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POLYMER-MODIFIED CONCRETE FOR MILITARY CONSTRUCTION.(U)
APR 77 J R KEETON, R L ALUMBAUGH
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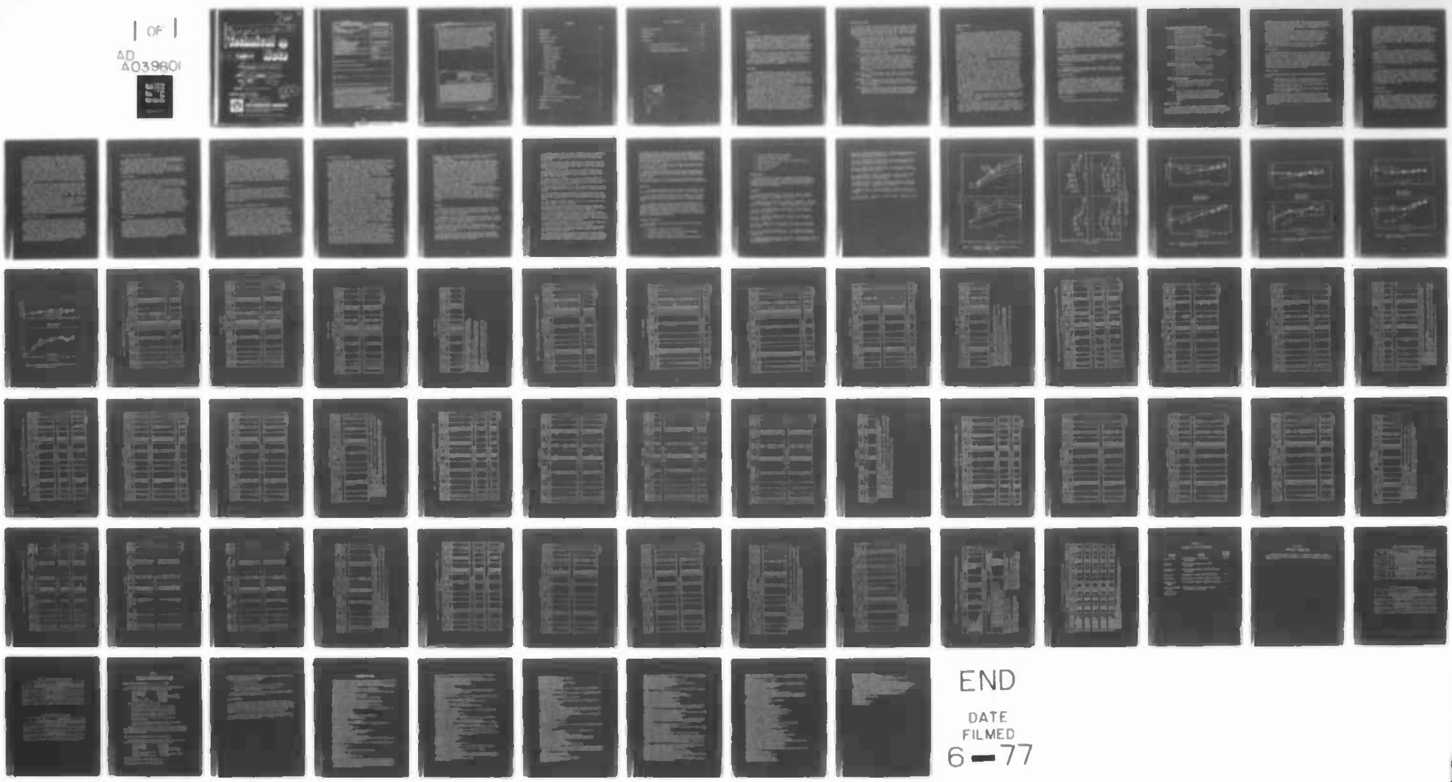

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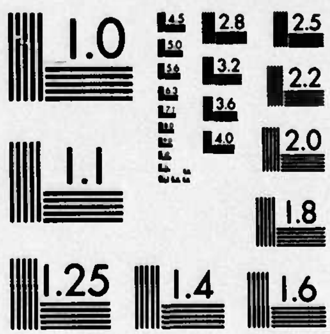

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Results are given of tests made with polymer-modified concretes in which the polymeric materials are added to the concrete in the mixer. Polymers used were either epoxy or saran latex. Epoxy- or latex-modified concretes provided compressive, splitting tensile, and flexural strengths from 2.8 to 4.6 times those of similar concrete without the polymer. Epoxy-modified concretes achieved compressive strengths from 7,770 psi to 10,150 psi over test ages of 1 day to 365 days. Latex-modified concretes reached compressive strengths from over

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4,160 psi to 10,110 psi over test ages from 3 days to 365 days. Splitting tensile strengths of epoxy-modified concretes ranged from 900 psi to 1,340 psi for test ages from 1 day to 365 days; corresponding strengths of latex-modified concretes ranged from 600 psi to 970 psi. Flexural strengths of epoxy-modified concretes ranged from 1,300 psi to 1,610 psi; corresponding strengths of latex-modified concretes ranged from 770 psi to 1,570 psi; Significant reductions were observed in water absorption of polymer-modified concretes. Bond strength of polymer-modified concrete was slightly higher than in concrete without the polymer. Young's moduli of polymer-modified concretes were only 1.4 to 1.8 times those of similar concrete without the polymer. Epoxy-modified concretes cost between \$432 and \$465 per cubic yard more than conventional portland cement concrete; corresponding cost of latex-modified concrete is about \$278. Typical mix designs and mixing, placing, and curing procedures are presented.

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Results are given of tests made with polymer-modified concretes in which either epoxy or saran latex are added to the concrete in the mixer. These concretes provided compressive, splitting tensile, and flexural strengths from 2.8 to 4.6 times those of similar concrete without the polymer. Compressive strengths of epoxy-modified concretes ranged from 7,770 to 10,150 psi over test ages of 1 to 365 days; latex-modified concretes, from 4,160 to 10,110 psi over test ages from 3 to 365 days. Splitting tensile strengths of epoxy-modified concretes ranged from 900 to 1,340 psi for test ages from 1 day to 365 days; latex-modified concretes, from 600 to 970 psi. Flexural strengths of epoxy-modified concretes ranged from 1,300 to 1,610 psi; latex-modified concretes, ranged from 770 to 1,570 psi. Water absorption was significantly reduced in polymer-modified concretes. Bond strength of polymer-modified concrete was slightly higher than in concrete without the polymer. Young's moduli of polymer-modified concretes were only 1.4 to 1.8 times those of similar concrete without the polymer. Epoxy-modified concretes cost between \$432 and \$465 per cubic yard more than conventional portland cement concrete; corresponding cost of latex-modified concrete is about \$278. Typical mix designs and mixing, placing, and curing procedures are presented.

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INTRODUCTION

This report summarizes results of research conducted in FY-74 and FY-75 on the use of polymers in concrete. An earlier Civil Engineering Laboratory (CEL) report of research conducted in FY-72 and FY-73 also contained results on the use of polymers in mortar [1]. In both of these studies, the polymers were introduced into the mixer along with aggregates, cement, and water. Hardening of the polymer (polymerization) was accomplished either by chemical means, by application of moist heat (steam), or by evaporation of water to coalesce the latex into a solid polymer.

Based on results of the first report, research in FY-74 and FY-75 was limited to the most promising of the polymers. Strength properties were determined on test specimens at ages from 1 day to 1 year.

This report also contains suggestions for uses of polymer-modified concretes, including recommended quantities of polymers and mixing, placing, and curing requirements. Incremental cost data are included as well as commercial sources of the materials.

BACKGROUND

In 1967 Brookhaven National Laboratory (BNL), the U. S. Bureau of Reclamation (USBR), and the Atomic Energy Commission (AEC) began a joint venture on the strengthening of concrete with polymers. Later the Office of Saline Waters (OSW) became involved by support of work at USBR on the properties of concrete exposed to hot brine and distilled water. The main thrust of their work was polymer impregnation of precast concrete. This research by these agencies resulted in five topical reports issued in 1968, 1969, 1971, 1972, and 1973 [2 through 6].

In 1969 the Federal Highway Administration (FHWA) initiated support of a research program at BNL to investigate the use of concrete polymer materials for highway applications, with eventual special emphasis on polymer impregnation of bridge decks. This research resulted in reports issued in 1970, 1972, 1973, and a final report in 1975 [7 through 10]. In the years between 1970 and the present, many state highway departments, universities, and other agencies have conducted laboratory research and related field studies on the use of polymers in concrete. Very few long-term studies have been made on polymers added at the mixer. One of the notable exceptions was a study conducted in the Soviet Union by V. I. Solomatov, the results of which were published in Russian in 1967. The AEC completed and published a computer translation of this report in 1970 [11]. Work with latexes was published by Eash and Shafer [12].

DEFINITION OF TERMS

For the most part the terms used in this report relating to polymers in concrete (and mortar) are those adopted by American Concrete Institute (ACI) Technical Committee 548, Polymers in Concrete. Membership of ACI Committee 548 includes representatives of BNL, FHWA, USBR, CEL, and many other universities, federal and state agencies, and companies involved and interested in the use of polymers in concrete.

Polymer-modified Portland Cement Concrete (PPCC) - liquid polymeric material is introduced into the mixer along with aggregates, portland cement, and water; the polymeric material is subsequently hardened. (For mortar, involving no aggregate larger than U. S. sieve size no. 4, the abbreviation is PPCM, other things being the same as for concrete.)

Polymer-modified Regulated Set Cement Concrete (PRCC) - same definition as for PPCC, except that Regulated Set Cement is used instead of portland cement.

Latex - a milk-like emulsion consisting of small globules of synthetic resin (plastic) dispersed in water. The globules of plastic are dispersed in the water either following polymerization or, more frequently, the globules are formed from a liquid monomer by a process called emulsion polymerization. The globules then coalesce into larger hardened polymeric particles as the water is removed from the system either by evaporation, by reaction with the cement (hydration), or by both mechanisms.

Epoxy Resin - a liquid polymer of relatively low molecular weight which forms a solid polymer when reacted chemically with a curing agent.

Hardening - the chemical process by which a liquid polymeric material is converted to a solid polymer; in the case of a latex, the polymeric particles coalesce upon loss of water and form a solid product.

Curing Agents - chemicals which produce hardening (polymerization), especially of epoxy systems, by entering into the reaction and becoming a part of the resulting polymer. The curing agent used in the tests reported herein was a modified polyamine.

RESEARCH PROGRAM

Approach

At the outset of the program, it was suspected that the natural high alkalinity of the cement-water solution (pH = 12 to 13) would tend to hydrolyze most polyester-type materials. For this reason, the polymers investigated in the initial study were epoxies and latexes believed to be relatively unaffected by the alkalinity of the cement paste. It was also reasoned that in order to achieve a stronger product by synergizing the inherent strength of the hardened cement paste with that of the hardened polymer, excellent bonding between the two must be accomplished. The basic gel-like structure of hardened cement paste, consisting of a matrix of solid material (mostly calcium silicates) encompassing many small pores (gel pores) and a fewer number of larger pores (capillaries), is well known. An ideal composite material would be one in which the polymer fills all the pores of the cement paste and bonds tenaciously to the solid material. Therefore, it was deemed necessary to accomplish as much cement hydration (formation of hardened cement paste) as possible prior to hardening of the polymer.

