conventional mortars and concretes to gain significant benefits by increasing their strength properties and reducing their permeability. Latexes are added to portland cement mortars and concretes primarily to reduce their permeability and to increase their adhesive strength. Walters (*110*) reported an experimental investigation of the combined use of silica fume and styrene-butadiene latex in portland cement mortars and concretes. Silica fume latex-modified mortars and concretes had improved properties compared to those using one or the other of the admixtures alone. There was no need for any modification of the currently used equipment in placing, consolidating, or finishing the silica fume latex-modified concretes.

Effect of Fly Ash on Latex-Modified Concrete

The compatibility of fly ash with SBR latex-modified concrete was reported by Diamond (*111,112*). Concretes batched with SBR latex and incorporating 15 percent and 25 percent fly ash did not have any adverse effects. Four different Indiana fly ashes, including one class C and three class F ashes of varying properties, were used in the investigation. The fly ashes did not seriously degrade strength development in latex-modified concretes. Some reduced chloride permeability was observed. Different fly ashes affected the performance of latex-modified concrete differently; the particular class C ash used showed generally superior effectiveness. However, the differences did not appear to be of great practical importance. The differences between the results of 15 percent and 25 percent fly ash treatment levels for a given fly ash were not very great (*111,112*).

CHAPTER SIX

CONSTRUCTION PRACTICES AND SPECIFICATIONS

CONSTRUCTION PRACTICES

Construction practices vary according to the type of application. As pointed out in Chapter Five, the predominant use of latex-modified concrete in the U.S. is for bridge-deck overlays (both new and old) and for the construction or rehabilitation of parking garages. Therefore, good construction practices followed for bridge-deck overlays are described in this chapter. Most good practices are also applicable to other construction as well. Some minor modifications and variations are practiced in different parts of the country or during different seasons to suit the local conditions and the prevailing weather.

Mixing and Equipment

Because of the limited mixing time available for latex-modified concretes, usually the concrete is mixed very close to the site of application. For larger volume applications, a mobile mixer is often used. The equipment is designed for continuous mixing at a rate of 6 to 60 yd^3/hr (4.6 to 46 m^3/hr). The mixer is calibrated to ensure a specified mixture design. If the placement exceeds 100 yd^3 (76 m^3), the cement and latex calibration should be checked at 100 yd^3 (76 m^3) intervals. Slump is measured 4 to 5 minutes after discharge from the mobile mixer. It is recommended that the yield be within a tolerance of 2 percent. The job site mixing helps eliminate setting time problems. Capacity for water spraying should be available at the job site.

When required, as in the case of parking garages and other building projects, latex-modified concrete is pumped using standard concrete pumps. In smaller projects, on-site drum mixers are used. However, the size of the batches mixed is limited corresponding to the time available for placing and consolidating the concrete. Total mixing time is limited to 5 minutes. Transit-mixing truck and central plant mixing procedures are not suitable for latex-modifed concrete.

Surface Preparations

Substrate surfaces such as existing concrete, steel, or wood are thoroughly cleaned and all contaminants and bond-breaking materials such as oil, grease, paint, hardened curing compounds, and old polymer mortar patches, are removed. In concrete substrates, the coarse aggregates are exposed and the reinforcement is cleaned of rust. All weakened concrete is also removed. The surface preparation is done by mechanical scarification, chipping, hydrodemolition, sand blasting, shot blasting, water blasting, or any other method approved for concrete surface preparation (*22*). Pavement breakers of less than 30 lbs (13.5 kg) and chipping hammers of less than 15 lbs (6.75 kg) are also used. Additional hand-chipping is done when there are deep pockets. The debris and other loosened material are removed with vacuum or air or water. The surface is always kept clean by suitable covering until it is ready for overlaying. Whenever there is a cold joint, the edge of the previously placed slab is roughened by abrasive blasting (sand blasting).

Complete wetting of the prepared and cleaned surface, at least one hour prior to placing, is done. Before placement, excess water, including pooled water on the surface, is removed. Proper surface preparation must be ensured in order to obtain proper bonding of the latex-modified concrete to the existing substrates. Expansion joints in the overlay are located directly over those in the deck and are installed at the time of placement of the overlay. Casting across an expansion joint and sawing later is not recommended.

Placement

Placement is completed as quickly as possible after mixing to avoid unnecessary handling. The concrete is placed directly from the mobile mixer or it is pumped to the location where it is required. Buckets and buggies are also used for transporting the concrete. Just before placement, the surface to be bonded is coated with paste from the same concrete that will be placed. This is done either by brooming or painting and the excess aggregates left after brooming are removed and discarded. The entire operation of placing, screeding, and brooming is completed within 10 to 15 minutes. Sometimes, to achieve the required grade and profile, bulkheads are installed prior to placement. Screed rails are placed and positioned to ensure finishing to the required profile. Rigid plastic foam and joint fillers are used, when needed, for creating joints.

Finishing

For small work areas, such as parking garages, building floors, or projects of limited size and access, shovels and brooms are used to brush in freshly mixed modified concretes and for distribution to approximately the correct striking-off level. Hand-operated vibrators and screeds are used for finishing. The placement, compaction, and finishing of the surface is a continuous operation and it is completed while the concrete is workable.

For large work areas, screeding and finishing of latex-modified concrete require fast and efficient work. Therefore, a propelled roller finisher running on screed rails and calibrated to obtain the required overlay thickness is the most popular tool used for finishing. This system has augers, rollers, and a vibrating pan which in combination provide a properly consolidated overlay of required thickness. A suitable attachment to the finishing machine enables the contractor to give a drag or broom finish wherever it is desired. The finishing operation is completed before the overlay begins to dry.

After placement, the concrete is consolidated and finished to the final grade with vibrating devices. Spud vibrators are used in deep pockets, edges, and near bulkheads. Hand finishing with metal trowels is done at scuppers, gutters, joints, and in other hard to reach areas. For latex-modifed concretes, excess vibration is strictly avoided because of potential segregation in the LMC.

When a uniform surface has been achieved, it is texturized for skid resistance before it becomes dry. Effects, if any, due to saw cutting are not known; there is a need for investigation in this area.

