

# REACTIONS OF POLYMER LATEXES WITH PORTLAND CEMENT CONCRETE

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This paper explains the physical and chemical actions and reactions of polyvinylidene chloride and styrene-butadiene polymer latexes on the aggregate and portland cement in concrete. It also describes how the polymer particles irreversibly bond to the aggregate and cement, form a monolayer of plastic particles over their surfaces, and subsequently coalesce to form a continuous polymer phase throughout the concrete. The need for curing procedures with latex concrete different from those required for the optimum cure of conventional concrete is also discussed. These basic data are expanded to explain how polymer latexes reinforce concrete, improve its structural properties, control its elastic behavior, and greatly enhance its durability. Data are presented to describe polymer latex concrete with compressive strengths from 5,000 to 15,000 psi (34 500 to 103 000 kPa), flexural strengths from 800 to 2,000 psi (5520 to 13 800 kPa), elastic moduli from 2 to  $5 \times 10^6$  psi ( $13.8$  to  $34.5 \times 10^6$  kPa), bond strength to steel  $>2,500$  psi (17 200 kPa), and bond strength to concrete  $>600$  psi (4140 kPa) at which the concrete substrate fails. Practical applications of latex concrete over the past 20 years are described, and why the materials are ideally suited for each application is explained.

\*POLYMER latexes have been used in portland cement mortars and concrete for about 40 years; their major application has been in thin section overlays and in the repair of damaged concrete. They have been used in these areas because of the improved bond strength and durability properties they impart to portland cement concrete (PCC). Little was known about the reactions and interaction between latexes and portland cement. This report describes the research findings developed over the past 14 years by the Dow Chemical Company on the various mechanisms and reactions of styrene-butadiene and polyvinylidene chloride (Saran) latexes with portland cement and relates these findings to the improved properties in the resulting mortars and concrete.

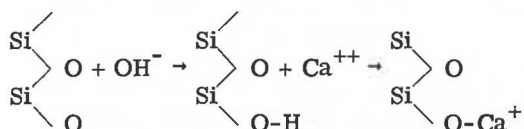
The hydration of portland cement is important to the interactions of latex, cement, and aggregate and to external surfaces in contact with the wet concrete. The hydration of portland cement is not discussed in this paper, although the effects of some of the reaction products of hydration, as they affect the polymer latexes, will be discussed. An excellent explanation of the hydration of portland cement is described by Lea (1).

Polymer latexes are a colloidal dispersion of plastic particles in water. The particles are stabilized in the water by coating the surfaces with anionic and nonionic surfactants that stabilize the plastic particles against agglomeration in the presence of polyvalent ions always in portland cement systems and that prevent coagulation of the particles under the high shear forces developed when concrete is mixed. These surfactants are usually good "soaps" that produce excessive amounts of foam when agitated. Therefore, an effective antifoaming agent must be incorporated in the polymer latex to prevent excessive air entrapment in the PCC containing the latex.

The ingredients and handling characteristics of polymer latex PCC are similar to those of conventional concrete. Polymer latex PCC is made of portland cement, coarse and fine aggregates, water, and from 1 to 4 percent polymer based on the weight of the concrete.

## CHEMICAL REACTION

The initial reactions that take place in both polymer-modified and conventional concrete are the same. Water reacts with the portland cement, produces sodium, potassium and calcium hydroxide, and dissolves some of the calcium sulfate. The hydroxide ions in turn react with silica and form a basic surface on the aggregate. Calcium ions available from the hydration of the portland cement under alkaline conditions react with the basic silica surface and deposit calcium ions on the aggregate surface to form a calcium silicate. Our observations on these reactions are consistent with those reported by Iler (2) and Kolthoff and Stenger (3). This total reaction is complex but can be shown in a simple form as follows:



At this point in the reaction, the polymer latex particles associate in a monolayer on the aggregate surface through the  $\text{Ca}^+$  ion linkage. If the calcium ion on the silica surface is replaced with a sodium ion, no polymer association will take place. The association of the polymer particle with the calcium silicate surface of the aggregate is irreversible in that it cannot be removed by washing with distilled water or with hydrochloric acid. A portion of the calcium ion cannot be removed by acid washing at this point; this indicates that it is chemically bound to the latex particle. We do not know the chemical reaction that takes place between the polymer and the calcium ion on the silica surface; however, we are pursuing two hypotheses at the present time: (a) that the calcium ion reacts with double bonds either present or formed in the polymer and (b) that the calcium ion reacts with the surfactants on the surface of the polymer. We do know that the polymer particle, either styrene-butadiene or Saran, is irreversibly and strongly affixed to the surface of the silica aggregates in the concrete. This eliminates one of the weak points in concrete: the bond of the cement paste to the aggregate.