Initially, the cement chosen for the study was portland Type III, High Early Strength. Initial set of Type III cement takes place in 2 to 4 hours and the 7-day compressive strength of concrete made with this cement is approximately equivalent to the 28-day strength of concrete made with conventional portland cement. In the initial tests, polymer was added to the mixer immediately following addition of the mixing water. Results of these initial tests were poor, however, and it was reasoned that (1) the presence of the polymer may have impeded early hydration and (2) the cement should be allowed to begin to hydrate for some time prior to addition of the polymer. Accordingly, subsequent procedures allowed the portland cement mixtures to stand for periods up to 1 hour before addition of the polymer. Test results showed compressive strengths several orders of magnitude higher than when the polymer was added immediately after addition of the mixing water. Still later in the program, an experimental nonchloride accelerator was made available to CEL which enabled rapid hydration of the portland cement and allowed addition of the polymer within 15 minutes of initial mixing of the cement and water.

Regulated Set cement was then introduced into the program. Initial set of this type of cement normally occurs within 20 to 30 minutes, and the introduction of polymers and curing agents extended this time to between 1 and 1-1/2 hours.

At the beginning of the study it was hoped that curing of the concrete mix containing the polymeric material in ambient laboratory air would enable sufficiently rapid strength gain. It was soon learned, however, when using epoxies and curing agents in portland cement concrete, that the cement hydration process needed acceleration, so low pressure steam curing for 16 hours at 150°F was utilized thereafter. The steam accelerated both the hydration of the cement and the hardening of the epoxy. Although latex manufacturers normally recommend only air curing for their products when used in concrete, some of the latex specimens in this study were also steam-cured for comparison.

As reported previously [1], the first portion of this research program involved investigation of as many polymeric ingredients as possible, using early compressive strength (1 to 7 days) as the criterion of relative success of a given product. About 40 different combinations of materials were tested in this period (FY-72 and FY-73), with most of them eliminated from further investigation because of unsatisfactory results. Research in FY-74 and FY-75 concentrated on more complete studies utilizing (1) one epoxy and an epoxy curing agent and (2) one latex. Compressive strengths, Young's moduli, splitting tensile strengths, and flexural strengths were determined on multiple specimens for test ages up to 1 year.

Aggregates Utilized

Aggregates used in the research program consisted of local sand and gravel from the Santa Clara River. Except for a few tests involving gap grading, sand and gravel gradations conformed to ASTM C 33-71. Maximum size aggregate was 3/8-inch (pea gravel).

Cements Utilized

Cements involved in the program were (1) Type III portland, High Early Strength and (2) Regulated Set Cement. Sources of these cements are included in Appendix A.

Polymers Utilized

As stated earlier, research in this portion of the study was limited to concrete mixtures made with one epoxy (Celanese Epi-rez 5077), and one epoxy curing agent (Ancamine T-1, a modified polyamine). Ratio of curing agent to epoxy was 1:5. Shell Epon 815 showed similar results in the first portion of the study and could be substituted for the Epi-rez 5077. The latex used was Dow 464, a saran. An anti-foaming agent (Dow Corning Antifoam B), was used to prevent foam formation when using the latex. Appendix A contains listing and source of all pertinent materials used in the program.

Mixing Procedures

Mixing procedures used in preparing the test specimens follow.

Portland Cement Concretes Without Accelerator.

1. Mix aggregates and cement dry for 1 minute.
2. Add required water and mix for 3 minutes.
3. Stop mixer and allow concrete to stand for 1 hour, mixing for 15 seconds each 10 minutes.
4. Add polymer and mix for 3 minutes.
5. Place polymer-modified concrete in molds.

Portland Cement Concretes With Accelerator.

1. Mix aggregates and cement dry for 1 minute.
2. Add required water and accelerator and mix for 3 minutes.
3. Stop mixer and allow concrete to stand for 15 minutes.
4. Add polymer and mix for 3 minutes.
5. Place polymer-modified concrete in molds.

Regulated Set Cement Concretes.

1. Mix aggregates and cement dry for 1 minute.
2. Add required water and mix for 3 minutes.
3. Add polymer and mix for 3 minutes.
4. Place polymer-modified concrete in molds.

Epoxy and Curing Agent.

1. Mix epoxy and curing agent and let stand for 10 minutes to allow curing agent to begin to react.
2. Add to concrete mix at required time.

Latex.

1. Add the antifoaming agent to the premixed latex.
2. Place in the mixer at the required time. (Latex 464 is 50% solids and 50% water, so this water must be taken into consideration when adding the mixing water.)

Compaction Methods

At the beginning of the program, the mixtures containing epoxies were compacted into the cylinder molds by vibration. It was soon obvious, however, that the material does not respond well to vibration. For most of the epoxy mixtures, vibration provided minimal compaction. Hand packing (like ice cream is hand-packed into a carton) of the material in the molds was the next method utilized. This method performed fairly well when used in conjunction with vibration. A third method of compaction, the most effecient developed to date, was hand-tamping in two layers, combined with vibration.

Most of the epoxy materials, when mixed with cement and water, cause severe water separation, or bleeding of the mixing water, as the mixture is compacted into a mold. Compressive strength test results seem to indicate that this bleed water is the excess water usually required in concrete for workability, and therefore the elimination of this water does not affect deleteriously the subsequent strength-producing cement hydration.

Latex materials seemed to mix well with the basic concrete, and compaction into molds was easily accomplished by vibration.

Curing Methods

Curing methods used in this study were (1) low pressure steam (S+A) and (2) ambient laboratory air (A). The curing cycle of specimens to be steam-cured was as follows: (1) steam-curing at 150°F for 16 hours, (2) removal from mold at age 1 day and ambient air-curing for the remaining time until tested. ''Ambient air curing'' means that the specimen was placed in a laboratory room at ambient temperature and humidity, uncontrolled except for normal heating. Specimens to be air-cured were removed from molds at age of 1 day and then placed in the same laboratory room (mentioned above) until time to be tested.

Concrete Mixes

Experimental tests were made with the following basic concrete mixes:

1. Water-cement ratio (W/C) = 0.50; cement content = 8.0 sacks (752 pounds) per cubic yard; nominal slump = 3 inches.
2. W/C = 0.60; cement content = 6.9 sacks (649 pounds) per cubic yard; nominal slump = 3 inches.
3. W/C = 0.70; cement content = 5.9 sacks (555 pounds) per cubic yard; nominal slump = 3 inches.

For the sake of brevity in this report, the means of identifying the basic concrete mix design is by the cement content; e.g., ''5.9 PPCC'' means the basic concrete mix had a cement content of 5.9 sacks (555 pounds) per cubic yard, a W/C = 0.70, and made with portland cement. The term ''5.9 PRCC'' means the same basic concrete mix made with Regulated Set cement.

Results of tests made on concretes containing no polymers are referred to as ''control'' data. A few polymer-modified concrete tests were made with concretes having cement contents of 6.9 and 8.0 sacks/cu yd, but most of the experimental studies were made on the 5.9 sack mix because: (1) polymers did not significantly increase the concrete strengths compared to the control strengths (strength ratios) in the 6.9 and 8.0 sack mixes and (2) the 5.9 sack mix is a cheaper and basically weaker mix and addition of polymers showed dramatic strength increases compared to the control strengths. The control strengths are shown in Appendix B.

Polymer Loading

In this report the loading or concentration of the polymers is stated in relation to the weight of cement used in the basic mix. For example, an epoxy loading of 50% in the 5.9 sack mix (555 lb/cu yd) means 0.50 x 555 pounds = 277 pounds of epoxy per cubic yard of concrete. Relating polymer loading to weight of cement is more meaningful than relating it to total weight because the total weight is dependent also on the amount of water needed for each batch, whereas the cement content is constant once a given mix design is chosen.

Strength Tests

Compressive strength and Young's modulus tests were made on cylinders 4 inches in diameter and 8 inches long in accordance with ASTM C 39-72 and ASTM C 469-69 (1975), respectively. Splitting tensile strengths were determined on cylinders 4 inches in diameter and 8 inches long in accordance with ASTM C 496-71. Flexural strengths (rupture modulus) were determined on beams 3 inches square and 11 inches long in accordance with ASTM C 78-64 (1972). Tests to determine bond strength were conducted according to ASTM C 234-71.

TEST RESULTS

Compressive Strength

Figure 1 shows the relationship between polymer loading and compressive strength for epoxy-modified concrete; Figure 2 shows the same relationship for latex-modified concrete. In PPCC mixes, the more epoxy, the higher the compressive strength; for PRCC mixes, however, the optimum loading is 75%. In the latex mixes, the optimum loading varied between 30% and 40%. The decision to use epoxy loadings of 50%, 75%, and 100% and latex loadings of 20%, 30%, and 40% in the second portion of the study was based on the results presented in Figures 1 and 2.

Compressive strength ratios are shown in Table 1 for test ages of 1, 3, 7, 28, 91, 175, and 365 days. Strength ratio is obtained by dividing the compressive strength of the polymer-modified concrete by the compressive strength of the control concrete. Strength ratios are shown in column 1 in descending order. The relative position of a given polymer-modified mix changed with time. For example, 5.9 PPCC latex with 30% loading and air-cured showed the highest strength ratio after 1 day (4.6) but dropped to third highest after 3 days, next to lowest at 7 days, third highest after 28 days, lowest at 91 days, next to lowest at 175 days, and third from lowest after 365 days. These and other similar variations can be accounted for partly by the difference in the time-dependent strength gain between the polymer-modified concrete and the control concrete and partly by the fact that the higher polymer loadings produce higher compressive strengths of the polymer-modified concretes at later ages.

Column 6 of Table 1 lists the actual compressive strengths of each mix. When a prospective user of polymer-modified concretes is determining which mixture to use, he may be influenced more by his need for a certain minimum compressive strength at a certain age than he is by the strength ratio. At test ages of 7, 28, 91, and 175 days the epoxy-modified concretes have the highest strength ratios; however, the latex-modified concretes are very close in the later ages. Table 1 shows only the higher strength ratios for each test age.

Table 2 lists the compressive strengths of the polymer-modified concretes in descending order for each test age (column 2). As observed before, the epoxy-modified concretes dominate in early ages, but the latex-modified concretes have only slightly lower strengths in later ages. Appropriate strength ratios are shown in column 7.

Since compressive strength ratios for the 6.9 and 8.0 mixes were not significantly high and since these mixes are basically more expensive than the 5.9 mix, long-term tests to determine splitting tensile and flexural strengths and Young's moduli were limited to the 5.9 mix.

Splitting Tensile Strength

Splitting tensile strength ratios are presented in Table 3, which includes the same type of data shown in Table 1. As observed with compressive strength ratios, the epoxy-modified concretes show highest values throughout, but at later test ages the latex-modified concretes narrow the gap. It can also be noted here that the splitting tensile strength ratios start high at 1 day, decrease slightly at 7 and 28 days, and then increase at later ages to about the same value as for 1 day.

Table 4 shows splitting tensile strengths in descending order for each test age. The epoxy-modified concretes provide the highest values throughout the test series. Highest splitting tensile strengths of latex-modified concretes average about 71% of those of the epoxy-modified concretes over the whole test series.

Flexural Strength (Rupture Modulus)

Table 5 lists flexural strength ratios in decreasing magnitude at each test age. As observed in the other tables, epoxy-modified concretes show higher strength ratios at the earlier test ages, but the latex-modified concretes overtake them at later test ages.