Curing

Soon after surface texturizing, the surface is covered with clean burlap that is wet, but not dripping wet. The burlap is then covered with a polyethylene sheet. This wet curing is done for 24 ± 2 hrs. After wet curing is complete, the polyethylene sheet is removed and the surface is allowed to dry for 3 days or until a specified strength is achieved. Recently it was reported (*113*) that it may be beneficial to extend the wet curing to 2 days instead of the currently used one day. Recent research has shown that during the initial wet cure period, slight expansion of the concrete occurs; therefore, by extending the wet curing period to 2 days, the potential shrinkage stresses that occur during the subsequent drying will be compensated (*113*). Several highway departments have recently adopted 2-day wet curing for latex-modified concrete overlays.

The main objective of wet curing is to keep the surface with a high enough moisture content to prevent the latex from forming a skin or crust before the concrete attains its final set. As explained in Chapter Four, if enough moisture is lost to allow the skin or crust to form, the surface will have extensive plastic shrinkage cracks. Wet curing is continued for 24 to 48 hours to prevent drying shrinkage cracks.

Use of special liquid membrane curing materials to cure latex-modified concrete overlays to provide the same effect as wet burlap and polyethylene sheet covering is being evaluated by some state highway departments. This procedure, such as spraying the surface with a film-forming polymer latex or water-dispersed epoxy, is reported to be successful (*114-117*). One new product reportedly permits 48 ± 2 hrs for wet curing followed by the normal dry curing. Some states (e.g., Pennsylvania) prohibit the use of liquid membrane curing.

Latex-modified mortars and cementitious coatings with high water/cement ratios are used without cure or cover systems. These mixtures are successful because they have an adequate quantity of water for evaporation, so plastic shrinkage cracks do not occur.

Testing and Quality Control

Tests commonly used for freshly mixed concretes and mortars, including slump, air content, temperature, setting times, unit weight, and yield are also used for latex-modified concretes as quality control measures. These tests are conducted according to ASTM procedures.

In order to monitor the strength development, test cylinders and prisms (when specified) are made and cured at the job site in the same manner as the overlay concrete. Cylinders are tested to determine compressive strength and beams are tested to determine modulus of rupture.

Generally, the overlay is opened for traffic when the overlay concrete reaches a strength of 3,000 psi (20.7 MPa) or some other specified strength. If specified, the adhesion of the latex-modified concrete overlay to the substrate is determined by an in-place bond strength test. Recently, a permeability test using an FHWA-developed test procedure (AASHTO T-277) has been used to assess the permeability to chloride ions.

Cleanup

All tools and equipment are cleaned with water immediately following their use. Latexes are water dispersible in their initial state; if the cleanup is delayed, the latexes will set (within 15 min) after exposure to air and will strongly adhere to the surfaces of tools and equipment. The adhered latexes will be very difficult to remove and cleanup can be done only by mechanical means.

SPECIFICATIONS AND GUIDELINES

Despite successful applications of latex-modified mortars and concretes for the past 30 years, there are no standard ASTM, AASHTO, or ACI specifications for their application. Various latex manufacturers have published brochures (*14*) with recommended specifications and/or guidelines specifically applicable to their own products. Many states have specifications and/or required procedures to be followed in using latex-modified mortars and concretes. These are adopted mainly from the latex manufacturer's recommendations with minor modifications based on local experience.

The Dow Chemical Company published recommendations (*14,58*) and specifications for the construction of latex-modified concrete overlays on concrete bridge decks using Dow Modifier A (a styrene-butadiene latex). Most highway departments are using such guidelines with minor modifications as their specifications.

Recently, American Concrete Institute Committee 548 prepared a "Standard Specification for the Construction of Styrene-butadiene Latex-Modified Concrete Overlays on Concrete Bridge Decks (ACI 548-1)." This reference standard covers materials and methods of construction that are applicable for both new construction and restoration of damaged concrete decks. The standard covers certification requirements of latex products, storage, handling, surface preparation, mixing, application, and limitations. A specification guide and checklist to assist designers and specifiers in choosing the necessary requirements for project specifications are also included.

The mixture proportions, originally used by Dow Chemical Company, recommended in this specification are based on years of field experience and were evaluated and reported by FHWA (*23*). The water demand will be increased (resulting in lower strength) to achieve workability when a lower latex/solids/cement ratio is used.

There are no ASTM standards for latexes used in concrete. Prequalification requirements are specified in Report FHWA-RD-78-35. Therefore, all highway departments and other users have specifications requiring a certification of compliance to FHWA Office of Research and Development Materials Division report RD-78-35 for each batch of latex. The latex products should be stored at temperatures from 40-85° F (4-29° C) and they should not be allowed to freeze.

In Japan, polymer-modified mortars are more widely used in the construction industry than polymer-modified concretes. The standardization work of latex-modified mortars is far more advanced in Japan than in the U.S. There are already 10 standards concerning quality assurance and testing methods for dispersion-type cement modifiers and polymer-modified mortars (using dispersion-type cement modifiers) published as Japanese Industrial Standards (JIS) (*118*).

CHAPTER SEVEN

LIMITATIONS AND PROBLEM AREAS

LIMITATIONS

As with any construction material, latex-modified mortars and concretes have limitations. There are general limitations applicable to all latex systems and there are some specific limitations applicable to particular types and products. General limitations and problem areas are discussed in this chapter.

Weather Conditions

Of primary concern in the application of latex-modified mortars and concretes are extreme weather conditions. At higher temperatures, above 85° F (29.4°C), accelerated setting can occur. A combination of high wind and low humidity is the worst condition for placing latex-modified concretes or mortars. This is also true in the case of conventional concretes. The latex systems are particularly sensitive to plastic shrinkage cracking because of the film-forming characteristics of latex and the low water/cement ratio. Rapid drying of the surface will induce a crust (skin) formation and will adversely affect the finishing operation and the permeability of hardened concrete. Due to rapid drying, extensive shrinkage cracking (known as "mud-cracking") may occur on the exposed surface which could present a poor appearance. Therefore, adequate precautions should be adopted to protect the concrete surface from rapid drying. If these cracks are deeper than ⅛ in., the cracks should be repaired or the overlay should be removed. It is recommended (*22*) that ACI Standard 305R-86 "Recommended Practice for Hot Weather Concreting" be strictly followed. It is also recommended that latex-modified systems not be placed in conditions where the evaporation rate exceeds 0.10 lbs (Virginia uses a limiting rate of 0.05 lbs) of water/ft^2/hr (0.50 kg/m^2/hr) unless special precautions are taken to prevent evaporation of water.