The latex particles also bond to the surface of all the portland cement particles in the concrete. We believe this reaction is the same as that to the calcium silicate surface of the aggregate and takes place early in the reaction process of portland cement. Fifteen percent styrene-butadiene or 20 percent Saran, based on the weight of portland cement, have almost equal numbers of polymer particles introduced into the concrete and are enough to deposit about two layers of latex particles over the total surface of the unhydrated cement grains and aggregate particles. The latex particles are coated with surfactants that are also highly effective dispersants for portland cement when associated with latex. The result of this is that the latexes act as effective water-reducing agents in concrete. The hydration process continues as water passes around the latex particles into the surface of the cement and reacts to form the portland cement hydrate or gel. As the reaction proceeds, the gel increases in size, and the surface area is increased. Additional latex particles deposit in a monolayer on this new surface area. The latex particles do not penetrate the gel area, and the gel does not form around the particles. This has been determined by X-ray analysis of fractured cement particles on a scanning electron microscope. The hydration process continues until the surface comes in contact with another cement particle or an aggregate surface. At this point in time, because of the greatly increased surface area produced by the hydration of the portland cement, there are enough latex particles present to coat all surfaces with a monolayer. When these surfaces come in contact, the latex particles on the surfaces are forced together, and free water is removed from the immediate area around the particles. The latex particles then coalesce and start to form a continuous film about two particles thick throughout the concrete matrix. A new continuous polymer phase has now been introduced into the concrete.

## CURING MECHANISM

There are major differences in the curing of polymer latex concrete and that of regular concrete. In conventional PCC, long exposure to a moist or wet environment allows the portland cement to continue to hydrate and gain strength properties. This is also true with latex-modified PCC, but the method of obtaining the optimum cure is different. Latex concrete must undergo a second curing mechanism in addition to the hydration of the cement. The latex particles must coalesce to form a film, and this film must cure to gain its maximum strength. The curing of the latex film is best achieved under a dry environment. It would appear that it would be impossible to obtain a good cure for both reactions. Fortunately, this is not true. Portland cement continues to hydrate as long as a relative humidity  $\geq 78$  percent is maintained. Latex films will cure at relative humidities below about 98 percent; the lower the humidity is, the faster the cure will be. Therefore, in latex PCC, the relative humidity in the concrete should be maintained between 78 and 98 percent to obtain optimum results.

Another phenomenon in latex concrete is that some of the latex particles migrate to any surface exposed to the air and form a latex film on this surface. Subsequently, this film will prevent any rapid loss of water from the concrete. This results in an optimum wet curing condition within the concrete even though the surface of the concrete is exposed to a dry cure. It is desirable to cover or to wet the surface of latex concrete for up to 24 hours to prevent excessive drying out of the surface of the concrete. When the plastic film in latex concrete has attained its initial cure, the latex will be unaffected by repetitive wetting with water and, in fact, will continue to gain strength under these conditions (4).

Latex concrete will develop about 75 to 85 percent of its ultimate strength in 28 days when cured under ambient conditions of 73 F (22.8 C) and 50 percent relative humidity.

## FUNDAMENTAL BEHAVIOR OF LATEX CONCRETE

The understanding of how latexes react in PCC is of great interest to the chemist, but in itself is of little practical value to the material or structural engineer. However, by studying how the latexes reinforce PCC, we can develop some interesting insights into why they improve the performance properties of concrete, and this is of great interest to the engineer.

When PCC dries out, the cement hydrate or gel shrinks because of the loss of water, which creates structural stresses within the gel. When these stresses exceed the tensile strength of the gel, the material yields producing microcracks as shown in the micrograph in Figure 1. This is the typical condition of all PCC. As structural and thermal stresses are applied to concrete, these microcracks propagate, join with other microcracks, and lower the tensile capacity of the concrete. If the stresses are high enough or repeated often enough, the concrete can fail in tension or through fatigue.