Flexural strengths listed by order of magnitude for each test age are presented in Table 6. Epoxy-modified concretes showed highest flexural strengths throughout the test series, but flexural strengths of latex-modified concretes were 91%, 95%, and 98% of the epoxy-modified concretes at 91, 175, and 365 days, respectively.

Young's Modulus

Young's modulus strength ratios are shown in decreasing order of magnitude for each test age in Table 7. Latex-modified concretes showed strength ratios equal to or higher than those of epoxy-modified concretes at all test ages. Strength ratios for Young's modulus are significantly lower than for the other strength properties.

Ranking of Young's moduli by magnitude is presented in Table 8. Except for 1- and 365-day tests, latex-modified concretes showed the highest Young's moduli. Young's modulus is one property which does not seem to be enhanced significantly by polymer loading. The principal reason for this may be that the polymer, whether epoxy or latex, is a plastic and therefore tends to ''creep'' or ''flow'' when stressed; in a modulus test (in compression), the creep increases the recorded strain for a given load, thereby reducing the computed modulus (stress divided by strain). This is to say that although compressive strength is increased significantly (Tables 1 and 2), stresses in a specimen being tested for Young's modulus will eventually be transferred at least partially to the plastic which deforms at a faster rate than does the basic concrete structure. At the most it can be said that there is a modest increase in Young's modulus in polymer-modified concretes.

Bond Strength

Tests were made both on polymer-modified and control concretes to determine the bond developed with reinforcing steel (ASTM C 234-71). Bond strength of epoxy-modified concrete (polymer loading of 100% of cement weight) was 1,470 psi, while bond strength of control concrete was 1,360 psi; in both cases, averages were of three specimens. These results indicate very little increase in bond strength in the polymer-modified concrete but do show that bond strength is adequate. It should be emphasized that this ASTM test is intended to compare concretes on the basis of the bond developed with reinforcing and is not to be used for establishing bond values for structural design.

Water Absorption

Tests were made to determine the water absorption of polymer-modified concretes compared to control concrete. Cylinders (in triplicate) at least 28 days old were oven-dried, allowed to cool, and then submerged in water. Increases in weight were recorded at periodic intervals until constant weight had been achieved. Results are shown in Table 9. Epoxy-modified concretes show the lowest water absorption, particularly at 100% polymer loading. In terms of reduction in absorption from that of the control, epoxy-modified concretes provided as much as 69% reduction (100% epoxy loading, PRCC, S+A). The highest reduction for air-cured latex-modified concretes was 58% (40% loading, PPCC), although 40% loading, PRCC was a close second at 54%. The highest reduction for steam-cured latex-modified concretes was 62% (40% loading, PRCC).

Gap Grading of Sand

Control tests were made with several gap gradings; the one which provided the highest compressive strengths was one in which the following size gradations were included: -3/8 + 4, -8 + 16, -50 + 100, -100 + pan. A few tests were made using this sand grading with epoxy-modified concretes at 50%, 75%, and 100% loading. Compressive strengths of the gap graded epoxy-modified concretes were not as high as with normal grading.

INCREMENTAL COSTS OF POLYMER-MODIFIED CONCRETE

Since the delivered cost of a cubic yard of concrete varies from locality to locality, it is more meaningful to examine how much more polymer-modified concrete costs than plain portland cement concrete made with Type I or Type II cement. A compilation of these incremental costs (as of 1976) is shown in Table 10, together with a listing of total incremental costs for selected mixes. Since best strength results were obtained with polymer loadings of 75% epoxy and 40% latex, the cost computation shown in Table 10 uses these loadings. Although difficult to quantify in terms of cost, it should be emphasized that compaction of PPCC and PRCC mixes with epoxies requires more effort and that equipment used in these mixes must be properly cleaned with solvents.

It becomes rather obvious when examining the costs shown in Table 10 that these concretes will be used only when special conditions require the strength advantages furnished by the mixes. More attention is given to alternative choices in a subsequent section of this report.

DISCUSSION OF TEST RESULTS

The choice as to which of the polymer-modified concretes is optimum will, of necessity, depend upon the strength needs as well as the economic flexibility of the prospective user. Each type of polymer mix has inherent advantages and disadvantages which should be carefully considered before a choice is made. For example, if early high compressive strength is required and the structure must be quickly usable, magnitudes of other strength properties are less important - although it is also necessary that long-term strengths be adequate. On the other hand, a high flexural strength or high tensile strength may be required in 28 days and other considerations may be secondary.

Figures 3, 4, and 5 show relatively high strength ratio and values of compressive strength, splitting tensile strength, and flexural strength, respectively. For easy comparison, polymer-modified concrete mixes are shown by the same plotting symbols on all three of the figures. In all three cases, the upper portion (a) of the figure presents the strength ratio versus test age and the lower portion (b) shows actual strengths versus test age. Although Young's moduli were not increased significantly by using polymers, Figure 6 shows time effects on Young's moduli for one epoxy- and one latex-modified concrete, each of which provided significant increases in the other strength properties. Although Young's modulus strength ratios (Figure 6a) are not significant, actual values (Figure 6b) approach reasonable levels at later ages.

Examination of the lower portions of Figures 3 through 5 reveals that epoxy-modified concretes are generally superior to latex-modified concretes only when early high strengths are required; with the exception of splitting tensile strength, latex-modified concretes showed strength properties approximately equal to those of the epoxy-modified concretes at 365 days. Strength ratio plots in the upper portions of Figures 3 through 5 show about the same relationships. Considering the relative ease of mixing and placing as well as lower cost, the air-cured latex-modified concrete is the obvious choice for concrete not requiring early high strength properties. In reality, however, the 7- and 28-day strength properties of the latex-modified PPCC concrete are moderately high; it is comparison of these values with those of the epoxy-modified concretes which causes them to appear low.

Ratios of splitting tensile and flexural strengths to compressive strengths have been developed [13, 14]. An interesting and important phenomenon of polymer-strengthened concrete is shown in Table 11. Comparisons of columns 5 and 7 and of columns 6 and 8 reveal that ratios of both splitting tensile and flexural strengths to compressive strengths are consistently higher in polymer-modified concrete than in plain concrete. At later ages these ratios for polymer-modified concretes are about 50% higher than those for the plain concrete. The significance of this observation is that for a given compressive strength, both the tensile and flexural strengths are at least 50% higher than would normally be expected. Since it is commonly accepted that tensile and flexural strengths as well as shear strength are a function of or are based on compressive strength, this is an important asset for polymer-strengthened concrete.

Economic considerations always have a significant influence upon ultimate decisions. Since latex-modified concretes cost about one-third less than the epoxy-modified concretes, their strength properties and other inherent advantages merit serious consideration. Some of these other advantages include the ease of mixing and placing. No noxious odors are generated, no solvents are required, and the equipment cleanup is easily accomplished. On the other hand, epoxy-modified concretes, when mixed, are extremely sticky and are difficult to compact in-place. As the material is compacted, it releases water which must be drained away. All equipment must be cleaned as soon as possible with an organic solvent such as methyl ethyl ketone. A significant advantage of the latex-modified concrete over the epoxy-modified concrete is that it requires no special curing, whereas epoxy-modified concrete requires steam-curing to obtain adequate strengths.

Another important aspect when considering the use of polymer-modified concretes is that the higher strength properties obtainable may reduce the required size of the structure to be built. The cost determination, then, would be based on the smaller, thinner structure. For example, in a given circumstance, having a compressive strength or flexural strength three times higher might enable the proposed structure (or portion of a structure) to be one-third as thick as originally planned.

FINDINGS

1. Compressive strength ratios of epoxy-modified concretes and latex-modified concretes were as high as 3.7 and 3.2, respectively, after 365 days. Strength ratios of epoxy-modified concretes reached 4.6 and 3.5 after 1 day and 7 days, respectively.

2. Compressive strengths of epoxy-modified and latex-modified concretes reached 10,150 psi and 10,110 psi, respectively, after 365 days. Compressive strengths of epoxy-modified concretes were as high as 7,770 psi and 8,860 psi in 1 day and 7 days, respectively.

3. Splitting tensile strength ratios of epoxy-modified and latex-modified concretes reached 3.4 and 2.9, respectively, after 365 days. Strength ratios of epoxy-modified concretes were 3.3 and 3.0 after 1 day and 7 days, respectively.

4. Splitting tensile strengths of epoxy-modified and latex-modified concretes reached 1,340 psi and 970 psi, respectively, after 365 days. Splitting tensile strengths of epoxy-modified concretes reached 900 psi and 1,180 psi in 1 day and 7 days, respectively.

5. Flexural strength ratios of both epoxy-modified and latex-modified concretes reached 2.8 after 365 days. Flexural strength ratios of epoxy-modified concretes reached 3.8 and 3.5 after 1 day and 7 days, respectively.

6. Flexural strengths of epoxy-modified and latex-modified concretes reached 1,610 psi and 1,570 psi, respectively, in 365 days. Flexural strengths of epoxy-modified concretes reached 1,300 psi and 1,380 psi in 1 day and 7 days, respectively.

7. Strength ratios for Young's modulus of both epoxy-modified and latex-modified concrete reached 1.8 after 365 days. Young's modulus strength ratios for latex-modified concretes reached 1.4 and 1.7 in 1 day and 7 days, respectively.

8. Young's moduli for epoxy-modified and latex-modified concretes reached 3.90 and 3.62 x 10^6 psi, respectively, after 365 days. Young's moduli at early ages were low; the highest value for latex-modified concrete was only 3.08 x 10^6 psi at 7 days.

9. Epoxy-modified concretes must be steam-cured to obtain satisfactory strengths. Latex-modified concretes obtain adequate strengths with air-curing.

10. Epoxy-modified concretes absorbed as much as 69% less water than control concrete; latex-modified concretes absorbed as much as 62% and 58% less than control concrete with steam-curing and air-curing, respectively.

11. Bond strength of epoxy-modified concrete was slightly higher than the bond strength of control concrete.

12. Consistency of epoxy-modified concretes is extremely thick and sticky and the material is difficult to place (compact). Consistency of latex-modified concrete is good and it is easily compacted.

13. When making epoxy-modified concrete with portland cement (PPCC), the basic portland cement concrete mixture must be allowed to stand for 1 hour prior to adding the epoxy; with an accelerator, this time can be reduced to 15 minutes. When epoxy-modified concrete is made with Regulated Set cement, no waiting period is necessary.

14. Epoxy-modified concrete with gap graded sand had lower compressive strengths than similar concrete with normal sand grading.

15. Generally speaking, consistently highest strengths were obtained over all test ages (1) with 75% epoxy loading in PPCC or PRCC and (2) with 40% latex loading in PPCC.

16. Epoxy-modified concretes generally provided early high strengths which did not increase significantly up to 365 days. On the other hand, latex-modified concretes generally had relatively lower early strengths but showed significant increases in strength with increasing test age.

17. PPCC with 75% epoxy loading of Epi-rez 5077 costs $465.37/cu yd more than conventional concrete; the same loading and mix with Epon 815 epoxy costs $432.09/cu yd more than conventional concrete. PRCC with 75% epoxy loading of Epi-rez 5077 costs $466.48/cu yd more than conventional concrete; the same loading and mix with Epon 815 epoxy costs $433.20/cu yd more than conventional concrete.