Cold weather is not a serious limitation since latex-modified concretes are less sensitive to cold weather than conventional concretes. However, most state highway departments specify a minimum of 45°F (7.2°C) for placing latex-modified concretes. During cold weather the freshly placed latex-modified concrete should be protected from temperatures below 45°F (7.2° C) during the first 3 days of curing. Recommended practices for cold weather concreting mentioned in ACI 306.1 should be observed.

Mixing Time

Overmixing of latex-modified concretes should be avoided. If overmixed, the surfactants contained in latexes will incorporate air and form a froth; this can result in unacceptably high air contents. High air content leads to lower strength. Therefore, mixing periods are kept to a minimum, usually less than 3 minutes. Conventional ready-mix trucks or central mixing procedures cannot be used in the case of latex-modifed concretes. For large jobs, expensive concrete mobile mixers are required.

Chemical Resistance

The latex-modified systems generally exhibit only low or moderate chemical resistance as reported in Chapter Four. Therefore, in applications involving severe chemical exposure, many latexes are not recommended.

Underwater or Moist Conditions

As stated in Chapter Four, initial air-drying of latex-modified systems is necessary for latex film formation and to achieve optimum properties. Therefore, latex-modified concretes are not suitable for underwater applications. However, after the latex-film formation is completed, they can be immersed in water.

As pointed out before, polyvinyl acetate (PVAC) should not be used for exterior applications where exposure to moisture is likely. A case was reported (*75*) where a PVAC latex was used in mortar to hold air conditioning units in the walls of a high rise apartment. The moisture condensation from the air conditioner led to hydrolization of the latex and deterioration of the mortar.

Precast concrete elements made with latex-modified concretes cannot be used underwater if they are made with a re-emulsifiable latex. Due to reversible chemical reactions in the presence of water, such elements may degrade.

Freshly mixed or placed latex-modifed concrete should be protected from rain. During periods of rain, the placing operation should be stopped and any concrete already placed which is damaged by rain should be removed and discarded.

CORROSION POTENTIAL OF PVDC LATEX

As noted in Chapter Two, polyvinylidene chloride, an organic chloride-based latex, had been used as a mortar additive and a concrete admixture. PVDC has been alleged to increase the potential for chloride-induced steel corrosion (*119A, 119B*). Although no longer generally used in the United States, PVDC has been the subject of litigation (*119C*) over past applications, with mixed findings regarding its effect on corrosion.

CHAPTER EIGHT

PERFORMANCE, COSTS, AND BENEFITS

PERFORMANCE

Since the introduction of latexes in concrete construction more than 30 years ago, the bulk of their use has been in thin overlays in old and new bridges, and to a minor extent, in parking garages. Substantial amounts of information and data about the field performance history of latex-modified concretes in thin overlay systems make it possible to assess their suitability for these applications.

A perusal of available information (*14*) has shown that very few data are available about the field performance of latexes in other applications.

Nationwide Surveys

Four nationwide surveys have been conducted by mailed questionnaire (*120-123*) on the status, service life, and performance of latex-modified concrete in transportation structures, with particular emphasis on bridge-deck overlays. Some meager information is available about the use and performance of latex-modified concrete in other concrete structural components and structures. It is not known whether any nationwide surveys have been conducted on the performance history of latex-modified mortars and concretes in other applications.

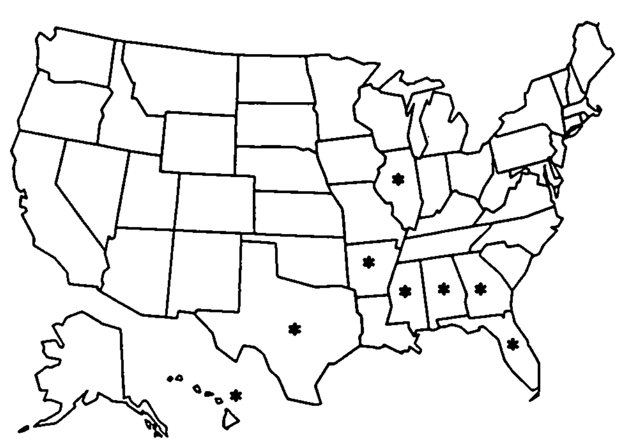
Task Force 30, Concrete Overlays for Bridge Decks, of the Joint Committee of the American Association of State Highway and Transportation Officials (AASHTO), Associated General Contractors of America (AGC), and American Road and Transportation Builders Association (ARTBA) has published (*120*) the results of a survey of AASHTO member agencies. The survey was conducted in 1987 and response to their mailed questionnaire was excellent, 54 out of 63 agencies supplied information.

The performance of the following four commonly used bridge-deck overlays was evaluated:

- Latex-modified concrete (LMC)
- Low-slump dense concrete with 0 to 1 in. slump (LSDC)
- Low water/cement ratio concrete with water/cement ratio less than 0.44, (LWC)
- Other types, including epoxy concrete, epoxy-modified concrete, polymer concrete, silica fume concrete and superplasticized concrete.

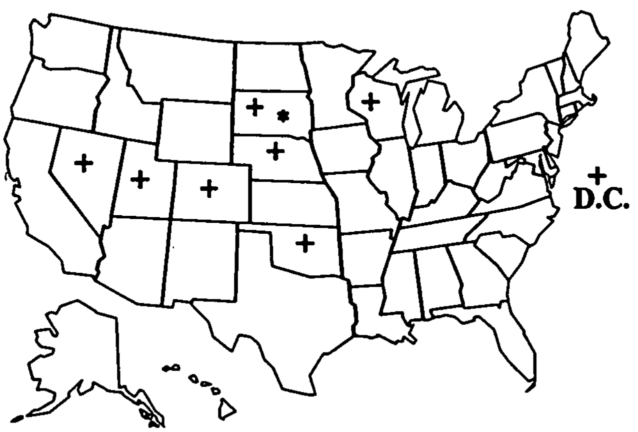
The survey (*120*) indicated that the most widely used bridge-deck overlay material was latex-modified concrete; 44 of the reporting 54 agencies had used it. LSDC was used by 40 agencies, and LWC was used by only 18 agencies. Most southern states had not used LMC, as shown in Figure 51, and it would be useful to find out why these states had not tried LMC on their bridge decks. Seventy-six percent of the state highway agencies who used LMC stated that their experience with LMC was good. Again, LMC received the highest percentage of good performance ratings among the overlay materials surveyed. Sixty-five percent of the users had good experiences with LSDC and 73 percent had good experiences with LWC. Twenty-four percent of the agencies reported bad experiences using LMC (Figure 52). Most of the states in the Midwest reported bad experiences; again, it would be worthwhile to find out whether the geographical location had any influence on the performance of LMC. One agency, South Dakota, reported both good and bad experiences using LMC.