An analysis of the microstructure has revealed some remarkable differences between latex concrete and regular concrete. Figure 2 shows the microstructure of concrete containing Saran latex. It is the first example of a concrete without any microcracks that we have ever observed. It is a seven-bag concrete with a water-to-cement ratio of about 0.30 to 1 and a 1-in. (25.4-mm) slump. It was cured under optimum conditions. Although we have achieved this optimum microstructure, it is not typical of most latex concrete. Figure 3 shows the typical microcrack structure of latex concrete. Polymer microfibrers bridge across the microcracks and restrain the propagation of the microcrack (5). Often these microcracks will terminate in polymer-rich areas. Because of the relatively low elastic modulus of the polymer in comparison to the portland cement, the polymer will undergo strain, thereby relieving the stresses in the cement hydrate. At this point we can see why it is so important that the latex particles bond well to the aggregate and to the cement hydrate. It is this high bond strength that allows the polymer to sustain high tensile loadings and that increases the tensile capability of the PCC.

The structural properties of the plastic film are all important to the resulting con-

Figure 1. Unmodified concrete paste phase.

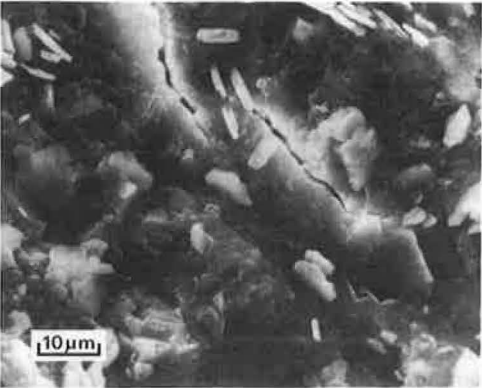


Figure 2. Saran latex concrete.

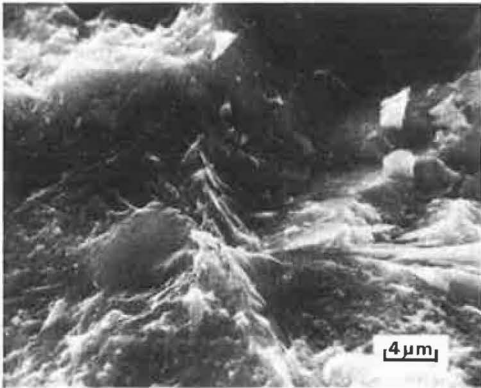


Figure 3. Polymer microfibers in latex concrete.

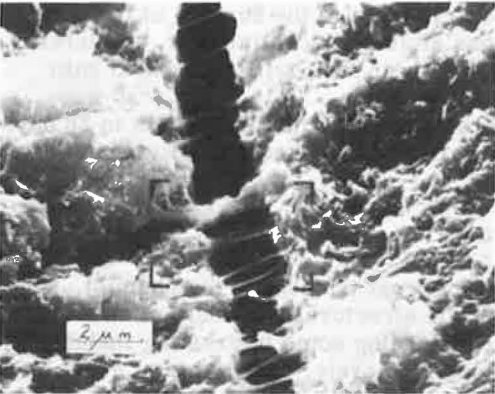


Table 1. Mechanical properties of mortars.

Mortars	Strength (psi)				Flexural Elastic Modulus (psi)
	Compressive	Tensile	Shear	Flexural	
Control <sup>a</sup>	4,480	350	50 to 200	820	$3.4 \times 10^6$
Styrene-Butadiene <sup>b</sup>	5,500	740	> 650	1,620	$1.92 \times 10^6$
Saran <sup>c</sup>	8,430	870	> 650	1,820	$2.52 \times 10^6$

Note: 1 psi = 6.8948 kPa.

<sup>a</sup>Water-to-cement ratio = 0.57/1.

<sup>b</sup>Water-to-cement ratio = 0.40/1; latex-to-cement ratio = 0.15/1.

<sup>c</sup>Water-to-cement ratio = 0.40/1; latex-to-cement ratio = 0.20/1.

crete properties. A latex that produces a film with a low elastic modulus will actually lower the elastic modulus of the concrete, make it quite ductile, yet impart high tensile properties to the concrete. A high-modulus, high-strength polymer will increase the elastic modulus of the concrete, improve its structural properties, and still impart improved ductility. Improved ductility usually improves the abrasion resistance properties of the concrete, and the low porosity due to the continuous polymer network improves the weathering, freeze-thaw resistance, and chemical resistance properties of the concrete. All these factors lead to greater durability.