18. PPCC with 40% latex loading costs $276.88/cu yd more than conventional concrete; the same latex loading with PRCC costs $277.99/cu yd more than conventional concrete.

19. Highest compressive strengths and highest flexural strengths were obtained with epoxy-modified concrete made with PRCC; highest splitting tensile strengths were obtained with epoxy-modified concrete made with portland cement.

20. At later ages ratios of splitting tensile and flexural strengths to compressive strengths are about 50% higher than they are in plain concrete.

CONCLUSIONS

1. For situations demanding high strengths at an early age (1 to 7 days), polymer-modified concretes made with epoxy resin should be used.

2. For designs requiring relatively high strengths at 28 days and beyond and in which early high strengths are not so important, latex-modified concretes should be chosen because they are cheaper and easier to use.

3. Generally speaking, compared to similar conventional concrete, properly prepared and cured polymer-modified concretes in which the polymeric materials are added at the mixer can be relied upon to provide increased compressive, splitting tensile, and flexural strengths, adequate bond strength and Young's modulus, and reduced water absorption. Appendix C contains the typical mix designs and mixing and curing procedures for polymer-modified concretes.

POTENTIAL APPLICATIONS

The following are considered potential applications for polymer-modified concrete.

1. Cladding for reinforced concrete piers.
2. Cladding for reinforced or prestressed concrete piling.
3. Caissons (breakwater units) and pontoons.
4. Repair of spalled or damaged reinforced concrete structures.

5. Concrete pavement and floor overlays.
6. Overlays of concrete bridge decks.
7. Prestressed concrete railroad ties and utility poles.
8. Canal and ditch linings.
9. Masonry curtainwalls.
10. Shear walls.

ACKNOWLEDGMENT

Mixing, casting, and breaking of specimens of polymer-modified concretes and control concretes were accomplished under the supervision of Engineering Technician John A. Crahan. Mr. Crahan also maintained accurate records and prepared tables summarizing over 400 batches of concrete involved in the program.

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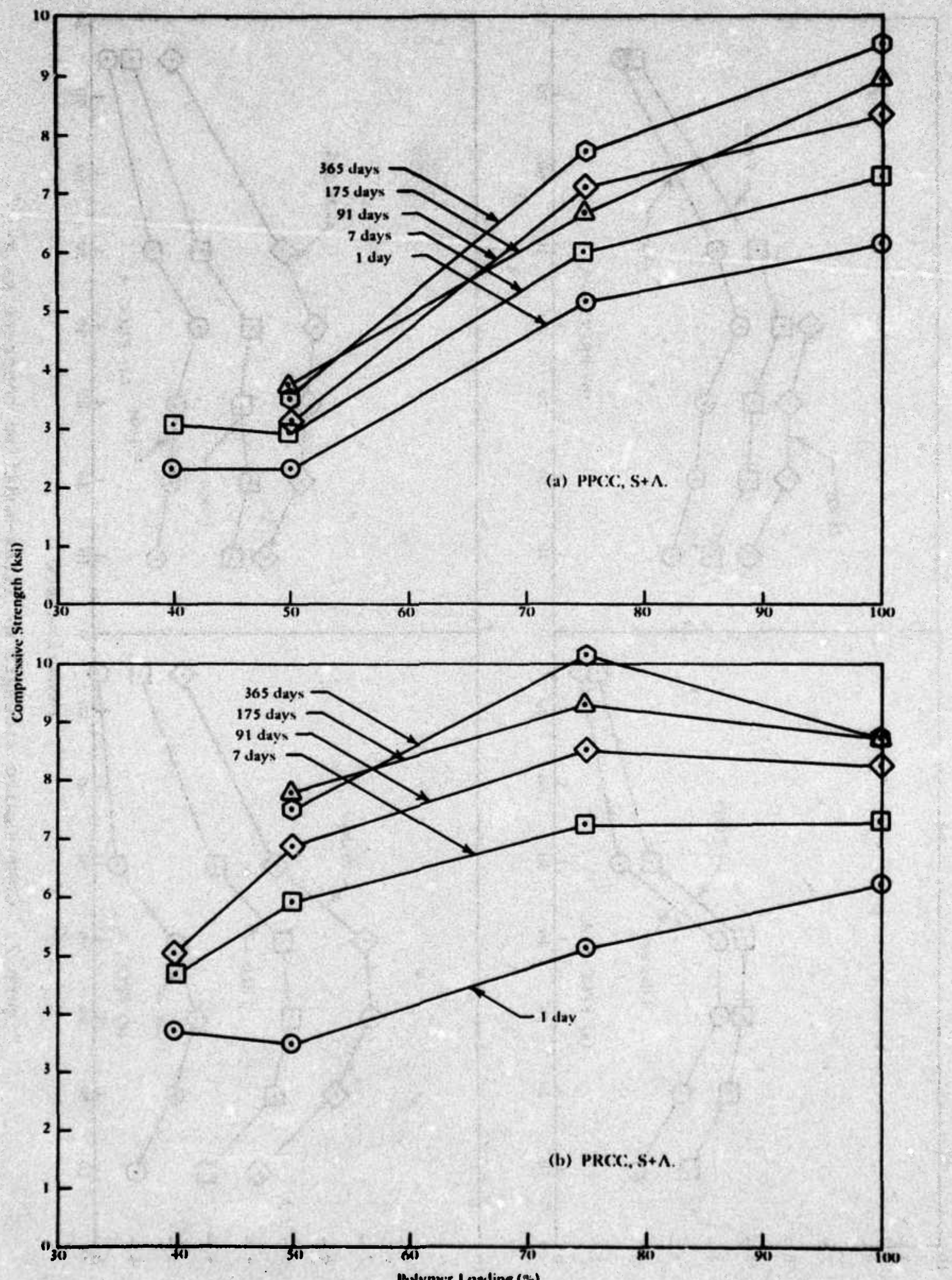

Figure 1. Compressive strength of epoxy-modified concrete as a function of polymer loading.

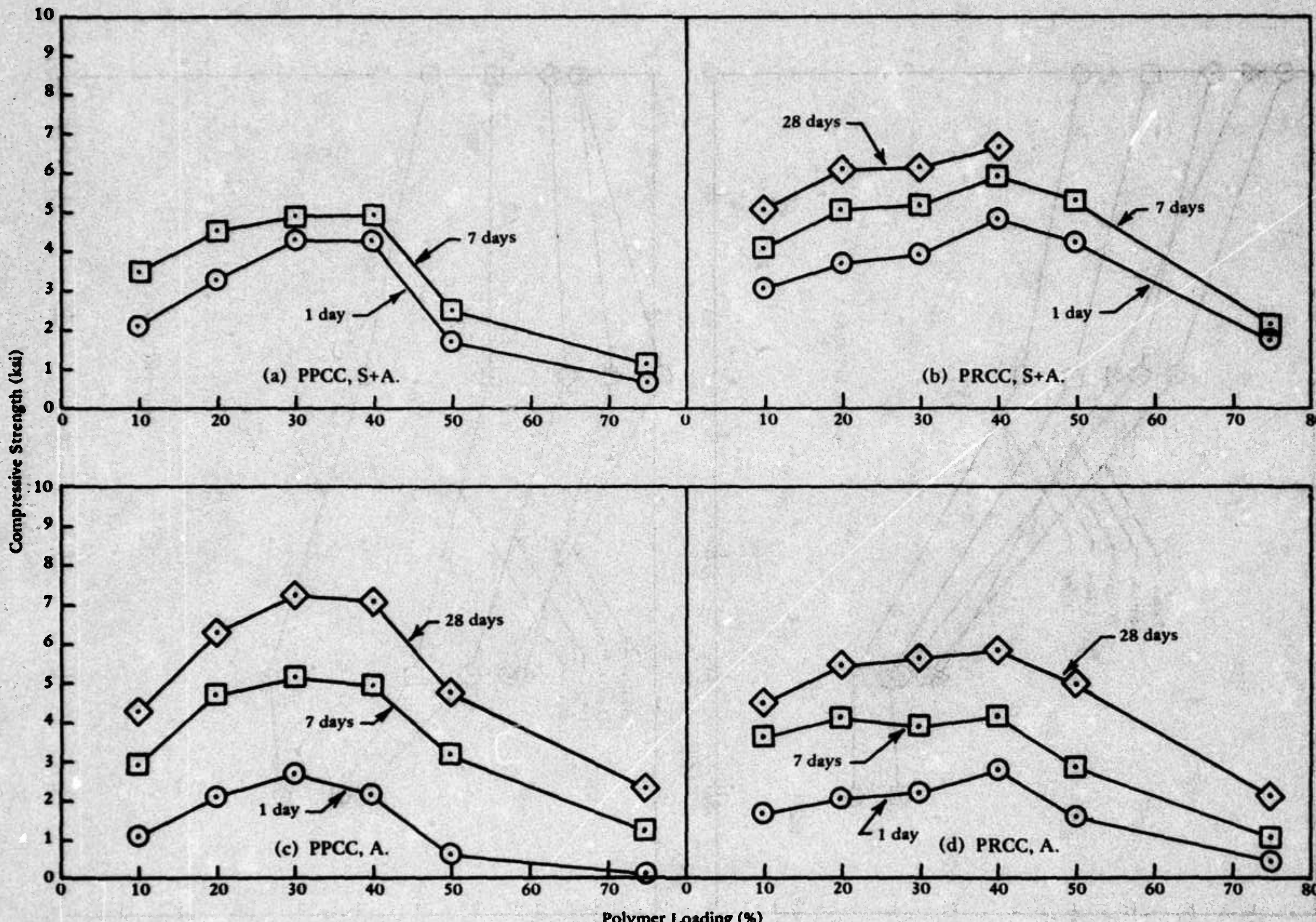

Figure 2. Compressive strength of latex-modified concrete as a function of polymer loading.