The South Dakota Department of Transportation (SDDOT) was contacted for an explanation of their experiences with LMC (Huft, David, Dan Johnston, and Clyde H. Jundt, private communication December 12, 1990). South Dakota "made the decision early to use LMC exclusively with only occasional use of LSDC for special situations. From 1976 through 1982, latex-modified concrete was the only specified overlay on the plans." They had good results for a number of years until the early 1980s when problems began to surface in construction. South Dakota went through a learning process with LMC overlays and the contractors had strong technical support from the latex supplier. The good quality control produced good results. Later, the contractors reported withdrawal of technical support by the latex



ALABAMA
ARKANSAS
FLORIDA
GEORGIA
HAWAII
ILLINOIS
MISSISSIPPI
TEXAS
MANITOBA (CANADA)

FIGURE 51 States that have not used latex-modified concrete. (from *120*)



COLORADO
DISTRICT OF COLUMBIA (D.C.)
NEVADA
OKLAHOMA

SOUTH DAKOTA
UTAH
WISCONSIN
ALBERTA (CANADA)

**SOUTH DAKOTA* reported both good and bad experiences.

FIGURE 52 States reporting bad experiences in using latex-modified concrete. (from *120*)

supplier. A South Dakota DOT bridge construction engineer had the following observations in regard to construction problems:

1. Latex-modified concrete seems very sensitive to weather conditions. Temperature, humidity, wind and evaporation rate have a more pronounced effect on finished product than on low slump.
2. Contractors have said the only advantage to using latex is the ability to make wider pours than with low slump.
3. Contractors say that variations in moisture in aggregates (sand) has a pronounced effect on slump of latex-modified concrete mix. More so than with low slump. They report that sometimes they have had to dry sand to zero moisture to keep slump within specifications. (Note: This problem could have been solved by adding less water to the mixture).
4. Cost — this is the big factor according to Contractors.
5. Contractor ranking of disadvantages with latex-modified concrete is as follows:
   1. Cost
   2. Requires ideal weather
   3. Very sensitive to small changes in sand moisture

Because of contractor demand for alternatives, LSDC was provided as an alternate. Thereafter, no LMC was applied in South Dakota by choice by contractors.

South Dakota's research engineer also reported a problem with the pH stability in the latex supplied. "A sample of latex submitted in 1985, which had a pH of 5.6 was adjusted to a pH of 10 with NaoH (specifications call for a pH of 8.5 to 10.0) and, when retested two days later, had a pH of 6.2, indicating a severe problem with stability."

The engineer correctly stated that the reasons for the bad experiences reported are contractors' problems with the material. Construction problems led to severe shrinkage cracking, debonding, and delamination. "Testing conducted by SDDOT had also indicated that the ultimate chloride permeability of LMC, although lower than LSC, is not significant enough to warrant the extra cost of the latex."

It would be useful to explore the reasons for the bad experience reported by other agencies and to conduct a detailed analysis of the performance of LMC in field applications. However, it should be noted that the AASHTO survey (*120*) indicated that 76 percent of the states reported good experiences and therefore the problems are usually local in nature and might be prevented by following the specifications more strictly.

Chamberlin and Weyers (*121*) surveyed the state and provincial highway agencies in the U.S. and Canada for the Strategic Highway Research Program (SHRP) Project C-103, "Concrete Bridge Protection and Rehabilitation: Chemical and Physical Techniques," by mailed questionnaire on the status and service life of protection and rehabilitation treatments that are being applied to concrete components of bridges. Responses were received from 47 states and 9 Canadian provinces, and the results were similar to the AASHTO survey (*120*). Graphical representation of the survey responses is shown in Figure 53. Table 29 compares the results of this survey with the results of two similar surveys, one conducted by TRB in 1977 (*122*) and another conducted by the New Mexico State Highway Department in 1984 (*123*). Areal treatments are those typically applied to the entire deck surface at one time, while those that are used to repair damage, such as spalls and cracks, at specific locations on a deck are considered as topical treatments. Areal treatments were further divided into standard and experimental.

For complete deck overlays (areal treatment), LMC was the favorite among the currently available materials. It has been used more than LSDC, and other types of systems including polymer concretes, sealers, cathodic protection and bituminous chip seals. Fifty-five (55.4) percent of the responding agencies used LMC as a standard treatment and an additional 7.1 percent used it as an experimental treatment. The acceptance frequency of LMC for conventional overlay treatment was the highest. The geographic distribution of acceptance of LMC for areal treatment (*121*) is shown in Figure 54. The survey also showed that LMC had not been used for bridge elements other than decks. Respondent's opinions regarding the average useful life of LMC overlays ranged from 5 to 60 years. However, when outliers were removed using accepted statistical techniques, the mean response was 16.6 years with a standard deviation of 5.4 (*124*) essentially the same as for LSDC overlays.

As part of the SHRP Project C-103, Chamberlin and Weyers (*124*) also compiled performance data on LMC bridge-deck overlays in the U.S. and Canada from published and unpublished records available through the summer of 1990. One hundred thirty-six overlaid decks were located for which spalls and delaminations had been measured at least once since the placement of the overlay. Mean service lives, taken to be the age at which 50 percent of the overlaid decks would attain 40 percent total damage (spalls + delaminations + patches), were extrapolated by both linear and curvilinear functions to be respectively 23.7 and 15.2 years (Figure 54A). The condition of the overlays was found to be independent of either traffic volume (measured by AADT) or climate (measured by mean annual snowfall and mean annual temperature).