## STRUCTURAL PROPERTIES

The structural properties of polymer latex mortar and concrete can vary considerably depending on the type and amount of latex, the type of aggregate, the cement factor, and the water-to-cement ratio. In general, increasing amounts of latex produce higher strengths. Styrene-butadiene latexes produce high tensile or flexural strengths, average compressive strengths, and a low elastic modulus. Saran latexes produce high compressive, tensile, and flexural strengths and a high elastic modulus. Small-sized aggregate produces higher strengths than larger aggregate. Table 1 gives typical mechanical properties of latex mortars versus a control mortar (sand-to-cement ratio = 3/1). All test specimens were cured 28 days unless otherwise noted. Table 2 gives the strength properties of small-aggregate concrete (water-to-cement ratio = 0.30/1) containing Saran latex, and Table 3 gives the compressive and flexural strength of latex concrete containing  $\frac{5}{8}$ -in. (15.9-mm) aggregate. Figure 4 shows the compressive strength stress-strain curve for a standard concrete with no latex, 15 percent Saran latex, and 15 percent styrene-butadiene latex. These curves are for the same concrete as described in Table 3. The Saran latex increases the elastic modulus of the concrete, and the styrene-butadiene latex decreases the elastic modulus.

The use of steel- and alkali-resistant glass fibers is of current interest. Table 4 gives the effect of Saran latex on the mechanical properties of small-aggregate concrete containing fibers.

Another important benefit of latexes in concrete is their ability to increase concrete's bond strength to reinforcing steel. Conventional concrete will develop bond pull-out strengths to No. 5 reinforcing bars of 300 to 800 psi (2068 to 5516 kPa). Styrene-butadiene latex will increase this strength from 1,700 to 2,200 psi (11 720 to 15 170 kPa), and the Saran latex bonds so well to the steel that the steel bar yields at a bond strength >2,700 psi (18 620 kPa), depending on the strength of the steel.

## APPLICATIONS OF LATEX CONCRETE

Polymer latex concrete was first used for restoring and resurfacing deteriorated concrete floors. The excellent bond strength to existing concrete allowed these materials to be used in thin sections,  $\leq 0.5$  in. (12.7 mm). This did not appreciably increase the dead weight loading on the floor. A natural extension of this application with the styrene-butadiene and Saran latexes was the resurfacing of exterior, deteriorated concrete and especially concrete bridge decks. The first resurfacing of bridge decks with latex concrete was in 1957 in Michigan (6). Figure 5 shows this bridge in 1970. Since that time, hundreds of bridge decks have been restored with latex concrete. The main advantages of latex concrete for this use are excellent bond strength to the base concrete, excellent freeze-thaw resistance, excellent resistance to the penetration of chloride ions from deicing salts, good ductility, good abrasion resistance, and greatly improved tensile and flexural properties.

Saran polymer latex mortars have been used in brick masonry construction since 1961. Although these mortars have excellent weathering and freeze-thaw durability, they are primarily used in this area because of their excellent flexural bond strength to brick. Saran latices increase the flexural bond strength by a factor of 4 or more, and allow a nominal 4-in. (101.6-mm) single-wythe wall to perform the same function

Table 2. Strength properties of small-aggregate concrete containing Saran latex.

Aggregate-to-Cement Ratio	Latex (percent)	7-Day Strength (psi)		28-Day Strength (psi)		
		Compressive	Tensile	Compressive	Tensile	Oven-Dry Tensile
3:1	0	8,640	580	8,760	520	550
	8	13,220	—	15,260	—	—
	14	11,650	700	14,370	860	1,290
	20	9,440	610	13,110	890	1,170
4:1	0	4,400	—	5,320	—	—
	8	12,010	—	13,260	—	—
	14	10,850	640	13,370	880	1,210
	20	10,430	650	13,570	890	1,450

Note: 1 psi = 6.8948 kPa.

Table 3. Strength properties of concrete made with 5/8-in. (15.9-mm) aggregate.

Latex (percent)	W/C	Strength (psi)	
		Compressive	Flexural
0	0.44/1	6,400	690
5 S	0.38/1	8,420	800
10 S	0.38/1	8,230	810
15 S	0.37/1	9,080	950
5 S/B	0.37/1	6,500	850
10 S/B	0.37/1	6,210	940
15 S/B	0.30/1	6,090	1,050