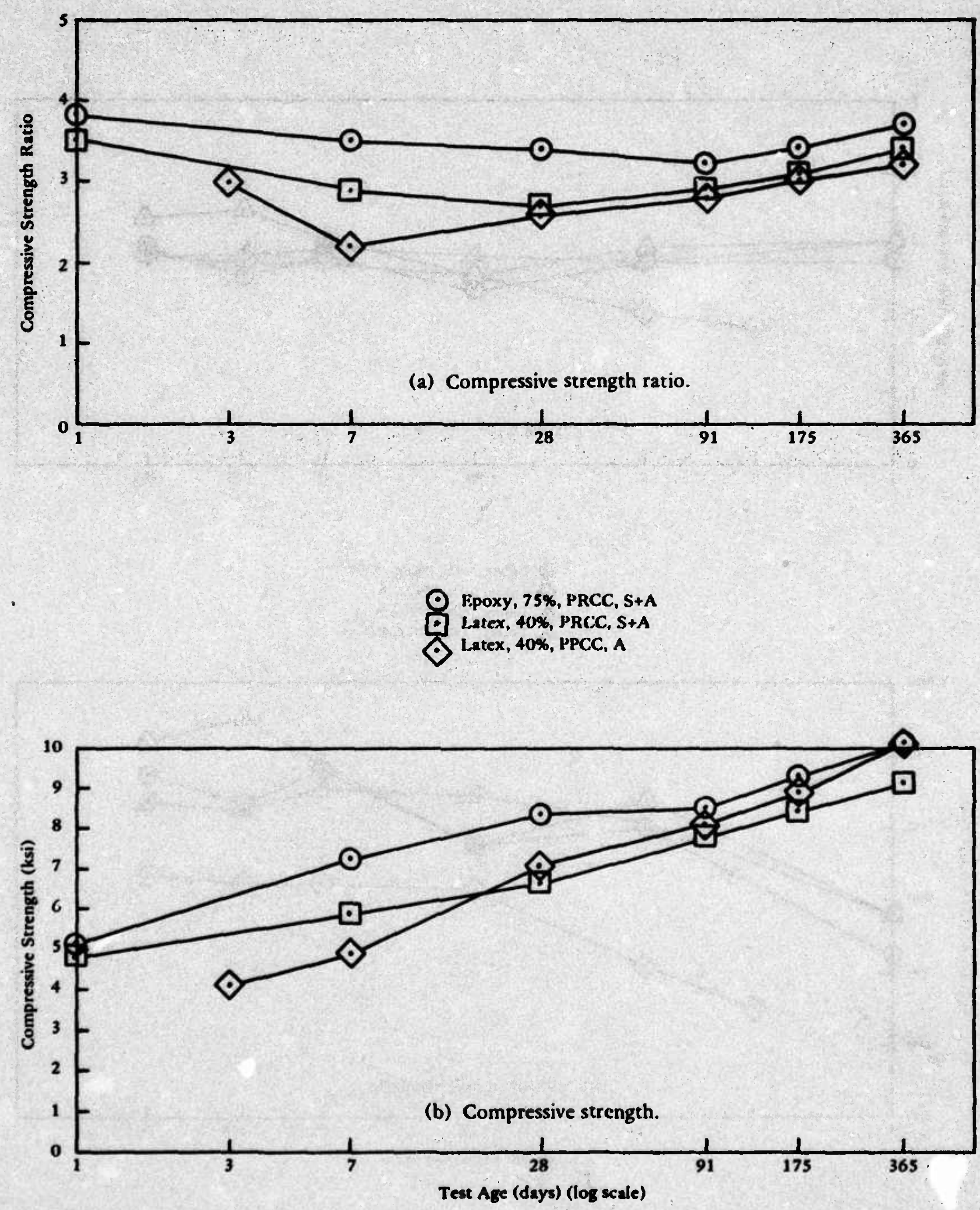

Figure 3. Compressive strengths of polymer-modified concretes as a function of test age.

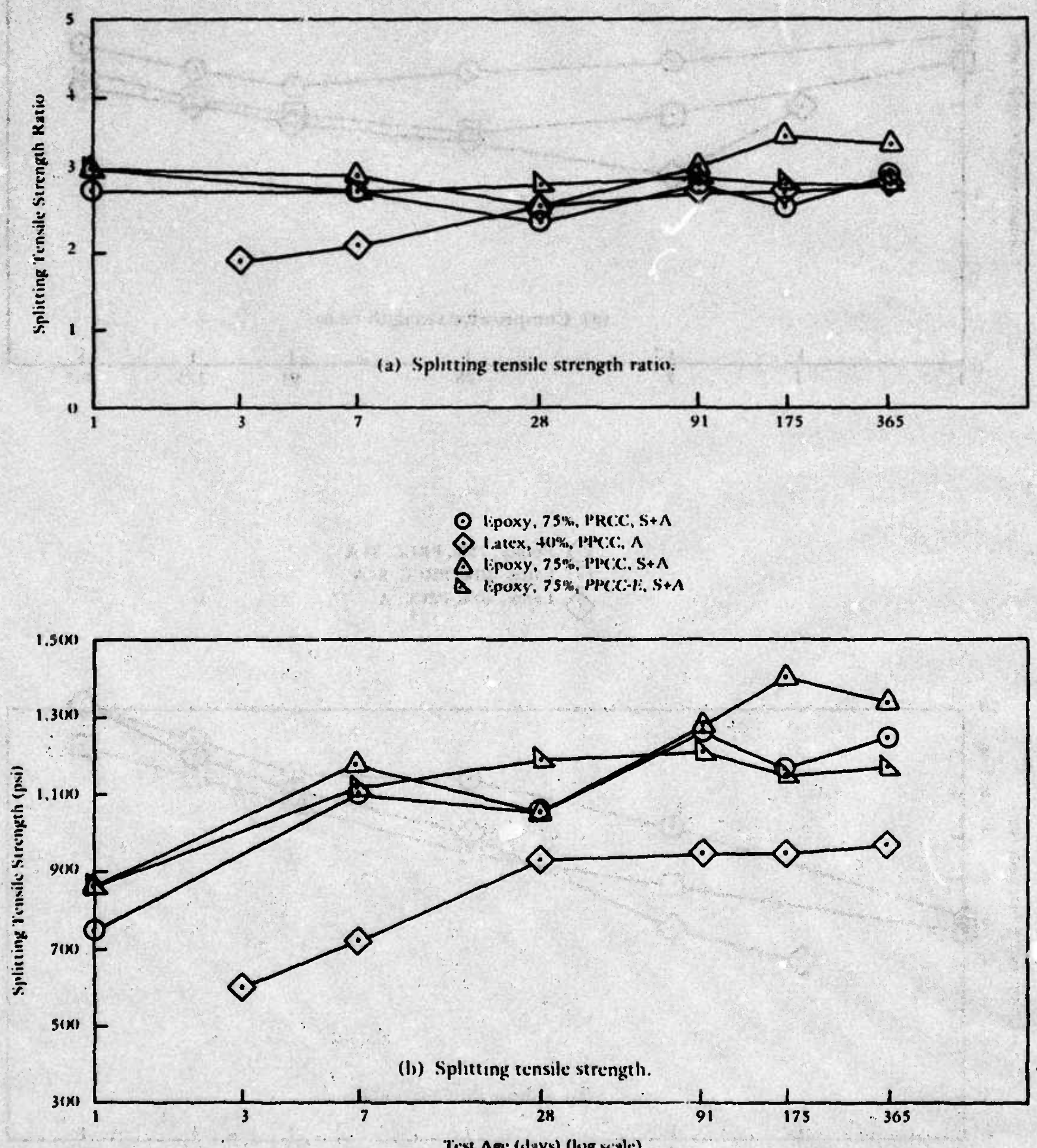

Figure 4. Splitting tensile strengths of polymer-modified concretes as a function of test age.

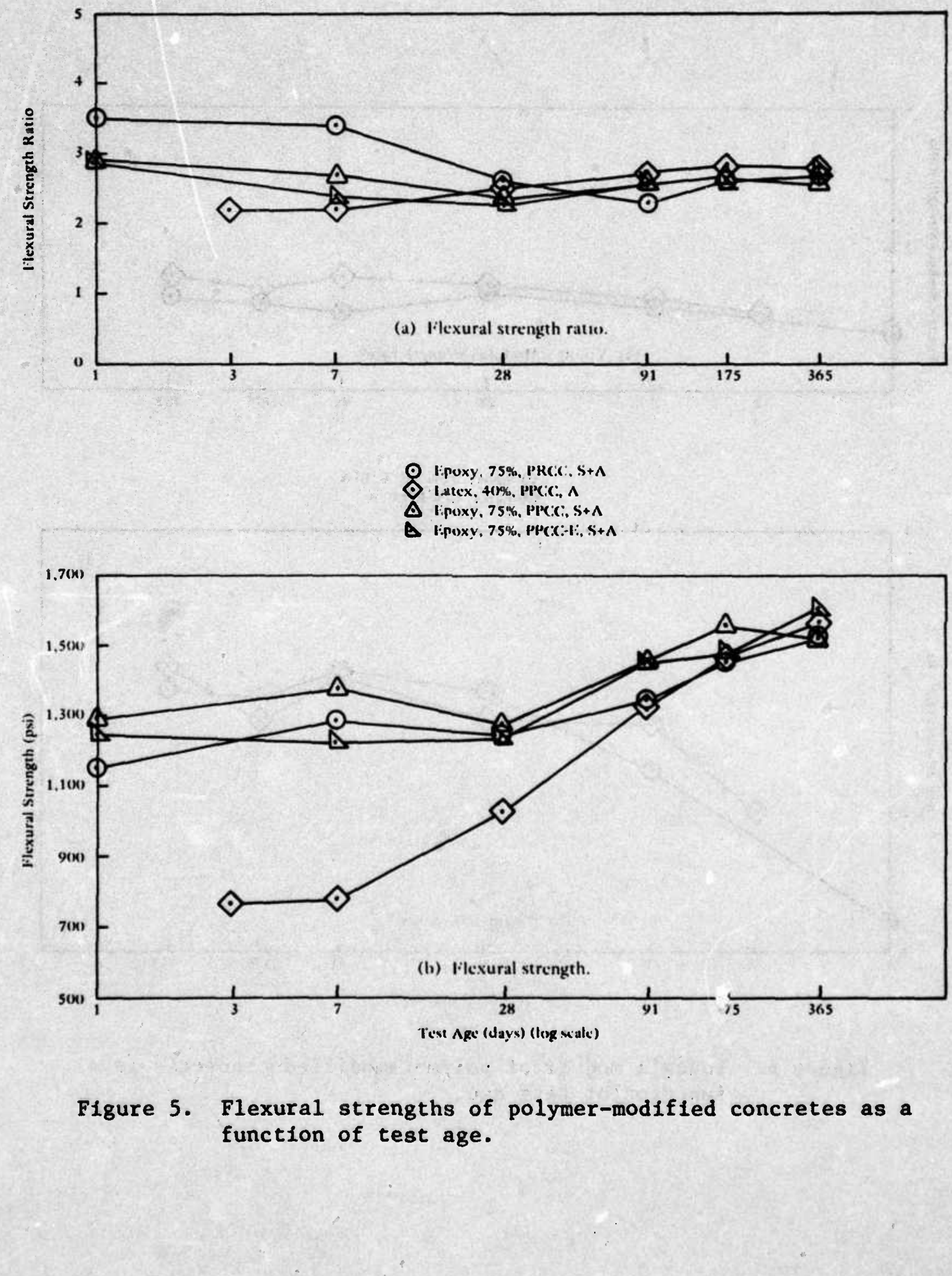

Figure 5. Flexural strengths of polymer-modified concretes as a function of test age.