State Evaluations

Many states have conducted performance evaluations of LMC overlays (*14, 125-130*). Field performance of latex-modified con-

TREATMENT	Status	N	%
Topical			
PCC, Quick-Set or Polymer Mortar Concrete Patching	S	40	71.4
	E	4	7.1
Epoxy Injection	S	16	28.6
	E	8	14.3
A C Patching	S	15	26.8
	E	1	1.8
Areal			
LMC Overlay	S	31	55.4
	E	4	7.1
LSDC Overlay	S	26	46.4
	E	4	7.1
Membrane + AC Overlay	S	29	51.8
	E	2	3.6
Sealers	S	24	42.9
	E	11	9
Thin Polymer Overlay	S	7	12.5
	E	15	26.8
Cathodic Protection	S	7	12.5
	E	26	46.4
MSC Overlay	S	2	3.6
	E	14	25
FRC Overlay	S	1	1.8
	E	6	10.7
Polymer Impregnated	S	1	1.8
	E	5	8.9
Rubber-Modified AC Overlay	S	0	0
	E	1	1.8
Bituminous Chip Seal	S	0	0
	E	1	1.8

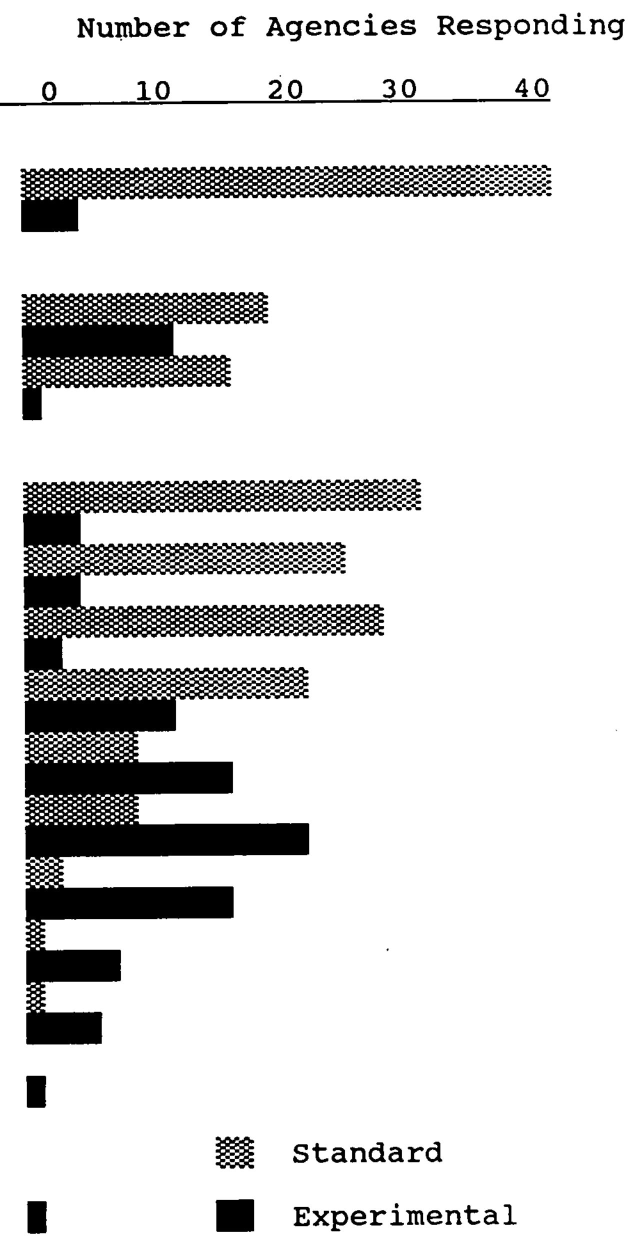


FIGURE 53 Status of bridge deck treatment (*121*).

crete overlays on four bridges on Interstate 90 at two locations in Pennington County, South Dakota was evaluated (*125*). Performance evaluation of the overlay concrete was conducted during construction and at the post construction phase. Some problems during placement were encountered due to inadequate quality control. However, SDDOT concluded that "Generally the operations followed an acceptable procedure. With some restrictions on placement and control, the quality of overlay concrete should be improved." Structural cracks appeared in the overlay concrete near abutments in the first winter season and there was an increase in the chloride content in the overlay concrete.

In 1984, Sprinkel (*126*) evaluated 12 bridges in Virginia with LMC overlays ranging in age from new to 13 years. He found that their general condition was good. The shear strength of the bond between the LMC overlays and the base concretes was about the same or greater than that of the base concrete. The good bond that was initially achieved was maintained. The permeability of chloride ions based on a rapid permeability test was an average of 773 coulombs (very low) for a 1.25 in. thick LMC overlay and 4,590 coulombs (high) for the base concretes. He evaluated these bridges again in 1990 (*130*) and found that their condition was still good. There were no signs of distress in the LMC overlays after 7 to 20 years of service. A Michigan DOT survey indicated that 23 LMC deck overlays ranging in age from seven to 11 years were performing quite well (*127*). Further, a

TABLE 29
REHABILITATION PRACTICES FOR U.S. BRIDGE DECKS AS REFLECTED IN THREE NATIONAL SURVEYS (*121*)

	Percentage of respondents indicating use of treatment					
	TRB 1977 (*122*) 48 responses		New Mexico 1984 (*123*) 43 responses		SHRP 1989 (*121*) 47 responses	
Treatment	Standard	Experimental	Standard	Experimental	Standard	Experimental
Sealers	8.3	10.4	NI*	NI	44.7	19.2
Silane	NI	NI	4.6	7.0	NI	NI
Epoxy Injection	6.2	4.2	NI	NI	34.0	12.8
Polymer impregnation	NI	NI	7.0	0.0	2.1	10.6
Patch w/ AC	10.4**	12.5**	NI	NI	29.8	2.1
Patch w/ PC mortar/ concrete			NI	NI	76.6	4.2
Membrane + AC overlay	48.8	12.5	37.2	39.5	46.8	4.2
Thin polymer overlay	NI	NI	NI	NI	12.8	29.8
Normal slump PCC overlay	8.3	0.0	NI	NI	NI	NI
LSDC overlay	31.2	6.2	32.6	39.5	51.1	8.5
LMC overlay	35.4	14.6	30.2	44.2	63.8	6.4
MSC overlay	NI	NI	NI	NI	2.1	29.8
FRC overlay	NI	NI	NI	NI	0.0	12.8
Cathodic protection	0.0	18.8	NI	NI	10.6	53.2

* NI = Not Included
** The 1977 survey did not distinguish among patching materials.

survey of four LMC deck overlays placed on concrete contaminated with more than 4 lb/yd^3 of chloride ions were performing satisfactorily after two to five years of service life (*127*).

In the city of Baltimore, placement of dual protective systems was stopped when it was concluded that LMC overlays were not providing any more protection against the intrusion of chloride ions than could be achieved with the Maryland DOT's standard bridge-deck concrete (*128*).