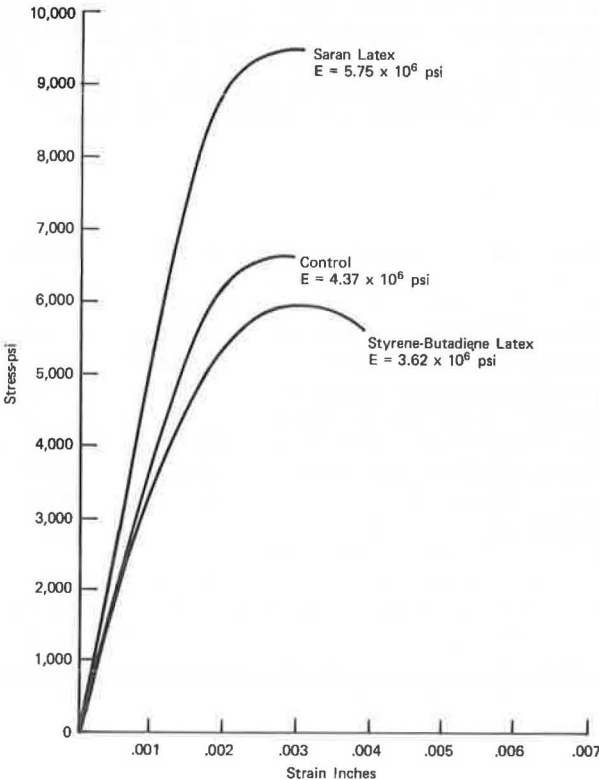
Note: S = saran latex; S/B = styrene-butadiene latex. Aggregate void volume = 28.5 percent; cement content = 7 bags/yd<sup>3</sup>; and wet density = 152 to 156 pcf. 1 psi = 6.8948 kPa. 1 in. = 25.4 mm. 1 yd<sup>3</sup> = 0.07646 m<sup>3</sup>. 1 pcf = 1.602 kg/m<sup>3</sup>.

Table 4. Mechanical properties of small-aggregate concrete containing fiber.

Item	Property (psi)		
	Compressive Strength	Flexural Strength	Flexural Elastic Modulus
Control			
No fiber	7,070	1,550	$2.6 \times 10^6$
Steel fiber	7,800	1,920	$2.4 \times 10^6$
Glass fiber	8,920	1,150	$2.3 \times 10^6$
Saran latex			
No fiber	11,900	2,680	$3.2 \times 10^6$
Steel fiber	12,700	2,700	$3.1 \times 10^6$
Glass fiber	13,300	2,710	$3.3 \times 10^6$

Note: Sand/cement = 2.5/1; water/cement for control = 0.44/1, for latex = 0.34/1; latex solids/cement = 0.20/1; fiber content = 1.75 percent by volume; 7-day curing at 100 percent relative humidity; 21-day curing at 73 F (22.8 C) and 50 percent relative humidity; and 7-day curing at 200 F (93.3 C), tested cool. The compressive strength was obtained on 2-in. cubes; flexural properties were obtained on bars 2 in. wide, 0.5 in. deep and 10 in. long, center point load. 1 psi = 6.8948 kPa, 1 in. = 25.4 mm.

Figure 4. Concrete compressive strength stress-strain curves.

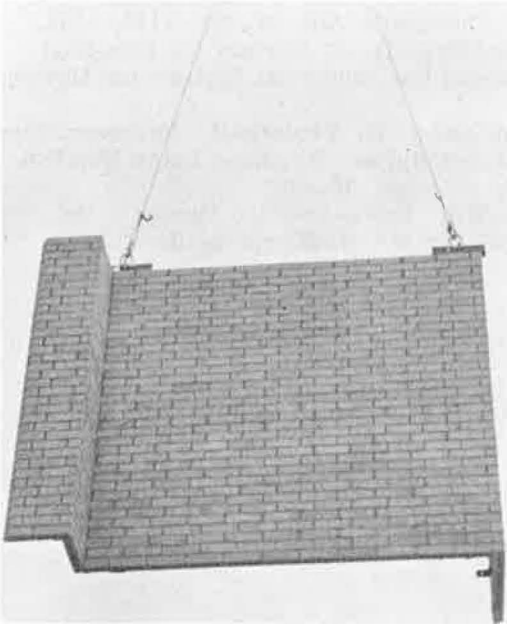




**Figure 5. Mortar bridge surface after 13 years of service.**



**Figure 6. Single-wythe architectural panel for high-rise building.**



**Figure 7. Architectural panels in place.**



as a conventional double-wythe masonry wall. Saran latex also allows the prefabrication of single-wythe architectural brick panels. Figure 6 shows a typical panel being lifted into place on a high-rise building in Austin, Texas. The almost completed building is shown in Figure 7.

## CONCLUSIONS

Currently, research is under way to investigate the structural properties of reinforced and prestressed flexural concrete containing polymer latexes. Of particular interest is the use of these materials in prestressed concrete railroad ties. The excellent durability of latex concrete and its structural properties and excellent bond strength to steel should produce another ideal use of polymer latex concrete, a new and remarkable material based on the established technology of the portland cement and plastics industries.

## ACKNOWLEDGMENTS

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