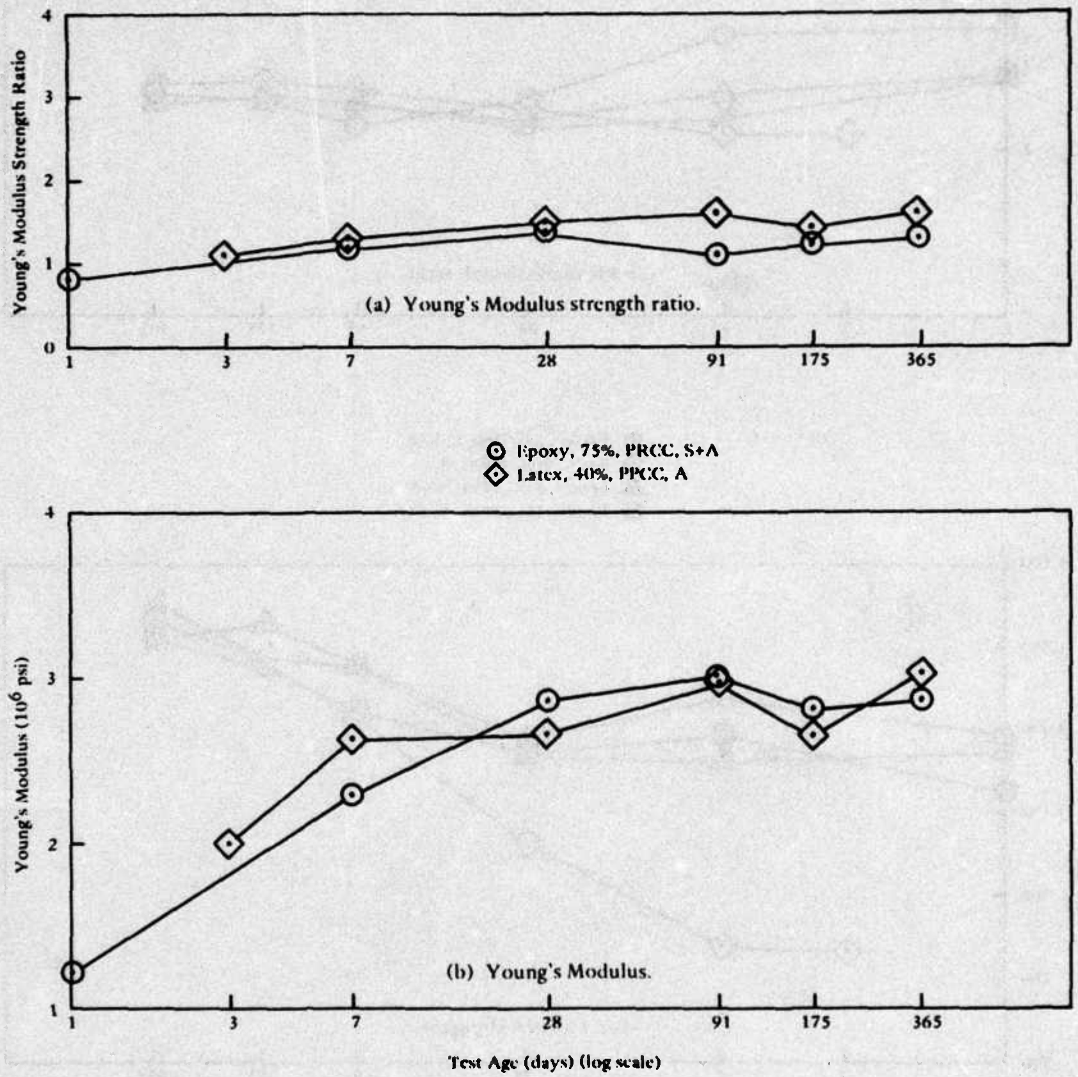

Figure 6. Young's moduli of polymer-modified concretes as a function of test age.

Table 1. Compressive Strength Ratios of Polymer-Modified Concretes

a. Test Age 1 Day

Strength Ratio	Polymer Type	Polymer Loading (% Cement Weight)	Concrete Mix	Curing Method	Compressive Strength (psi)	Number of Specimens
Column 1	Column 2	Column 3	Column 4	Column 5	Column 6	Column 7
4.6[a]	L[b]	30	5.9 PPCC[c]	A[d]	2,630	8
4.5	E	100	5.9 PRCC	S+A	6,220	6
3.8	E	75	5.9 PRCC	S+A	5,190	6
3.8	L	40	5.9 PRCC	A	2,160	2
3.6	L	20	5.9 PRCC	A	2,050	5
3.5	L	40	5.9 PRCC	A	2,800	2
3.5	L	40	5.9 PRCC	S+A	4,820	6
3.4	E	100	5.9 PPCC	S+A	6,120	9
3.4	E	75	6.9 PRCC	S+A	6,700	3
3.1	L	50	5.9 PRCC	S+A	4,330	3
3.1	E	100	5.9 PPCC-E[e]	S+A	5,660	3
2.9	L	30	5.9 PRCC	S+A	3,960	12
2.8	E	75	5.9 PPCC	S+A	5,140	8
2.8	L	30	5.9 PRCC	A	2,210	8
2.8	E	118	6.9 PPCC	S+A	7,770	3

b. Test Age 3 Days

Strength Ratio	Polymer Type	Polymer Loading (% Cement Weight)	Concrete Mix	Curing Method	Compressive Strength (psi)	Number of Specimens
3.0	L	40	5.9 PPCC	A	4,160	3
2.6	L	40	5.9 PRCC	A	3,620	3
2.3	L	30	5.9 PPCC	A	3,200	3
1.8	L	20	5.9 PRCC	A	2,540	3
1.8	L	30	5.9 PRCC	A	2,520	3

continued

Table 1. continued

c. Test Age 7 Days

Strength Ratio	Polymer Type	Polymer Loading (% Cement Weight)	Concrete Mix	Curing Method	Compressive Strength (psi)	Number of Specimens
Column 1	Column 2	Column 3	Column 4	Column 5	Column 6	Column 7
3.5	E	100	5.9 PRCC	S+A	7,310	6
3.5	E	75	5.9 PRCC	S+A	7,220	6
2.9	L	40	5.9 PRCC	S+A	5,930	5
2.9	L	40	5.9 PPCC-E	A	6,350	3
2.8	E	50	5.9 PRCC	S+A	5,910	6
2.7	E	100	5.9 PPCC	S+A	7,200	9
2.7	E	75	6.9 PRCC	S+A	7,580	3
2.6	E	100	5.9 PPCC-E	S+A	6,910	3
2.6	L	50	5.9 PRCC	S+A	5,320	2
2.5	L	30	5.9 PRCC	S+A	5,200	12
2.4	L	20	5.9 PRCC	S+A	5,100	9
2.3	L	30	5.9 PPCC	A	5,180	11
2.2	L	40	5.9 PPCC	A	4,960	6

d. Test Age 28 Days

3.4	E	75	5.9 PRCC	S+A	8,390	6
3.2	E	100	5.9 PRCC	S+A	7,780	6
2.7	L	30	5.9 PPCC	A	7,220	9
2.7	L	40	5.9 PRCC	S+A	6,670	3
2.6	L	40	5.9 PPCC	A	7,060	3
2.6	L	40	5.9 PPCC-E	A	7,150	3
2.5	L	30	5.9 PRCC	S+A	6,180	12
2.5	L	20	5.9 PRCC	S+A	6,080	9
2.5	E	75	6.9 PRCC	S+A	8,350	3

continued

Table 1. continued

e. Test Age 91 Days

Strength Ratio	Polymer Type	Polymer Loading (% Cement Weight)	Concrete Mix	Curing Method	Compressive Strength (psi)	Number of Specimens
Column 1	Column 2	Column 3	Column 4	Column 5	Column 6	Column 7
3.2	E	75	5.9 PRCC	S+A	8,540	6
3.1	E	100	5.9 PRCC	S+A	8,280	6
2.9	L	40	5.9 PRCC	S+A	7,860	3
2.8	L	40	5.9 PPCC	A	8,150	3
2.6	L	30	5.9 PRCC	S+A	7,050	3
2.6	L	20	5.9 PRCC	S+A	6,990	3
2.6	E	50	5.9 PRCC	S+A	6,890	6
2.5	L	30	5.9 PPCC	A	7,450	2

f. Test Age 175 Days

3.4	E	75	5.9 PRCC	S+A	9,320	3
3.2	E	100	5.9 PRCC	S+A	8,760	3
3.1	L	40	5.9 PRCC	S+A	8,490	3
3.0	L	40	5.9 PPCC	A	8,950	3
2.8	E	50	5.9 PRCC	S+A	7,770	3
2.8	L	30	5.9 PRCC	S+A	7,700	3
2.8	L	20	5.9 PPCC	S+A	7,610	3
2.5	L	30	5.9 PPCC	A	7,700	3
2.5	L	40	5.9 PRCC	A	7,730	3

continued

Table 1. continued

g. Test Age 365 Days

Strength Ratio	Polymer Type	Polymer Loading (% Cement Weight)	Concrete Mix	Curing Method	Compressive Strength (psi)	Number of Specimens
Column 1	Column 2	Column 3	Column 4	Column 5	Column 6	Column 7
3.7	E	75	5.9 PRCC	S+A	10,150	3
3.3	L	40	5.9 PRCC	S+A	9,190	3
3.2	L	40	5.9 PPCC	A	10,110	3
3.2	E	100	5.9 PRCC	S+A	8,750	3
3.0	L	30	5.9 PPCC	A	9,460	2
3.0	L	30	5.9 PRCC	S+A	8,170	3
2.8	I	40	5.9 PRCC	A	8,670	3

[a] Strength ratio is computed by dividing the compressive strength of the polymer-modified concrete by the compressive strength of an identical concrete without the polymer.

[b] Polymer types: L = latex; E = epoxy.

[c] Concrete mixes: PPCC = polymer-modified portland cement concrete; PRCC = polymer-modified Regulated Set cement concrete.

[d] Curing methods: A = air-cured; S+A = steam-cured for 16 hours, then air-cured for remaining time until test age.

[e] E symbol means that a nonchloride accelerator was used in the mix.

Table 2. Compressive Strengths of Polymer-Modified Concretes by Ranking

a. Test Age 1 Day

Ranking	Compressive Strength (psi)	Polymer Type	Polymer Loading (% Cement Weight)	Concrete Mix	Curing Method	Strength Ratio
Column 1	Column 2	Column 2	Column 4	Column 5	Column 6	Column 7
1	7,770	E[a]	118	6.9 PPCC[b]	S+A[c]	2.8[d]
2	7,520	E	50	8.0 PPCC	S+A	2.0
3	7,370	E	75	6.9 PPCC-E[e]	S+A	2.7
4	6,700	E	75	6.9 PRCC	S+A	3.4
5	6,220	E	100	5.9 PRCC	S+A	4.5
6	6,120	E	100	5.9 PPCC	S+A	3.4
7	5,660	E	100	5.9 PPCC-E	S+A	3.1
8	5,190	E	75	5.9 PRCC	S+A	3.8
9	5,140	E	75	5.9 PPCC	S+A	2.8
10	4,820	L	40	5.9 PRCC	S+A	3.5
11	4,330	L	50	5.9 PRCC	S+A	3.1
12	4,290	L	30	5.9 PPCC	S+A	2.3
13	4,290	L	40	5.9 PPCC	S+A	2.3
14	4,080	E	75	5.9 PPCC	S+A	2.2

b. Test Age 3 Days

1	4,160	L	40	5.9 PPCC	A	3.0
2	3,620	L	40	5.9 PRCC	A	2.6
3	3,200	L	30	5.9 PPCC	A	2.3
4	2,540	L	20	5.9 PRCC	A	1.8
5	2,520	L	30	5.9 PRCC	A	1.8