In Indiana, after investigating the chloride ion concentration in bridge decks with latex-modified concrete overlays, Fincher (*130*) concluded that "After 4 years of monitoring for chloride penetration, indications are that latex overlays, when placed on new decks, are effectively preventing the accumulation of chloride to values above the corrosion threshold at steel level." In another Indiana study (*131*), the following was concluded: "At an average age of about thirteen years, the overlays in the study

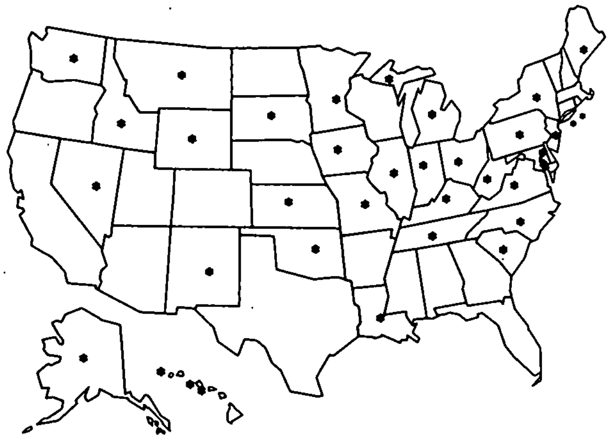


FIGURE 54 Geographic distribution of acceptance of LMC overlays. (from *121*)

were generally found to have a good riding surface. The amount of surface spalling and resultant patching was minor except for two bridges where the patching was being done as a part of larger projects in the same vicinity . . . with maintenance, it seems that these overlays can have an effective life of about 20 years." A survey conducted in 1988 on several of these Indiana bridges by Dow Chemical personnel was reported by Kuhlmann (*71*). This survey indicated that "These overlays, whose ages ranged from 9 to 15 years, are still in service and in good condition."

Percenchio and Marusin (*132*) have found that "All of the specialty concretes had lower permeabilities to the ingress of chloride-laden water than the control structural concrete. In most cases, the lower permeability could be attributed to a reduction of the water/cement ratio. However, in the case of styrene-butadine latex, permeability was considerably lower than the water/cement ratio of the concrete would indicate."

Bishara (*70*) reported the field performance data of 132 bridges in Ohio, Michigan, Kentucky, and West Virginia. He concluded that "Chloride contents at a given depth are much lower in decks that have latex overlays than in decks that lack such overlays, all other factors being equal." Virtually no scaling was observed on the bridge decks, therefore he stated that "It is safe to say that latex-modified concrete provides adequate freeze-thaw resistance."

A condition survey conducted in 1986 by Ohio DOT of 1,320 bridges with more than 1.5 million yd^2 (1.25 million m^2) of LMC overlays showed that 79 percent of these decks, some as old as 13 years, received Ohio's highest condition rating, number 1 (*71*).

COST

The cost of latex and the cost of latex-modified systems depends on the type and quantity of latex purchased; however, the cost of the latex is the predominant cost of the system. As an illustration, suppose the cost of styrene-butadiene latex per gallon is about $5.00. When used at the specified dosage of 24 gal/yd^3, the latex alone would cost $120/yd^3 of latex-modified concrete for bridge-deck overlays. In many parts of the country the materials (cement and aggregates) for a conventional low slump, low water/cement ratio, high density concrete may cost only $60/yd^3.

The nationwide survey (*120*) showed that the cost per square yard of latex-modified concrete overlay on bridge decks, includ-

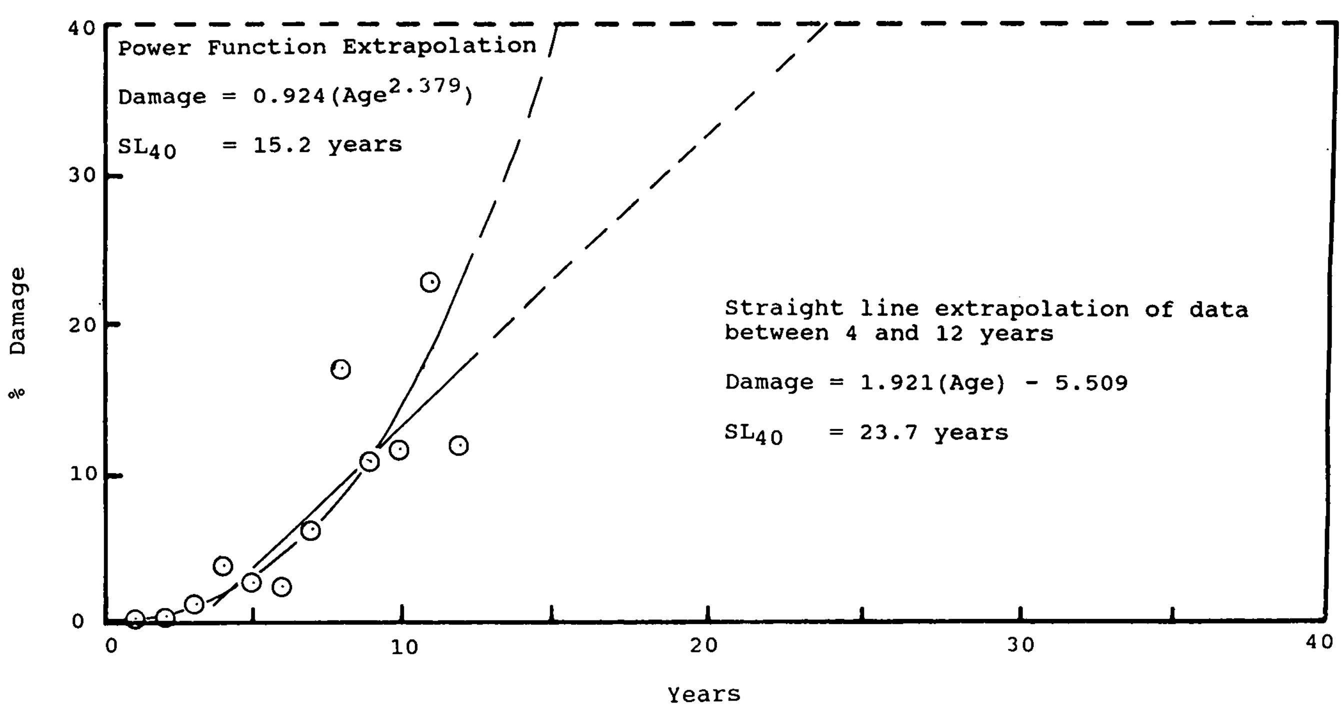


FIGURE 54A Service life estimates for LMC overlays (*124*).

ing the deck preparation such as scarifying, sandblasting, etc., but excluding the preliminary deck repairs, varied from \$20 to \$100. The other commonly used bridge-deck overlay costs varied as follows: low slump dense concrete with 0 to 1 in. slump - \$15.50 to \$121 /yd²; low water/cement ratio concrete - \$12.52 to \$45/yd²; and other materials such as epoxy aggregate mixtures, polyester aggregate mixtures, silica fume, superplasticizer, etc., \$21 to \$95 /yd².