continued

Table 2. Continued

c. Test Age 7 Days

Ranking	Compressive Strength (psi)	Polymer Type	Polymer Loading (% Cement Weight)	Concrete Mix	Curing Method	Strength Ratio
Column 1	Column 2	Column 3	Column 4	Column 5	Column 6	Column 7
1	8,860	E	75	6.9 PPCC-E	S+A	2.1
2	8,660	E	75	8.0 PPCC	S+A	1.6
3	8,640	E	50	8.0 PPCC	S+A	1.6
4	8,610	E	118	6.9 PPCC	S+A	2.0
5	7,580	E	75	6.9 PRCC	S+A	2.7
6	7,310	E	100	5.9 PRCC	S+A	3.5
7	7,220	E	75	5.9 PRCC	S+A	3.5
8	7,200	E	100	5.9 PPCC	S+A	2.7
9	6,910	E	100	5.9 PPCC-E	S+A	2.6
10	6,350	L	40	5.9 PPCC-E	A	2.9
11	6,240	L	30	6.9 PRCC	S+A	2.0
12	6,110	L	40	6.9 PRCC	S+A	2.2
13	5,990	E	75	5.9 PPCC	S+A	2.2
14	5,930	L	40	5.9 PRCC	S+A	2.9
15	5,910	E	50	5.9 PRCC	S+A	2.8
16	5,320	L	50	5.9 PRCC	S+A	2.6
17	5,300	L	20	6.9 PRCC	S+A	1.9
18	5,210	E	75	5.9 PPCC	S+A	1.9
19	5,200	L	30	5.9 PRCC	S+A	2.5
20	5,180	L	30	5.9 PPCC	A	2.3
21	5,100	L	20	5.9 PRCC	S+A	2.4
22	4,960	L	40	5.9 PPCC	A	2.2

d. Test Age 28 Days

1	9,940	E	75	6.9 PPCC-E	S+A	2.0
2	9,770	E	75	8.0 PPCC	S+A	1.7

continued

Table 2. Continued

Ranking	Compressive Strength (psi)	Polymer Type	Polymer Loading (% Cement Weight)	Concrete Mix	Curing Method	Strength Ratio
Column 1	Column 2	Column 3	Column 4	Column 5	Column 6	Column 7
3	9,160	E	118	6.9 PPCC	S+A	1.8
4	8,390	E	75	5.9 PRCC	S+A	3.4
5	8,350	E	75	6.9 PRCC	S+A	2.5
6	8,150	E	100	5.9 PPCC	S+A	2.4
7	7,780	E	100	5.9 PRCC	S+A	3.2
8	7,550	E	100	5.9 PPCC-E	S+A	2.2
9	7,220	L	30	5.9 PPCC	A	2.7
10	7,150	L	40	5.9 PPCC-E	A	2.6
11	7,090	L	40	6.9 PRCC	S+A	2.1
12	7,060	L	40	5.9 PPCC	A	2.6
13	7,020	E	50	6.9 PRCC	S+A	2.1
14	6,910	E	75	5.9 PPCC	S+A	2.1
15	6,670	L	40	5.9 PRCC	S+A	2.7
16	6,300	L	20	6.9 PRCC	S+A	1.9
17	6,290	L	30	6.9 PRCC	S+A	1.9
18	6,280	E	75	5.9 PPCC-E	S+A	1.9
19	6,250	L	20	5.9 PPCC	A	2.3
20	6,180	L	30	5.9 PRCC	S+A	2.5
21	6,080	L	20	5.9 PRCC	S+A	2.5
22	5,980	L	30	5.9 PPCC	S+A	1.8
23	5,870	L	40	5.9 PRCC	A	2.1
24	5,670	L	30	5.9 PRCC	A	2.0

e. Test Age 91 Days

1	8,740	E	100	5.9 PPCC-E	S+A	2.4
2	8,540	E	75	5.9 PRCC	S+A	3.2
3	8,320	E	100	5.9 PPCC	S+A	2.3
4	8,280	E	100	5.9 PRCC	S+A	3.1

continued

Table 2. Continued

Ranking	Compressive Strength (psi)	Polymer Type	Polymer Loading (% Cement Weight)	Concrete Mix	Curing Method	Strength Ratio
Column 1	Column 2	Column 3	Column 4	Column 5	Column 6	Column 7
5	8,150	L	40	5.9 PPCC	A	2.8
6	7,860	L	40	5.9 PRCC	S+A	2.9
7	7,450	L	30	5.9 PPCC	A	2.5
8	7,080	E	75	5.9 PPCC	S+A	2.0
9	7,050	L	30	5.9 PRCC	S+A	2.6
10	7,040	L	40	5.9 PRCC	A	2.3
11	6,990	L	20	5.9 PRCC	S+A	2.6
12	6,890	E	50	5.9 PRCC	S+A	2.6
13	6,330	L	30	5.9 PRCC	A	2.1
f. Test Age 175 Days						
1	9,320	E	75	5.9 PRCC	S+A	3.4
2	8,950	L	40	5.9 PPCC	A	3.0
3	8,900	E	100	5.9 PPCC	S+A	2.4
4	8,760	E	100	5.9 PRCC	S+A	3.2
5	8,490	L	40	5.9 PRCC	S+A	3.1
6	7,770	E	50	5.9 PRCC	S+A	2.8
7	7,730	L	40	5.9 PRCC	A	2.5
8	7,700	L	30	5.9 PRCC	S+A	2.8
9	7,700	L	30	5.9 PPCC	A	2.5
10	7,610	L	20	5.9 PRCC	S+A	2.8
11	7,290	L	30	5.9 PRCC	A	2.3
g. Test Age 365 Days						
1	10,150	E	75	5.9 PRCC	S+A	3.7
2	10,110	L	40	5.9 PPCC	A	3.2

continued

Table 2. Continued

Ranking	Compressive Strength (psi)	Polymer Type	Polymer Loading (% Cement Weight)	Concrete Mix	Curing Method	Strength Ratio
Column 1	Column 2	Column 3	Column 4	Column 5	Column 6	Column 7
3	9,460	L	30	5.9 PPCC	A	3.0
4	9,420	E	100	5.9 PPCC	S+A	2.5
5	9,190	L	40	5.9 PRCC	S+A	3.3
6	8,750	E	100	5.9 PRCC	S+A	3.2
7	8,670	L	40	5.9 PRCC	A	2.8
8	8,170	L	30	5.9 PRCC	S+A	3.0
9	8,070	E	75	5.9 PPCC-E	S+A	2.2
10	7,810	L	30	5.9 PRCC	A	2.5
11	7,560	L	20	5.9 PRCC	S+A	2.7
12	7,500	E	50	5.9 PRCC	S+A	2.7

[a] Polymer types: L = latex; E = epoxy.

[b] Concrete mixes: PPCC = polymer-modified portland cement concrete; PRCC = polymer-modified Regulated Set cement concrete.

[c] Curing methods: A = air-cured; S+A = steam-cured for 16 hours, then air-cured for remaining time until test age.

[d] Strength ratio is computed by dividing the compressive strength of the polymer-modified concrete by the compressive strength of an identical concrete without the polymer.

[e] E symbol means that a nonchloride accelerator was used in the mix.

Table 3. Splitting Tensile Strength Ratios of Polymer-Modified Concretes, 5.9 Mix

a. Test Age 1 Day

Strength Ratio	Polymer Type	Polymer Loading % Cement Weight	Concrete Mix	Curing Method	Splitting Tensile Strength, psi	Number of Specimens
Column 1	Column 2	Column 3	Column 4	Column 5	Column 6	Column 7
3.3[a]	E[b]	100	PRCC[c]	S+A[d]	900	3
3.2	E	100	PPCC	S+A	890	3
3.1	E	75	PPCC	S+A	860	2
3.1	E	75	PPCC-E[e]	S+A	860	3
2.8	E	75	PRCC	S+A	750	3
2.6	E	50	PRCC	S+A	700	2
2.2	L	40	PRCC	S+A	610	3
2.2	E	50	PPCC	S+A	630	2

b. Test Age 3 Days

2.0	L	40	PRCC	A	510	3
1.9	L	40	PPCC	A	600	3
1.6	L	30	PPCC	A	490	3
1.5	L	20	PRCC	A	370	3
1.4	L	30	PRCC	A	340	3

c. Test Age 7 Days

3.0	E	75	PPCC	S+A	1,180	2
2.8	E	75	PRCC	S+A	1,100	3
2.8	E	75	PPCC-E	S+A	1,110	3
2.6	E	100	PPCC	S+A	1,060	3
2.6	E	100	PRCC	S+A	1,040	3
2.2	E	50	PRCC	S+A	860	1

continued

Table 3. Continued

Strength Ratio	Polymer Type	Polymer Loading % Cement Weight	Concrete Mix	Curing Method	Splitting Tensile Strength, psi	Number of Specimens
Column 1	Column 2	Column 3	Column 4	Column 5	Column 6	Column 7
2.1	L	40	PPCC	A	720	3
1.9	L	30	PPCC	A	660	3
1.9	L	40	PRCC	A	610	3
1.9	L	30	PRCC	A	600	3
1.8	L	40	PRCC	S+A	730	3
1.8	E	50	PPCC	S+A	730	2
1.8	L	20	PRCC	S+A	710	3
1.8	L	20	PRCC	A	570	3
d. Test Age 28 Days						
2.9	E	75	PPCC-E	S+A	1,190	3
2.6	L	40	PPCC	A	930	3
2.6	E	75	PPCC	S+A	1,050	2
2.6	E	100	PPCC	S+A	1,080	3
2.5	L	30	PPCC	A	880	3
2.5	E	100	PRCC	S+A	1,120	3
2.4	L	40	PRCC	A	810	3
2.4	E	75	PRCC	S+A	1,060	3
2.2	E	50	PPCC	S+A	920	2
2.1	L	30	PRCC	A	730	3
2.0	L	20	PRCC	A	690	3
2.0	E	50	PRCC	S+A	880	2

continued

Table 3. Continued

e. Test Age 91 Days

Strength Ratio	Polymer Type	Polymer Loading % Cement Weight	Concrete Mix	Curing Method	Splitting Tensile Strength, psi	Number of Specimens
Column 1	Column 2	Column 3	Column 4	Column 5	Column 6	Column 7
3.1	E	75	PPCC	S+A	1,280	2
3.0	E	75	PPCC-E	S+A	1,210	3
2.9	E	75	PRCC	S+A	1,260	3
2.9	E	100	PPCC	S+A	1,180	3
2.8	L	40	PPCC	A	950	3
2.6	L	30	PPCC	A	890	3
2.6	E	100	PRCC	S+A	1,130	3
2.5	L	40	PRCC	A	870	3
2.5	E	50	PRCC	S+A	1,100	2
2.3	L	30	PRCC	A	810	3
2.0	L	40	PPCC	S+A	810	3
2.0	E	50	PPCC	S+A	800	2
2.0	L	40	PRCC	S+A	890	3
2.0	L	20	PRCC	A	720	3

f. Test Age 175 Days

3.5	E	75	PPCC	S+A	1,400	2
2.9	E	100	PPCC	S+A	1,170	3
2.9	E	75	PPCC-E	S+A	1,150	3
2.8	L	40	PPCC	A	950	3
2.8	L	30	PPCC	A	940	3
2.6	E	75	PRCC	S+A	1,170	3
2.6	E	50	PRCC	S+A	1,130	2
2.6	E	100	PRCC	S+A	1,130	3

continued

Table 3. Continued

Strength Ratio	Polymer Type	Polymer Loading % Cement Weight	Concrete Mix	Curing Method	Splitting Tensile Strength, psi	Number of Specimens
Column 1	Column 2	Column 3	Column 4	Column 5	Column 6	Column 7
2.4	L	40	PRCC	A	910	3
2.3	E	50	PPCC	S+A	930	2
2.2	L	30	PRCC	A	820	3
2.1	L	40	PRCC	S+A	910	3
g. Test Age 365 Days						
3.4	E	75	PPCC	S+A	1,340	1
3.0	E	75	PRCC	S+A	1,250	3
2.9	L	40	PPCC	A	970	3
2.9	E	75	PPCC-E	S+A	1,170	3
2.8	E	100	PRCC	S+A	1,150	3
2.8	E	100	PPCC	S+A	1,130	3
2.6	L	30	PPCC	A	870	3
2.4	L	40	PRCC	A	880	3
2.4	E	50	PRCC	S+A	980	2
2.3	L	30	PRCC	A	840	3
2.2	L	40	PRCC	S+A	910	3
2.2	E	50	PPCC	S+A	860	2

[a]Strength ratio is computed by dividing the splitting tensile strength of the polymer-modified concrete by the splitting tensile strength of an identical concrete without the polymer.
[b]Polymer types: L = latex; E = epoxy.
[c]Concrete mixes: PPCC = polymer-modified portland cement concrete; PRCC = polymer-modified Regulated Set cement concrete.
[d]Curing methods: A = air-cured; S+A = steam-cured for 16 hours, then air-cured for remaining time until test age.
[e]E symbol means that a nonchloride accelerator was used in the mix.