Sprinkel has reported (*126*) that in Virginia a 1.25 in. overlay of latex-modified concrete is usually installed at a cost of \$20 to \$30 /yd² exclusive of the cost for traffic control and deck preparation. In experimental bridge-deck overlays placed in 1974, the cost was estimated to be \$15 /yd² for using the conventional A4 bridge deck concrete as compared to \$24 /yd² for latex-modified concrete (*126*). Howard (*85*) reported that for the Marquam bridge repair job the bid unit cost of the latex-modified concrete overlay was \$15.09 /yd², where the total cost of the latex-modified concrete used in the project was \$956,712. This was the final cost at 1983 prices. The cost comparison of an unmodified and a styrene-butadiene latex-modified concrete given by Walters (*21*) showed that the modified concrete will cost about \$100 more per cubic yard (Table 30). Kuhlmann has presented (*113*) data from bids on three latex-modified concrete overlay projects of different sizes but in the same state (Table 31). For these projects the unit cost varied from \$19 to \$31 /yd² (\$23 to \$37/m²). The cost of the latex alone was a small portion of the total cost, it varied from 1.4 to 3.8 percent as shown in Table 31. For larger projects the percentage will be lower.

Lifetime Cost and Benefit-Cost Analysis

The true or final cost of a repair or a new construction depends on how long the repair or the structure will serve the purpose for which it was built. Therefore, the initial cost should be prorated over the expected lifetime of the structure or the repair. Such a lifetime cost analysis has been reported for latex-modified bridge-deck overlay concretes (*71,113,125*). A minimum life of 20 years had been assumed by Kuhlmann, based on reported performance evaluations (*113*). Based on the data presented in Table 31, a comparison of the cost of latex-modified concrete and an alternate overlay system annualized over the lifetime of each is presented in Table 32 (*71*). The true cost of the alternate systems was obtained by assuming values for inflation and interest rate. The initial cost of the alternate system was 28.6 percent less than latex-modified concrete, whereas the true cost (lifetime cost) of latex-modified concrete was 18 percent less than the alternate system. If the cost of traffic control during shutdown for repairs had been considered in the lifetime cost analysis, then the latex-modified concrete would look still more favorable (*71*). Sprinkel has presented (*126*) a logical benefit-cost analysis for thin bridge-deck overlay latex-modified concrete. The benefit due to lower permeability of chloride ions in latex-modified concrete overlays compared to that of conventional concretes has been taken as the main consideration for the benefit/cost analysis. Data from 12 bridge overlays built in Virginia over a period of 12 years were used in this study. Using a more conservative assumption, that benefit is provided by dividing the logarithm of the permeability of the conventional concrete by the logarithm of the permeability of latex-modified concrete, he obtained a benefit ratio of 1.27. This means that a latex-modified concrete overlay is worth 27 percent more than an overlay of conventional concrete. Based on the cost/benefit ratio analysis, Sprinkel showed that "the use of latex-modified concrete in a thickness of 1.25 to 2.0 in. is cost-effective relative to an A4 concrete overlay, when the benefits of low permeability provided by the latex-modified concrete are needed."

TABLE 30
COST COMPARISON OF UNMODIFIED AND MODIFIED CONCRETES (*21*)

Ingredient	Weight (lb/yd³)	Cost (\$/lb)	Extension (\$/yd³)
Unmodified Concrete			
Portland cement (Type I)	658	0.0580	38.16
Sand	1,645	0.0048	7.90
Pea gravel	1,315	0.0078	10.27
Cost / yd³ = \$56.33			
Latex-modified concrete			
Portland cement (Type I)	658	0.0580	38.16
Sand	1,645	0.0048	7.90
Pea gravel	1,315	0.0078	10.27
Styrene-butadiene latex	207	0.4850	100.40
Cost / yd³ = \$156.73			

TABLE 31
COST ANALYSIS OF LATEX-MODIFIED CONCRETE OVERLAYS (*113*)

State	Year	Project size (yd^2)	Unit cost ($\$/yd^2$) (range of bids)	Total cost ($) (range of bids)	Latex cost (% of total project)†
Indiana	1986	885	19 - 31*	107,988 - 149,482	3.8 - 2.7
Indiana	1986	2,287	18 - 30*	429,449 - 644,218	2.6 - 1.6
Virginia	1989	4,019	26 - 28**	495,201 - 1,154,374	3.3 - 1.4

* Does not include blasting and curing
** Includes blasting and curing
† Based on assumed bulk price of $4.75/gal

BENEFITS

As pointed out in Chapter Two, unlike solvent-based products, latexes are nontoxic, nonflammable, can be used with high solids content, and it is possible to tailor their properties. Latex-modified mortars and concretes have the following additional benefits:

- Less bleeding and segregation in fresh concrete
- Better water retention in fresh concrete
- High adhesive (bond) strength
- High tensile and flexural strengths
- Low permeability to water, air, and gases
- Better durability and weatherability
- Higher carbonation resistance
- Better corrosion protection for steel reinforcement
- Higher ductility and toughness
- Higher strain capacity in pre- and postcracking stages
- Less shrinkage
- Higher impact strength
- Better abrasion resistance
- Better skid resistance

When to Use Latex-Modified Concrete

The attributes listed above make latex-modified concrete a material highly suitable for bridge-deck overlays, and repair and rehabilitation works, particularly in situations where corrosion and durability are potential problems.

Latexes and latex-modified concretes and mortars are more costly than conventional concretes and mortars. Therefore the basic question is whether it is economical to use it. There is no simple or unique answer to this question. Economy depends on the cost/benefit ratio. The cost is a dependent variable; it depends on geographic location, season of the year, and availability of experienced contractors, trained personal, and special equipment. The cost is also dependent on the type of application (new construction or old concrete restoration, a thin section overlay or full depth concrete) and on the total quantities used in construction. Therefore, every case has to be analyzed for the cost/benefit ratio and the life cycle cost. Certainly latex is safer and more manageable in construction than polymer concrete or epoxy mortars and concretes for either new construction or for repair and rehabilitation work. Balancing the cost and the behavioral efficiency (performance and life) is a difficult problem. Adequate caution and careful lifetime cost/benefit analysis should be considerations in material selection.

TABLE 32
COST EFFECTIVENESS OF LATEX-MODIFIED CONCRETE OVERLAYS (*71*)

	LMC	Alternate system
Overlay life	20 years	10
Number of installations	1	2
Interest	9%	9%
Inflation	5%	5%
Installed cost	$\$35/yd^2$	$\$25/yd^2$
Present value	$\$35/yd^2$	$\$43/yd^2$

CHAPTER NINE

OBSERVATIONS, CONCLUSIONS, AND RECOMMENDATIONS

Rapid deterioration of concrete in our infrastructure has been recognized as a serious problem. The National Bridge Inventory (NBI) has shown that as of 1987 there were 575,000 bridges with about 2.3 billion ft^2 of bridge deck, and that approximately 200 million ft^2 (10 percent) of these decks were given a rating of 4 or less, meaning that these decks were highly deteriorated. A concrete overlay could cost-effectively extend the service life of many of the bridges to at least equal their design lives, provided any existing corrosion activity is not excessive. Latex-modified concrete can prove to be a suitable material for these overlays. There is a good balance between performance and cost for LMC as a repair material.

OBSERVATIONS AND CONCLUSIONS

Based on an intensive and objective review of the cited references, and on discussions held with researchers from various countries and with LMM and LMC users (mainly state highway engineers), the following conclusions are drawn:

- For the past 30 years, considerable research and development of LMM and LMC has been conducted, mainly in the U.S.A. and Japan, but with some minor work in Europe and India. In the U.S.A., most of the development work originated from latex producers and the research work was mainly applications oriented. Recently, many state highway agencies have done field performance evaluations of LMC. Very little basic research, particularly from universities, has been reported. As a contrast, most of the research work reported from Japan was basic in nature, including characterization of the material and latex modification mechanism, and was conducted at university laboratories.
- Property enhancements of conventional portland cement concretes and mortars are possible with the addition of appropriate types and quantities of latexes. These modified mortars and concretes have high adhesive (bond) strength, higher tensile and flexural strengths, low permeability to water, air, gases and chemicals, better durability and weatherability, higher carbonation resistance, better corrosion protection for steel reinforcement, higher ductility, higher toughness, higher strain capacity in precracking and postcracking stages, lower shrinkage, higher impact strength, better abrasion resistance and better skid resistance. Other benefits include less bleeding and segregation, and better water retention in the fresh concrete.
- Properly designed mortars and concretes have been proven to be safe, durable, beneficial, and economical, if they are wisely selected and properly used. They are suitable for various applications and have a high potential for success in repair and rehabilitation projects.
- Despite the fact that LMC and LMM have been used for the past 50 years, there are no current standard ASTM, AASHTO or ACI specifications for quality control and application of LMC and LMM. ACI Committee 548 will be publishing a standard for the construction of bridge-deck overlays with styrene-butadiene latex-modified concrete. In contrast, there are 17 Japanese Industrial Standards (JIS) for quality and testing methods of polymer-modified mortars and polyester concretes. Ten of these deal with latex-modified mortars.
- Styrene-butadiene latex has the longest track record of successful application and it is currently used much more than other latexes. In the U.S.A., LMC is primarily used for bridge-deck overlays and,to a minor extent, for parking garage overlays. It is used both in new construction and in repair of deteriorated decks.
- Nationwide surveys have shown that LMC has experienced high overall acceptance over other currently available advanced materials for bridge-deck overlays. According to one survey, 44 out of 54 agencies had used it and about 76 percent of the users had indicated good experience with it.
- Field performance of LMC has been generally good, even after 20 years of service, as indicated by various state evaluations and condition surveys. Bad experiences reported seem to be due to lack of adequate quality control and not strictly following the specifications during construction.
- The initial cost of latex is high; it may cost about \$120/yd^3 of LMC. However, the cost of the latex is usually a small portion (several percent) of the total cost of the project. When lifetime cost and cost/benefit analyses were done for bridge-deck overlay concrete, LMC was shown to be cost effective when the benefits of low permeability of LMC are needed.
- New applications are being explored for using latexes profitably and efficiently. These new and potential applications include the addition of latexes to fiber-reinforced concrete, conventional shotcrete, fiber-reinforced shotcrete, roller-compacted concrete, lightweight foam concrete, for controlling or eliminating alkali-aggregate and alkali-silica reactions, to improve skid resistance, and to enhance the properties of silica fume and fly ash concretes. Suggested new structural applications include foundations and structures subjected to dynamic loads, marine and offshore structures, mass production of large noncorroding structural elements, and weatherproof roof decks.

RECOMMENDATIONS

- There is a need for national standards and specifications, particularly performance-oriented specifications. These should be developed for quality control and testing of latexes, LMM, and LMC for various applications. Appropriate construction guidelines should be prepared for various applications of LMC and LMM and these should be made available to end users.

- Over the past 50 years almost the same mixture proportions have been used for LMC for bridge-deck overlay. Construction technology has changed considerably during this period, however no change has been initiated in mixture proportioning. Optimum mixture proportions should be developed for various applications. A rational mixture proportioning method should be developed.
- Prospective LMC and LMM users, including contractors and construction engineers, need training in quality control procedures. This can be achieved by conducting educational seminars and workshops. Future bad experiences could be avoided by strictly following any specifications and guidelines that are developed.
- Detailed investigation should be conducted to ascertain the causes for poor field performance of LMC revealed in national and state surveys. This information should be used in developing guidelines and standards.
- LMC and LMM should draw more attention as high performance materials in the construction industry. The industry should be made aware of new avenues for efficiently and profitably using these new materials.
- There is a need for more basic research and fundamental information about the characterization of various latexes, LMC, and LMM. Government and university laboratories should take a more active role in the development and optimization of new latex formulations.
- Additional investigations are needed to determine the durability aspects of currently used latexes, particularly the concentration required to produce durable LMC and LMM.
- The contribution of latex to controlling or eliminating the alkali-aggregate and alkali-silica reactions should be investigated.

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