Table 4. Splitting Tensile Strengths of Polymer-Modified Concretes By Ranking, 5.9 Mix

a. Test Age 1 Day

Ranking	Splitting Tensile Strength, psi	Polymer Type	Polymer Loading % Cement Weight	Concrete Mix	Curing Method	Strength Ratio
Column 1	Column 2	Column 3	Column 4	Column 5	Column 6	Column 7
1	900	E[a]	100	PRCC[b]	S+A[c]	3.3[d]
2	890	E	100	PPCC	S+A	3.2
3	860	E	75	PPCC	S+A	3.1
4	860	E	75	PPCC-E[e]	S+A	3.1
5	750	E	75	PRCC	S+A	2.8
6	700	E	50	PRCC	S+A	2.6
7	630	E	50	PPCC	S+A	2.2
8	610	L	40	PRCC	S+A	2.2

b. Test Age 3 Days

Ranking	Splitting Tensile Strength, psi	Polymer Type	Polymer Loading % Cement Weight	Concrete Mix	Curing Method	Strength Ratio
1	600	L	40	PPCC	A	1.9
2	510	L	40	PRCC	A	2.0
3	490	L	30	PPCC	A	1.6
4	370	L	20	PRCC	A	1.5
5	340	L	30	PRCC	A	1.4

c. Test Age 7 Days

Ranking	Splitting Tensile Strength, psi	Polymer Type	Polymer Loading % Cement Weight	Concrete Mix	Curing Method	Strength Ratio
1	1,180	E	75	PPCC	S+·	3.0
2	1,110	E	75	PPCC-E	S+A	2.8
3	1,100	E	75	PRCC	S+A	2.8
4	1,060	E	100	PPCC	S+A	2.6
5	1,040	E	100	PRCC	S+A	2.6
6	860	E	50	PRCC	S+A	2.2
7	730	L	40	PRCC	S+A	1.8

continued

Table 4. Continued

Ranking	Splitting Tensile Strength, psi	Polymer Type	Polymer Loading % Cement Weight	Concrete Mix	Curing Method	Strength Ratio
Column 1	Column 2	Column 3	Column 4	Column 5	Column 6	Column 7
8	730	E	50	PPCC	S+A	1.8
9	720	L	40	PPCC	A	2.1
10	710	L	20	PRCC	S+A	1.8
11	660	L	30	PPCC	A	1.9
12	610	L	40	PRCC	A	1.9
13	600	L	30	PRCC	A	1.9
14	570	L	20	PRCC	A	1.8
d. Test Age 28 Days						
1	1,190	E	75	PPCC-E	S+A	2.9
2	1,120	E	100	PRCC	S+A	2.5
3	1,080	E	100	PPCC	S+A	2.6
4	1,060	E	75	PRCC	S+A	2.4
5	1,050	E	75	PPCC	S+A	2.6
6	930	L	40	PPCC	A	2.6
7	920	E	50	PPCC	S+A	2.2
8	880	L	30	PPCC	A	2.5
9	880	E	50	PRCC	S+A	2.0
10	810	L	40	PRCC	A	2.4
11	730	L	30	PRCC	A	2.1
12	690	L	20	PRCC	A	2.0
e. Test Age 91 Days						
1	1,280	E	75	PPCC	S+A	3.1
2	1,260	E	75	PRCC	S+A	2.9
3	1,210	E	75	PPCC-E	S+A	3.0

continued

Table 4. Continued

Ranking	Splitting Tensile Strength, psi	Polymer Type	Polymer Loading % Cement Weight	Concrete Mix	Curing Method	Strength Ratio
Column 1	Column 2	Column 3	Column 4	Column 5	Column 6	Column 7
4	1,180	E	100	PPCC	S+A	2.9
5	1,130	E	100	PRCC	S+A	2.6
6	1,100	E	50	PRCC	S+A	2.5
7	950	L	40	PPCC	A	2.8
8	890	L	30	PPCC	A	2.6
9	890	L	40	PRCC	S+A	2.0
10	870	L	40	PRCC	A	2.5
11	810	L	30	PRCC	A	2.3
12	810	L	40	PPCC	S+A	2.0
13	800	E	50	PPCC	S+A	2.0
14	720	L	20	PRCC	A	2.0

f. Test Age 175 Days

1	1,400	E	75	PPCC	S+A	3.5
2	1,170	E	100	PPCC	S+A	2.9
3	1,170	E	75	PRCC	S+A	2.6
4	1,150	E	75	PPCC-E	S+A	2.9
5	1,130	E	50	PRCC	S+A	2.6
6	1,130	E	100	PRCC	S+A	2.6
7	950	L	40	PPCC	A	2.8
8	940	L	30	PPCC	A	2.8
9	930	E	50	PPCC	S+A	2.3
10	910	L	40	PRCC	A	2.4
11	910	L	40	PRCC	S+A	2.1
12	820	L	30	PRCC	A	2.2

continued

Table 4. Continued

Ranking	Splitting Tensile Strength, psi	Polymer Type	Polymer Loading % Cement Weight	Concrete Mix	Curing Method	Strength Ratio
Column 1	Column 2	Column 3	Column 4	Column 5	Column 6	Column 7
g. Test Age 365 Days						
1	1,340	E	75	PPCC	S+A	3.4
2	1,250	E	75	PRCC	S+A	3.0
3	1,170	E	75	PPCC-E	S+A	2.9
4	1,150	E	100	PRCC	S+A	2.8
5	1,130	E	100	PPCC	S+A	2.8
6	980	E	50	PRCC	S+A	2.4
7	970	L	40	PPCC	A	2.9
8	910	L	40	PRCC	S+A	2.2
9	880	L	40	PRCC	A	2.4
10	870	L	30	PPCC	A	2.6
11	860	E	50	PPCC	S+A	2.2
12	840	L	30	PRCC	A	2.3

[a]Polymer types: L = latex; E = epoxy

[b]Concrete mixes: PPCC = polymer-modified portland cement concrete; PRCC = polymer-modified Regulated Set cement concrete.

[c]Curing methods: A = air-cured; S+A = steam-cured for 16 hours, then air-cured for remaining time until test age.

[d]Strength ratio is computed by dividing the splitting tensile strength of the polymer-modified concrete by the splitting tensile strength of an identical concrete without the polymer.

[e]E symbol means that a nonchloride accelerator was used in the mix.

Table 5. Flexural Strength Ratios of Polymer-Modified Concretes, 5.9 Mix

a. Test Age 1 Day

Strength Ratio	Polymer Type	Polymer Loading % Cement Weight	Concrete Mix	Curing Method	Flexural Strength, psi	Number of Specimens
Column 1	Column 2	Column 3	Column 4	Column 5	Column 6	Column 7
3.8[a]	E[b]	100	PRCC[c]	S+A[d]	1,250	3
3.5	E	75	PRCC	S+A	1,150	3
3.0	E	100	PPCC	S+A	1,300	3
2.9	E	75	PPCC	S+A	1,290	2
2.9	E	75	PPCC-E[e]	S+A	1,260	3
2.5	E	50	PRCC	S+A	840	2
2.2	L	40	PRCC	S+A	710	3
2.0	E	50	PPCC	S+A	900	2
1.7	L	20	PRCC	S+A	570	3
1.6	L	30	PRCC	S+A	540	3
1.2	L	40	PPCC	S+A	550	3
1.2	L	30	PPCC	S+A	530	3

b. Test Age 3 Days

2.5	L	40	PRCC	A	610	3
2.2	L	40	PPCC	A	770	3
1.8	L	30	PRCC	A	440	3
1.8	L	20	PRCC	A	430	3
1.7	L	30	PPCC	A	590	3

c. Test Age 7 Days

3.5	E	100	PRCC	S+A	1,330	3
3.4	E	75	PRCC	S+A	1,290	3
2.7	E	50	PRCC	S+A	1,020	2

continued

Table 5. Continued

Strength Ratio	Polymer Type	Polymer Loading % Cement Weight	Concrete Mix	Curing Method	Flexural Strength, psi	Number of Specimens
Column 1	Column 2	Column 3	Column 4	Column 5	Column 6	Column 7
2.7	E	75	PPCC	S+A	1,380	2
2.5	L	40	PRCC	A	700	3
2.4	E	75	PPCC-E	S+A	1,230	3
2.4	E	100	PPCC	S+A	1,300	3
2.2	L	40	PPCC	A	780	3
1.9	L	20	PRCC	A	540	3
1.9	L	30	PRCC	A	530	3
1.9	L	40	PRCC	S+A	710	3
1.7	E	50	PPCC	S+A	860	2
1.7	L	30	PPCC	A	620	2
1.5	L	20	PRCC	S+A	580	3
1.4	L	30	PRCC	S+A	520	3
1.2	L	40	PPCC	S+A	640	3
1.2	L	30	PPCC	S+A	610	3

d. Test Age 28 Days

2.6	E	75	PRCC	S+A	1,250	3
2.6	E	100	PRCC	S+A	1,270	3
2.5	E	100	PPCC	S+A	1,240	3
2.5	L	40	PPCC	A	1,030	3
2.4	E	75	PPCC	S+A	1,280	2
2.3	E	75	PPCC-E	S+A	1,240	3
2.2	L	30	PPCC	A	910	3
1.9	E	50	PRCC	S+A	900	2
1.7	L	40	PRCC	A	800	3
1.6	L	30	PRCC	A	740	3
1.6	L	40	PRCC	S+A	780	3

continued

Table 5. Continued

Strength Ratio	Polymer Type	Polymer Loading % Cement Weight	Concrete Mix	Curing Method	Flexural Strength, psi	Number of Specimens
Column 1	Column 2	Column 3	Column 4	Column 5	Column 6	Column 7
1.5	L	20	PRCC	A	710	3
1.5	L	20	PRCC	S+A	740	3
1.5	E	50	PPCC	S+A	830	2
e. Test Age 91 Days						
2.7	L	40	PPCC	A	1,330	3
2.6	E	75	PPCC	S+A	1,460	2
2.6	E	75	PPCC-E	S+A	1,450	3
2.5	E	100	PRCC	S+A	1,430	3
2.3	L	30	PPCC	A	1,170	3
2.3	E	75	PRCC	S+A	1,350	3
2.3	E	100	PPCC	S+A	1,300	3
2.2	L	40	PRCC	A	1,100	2
2.1	L	30	PRCC	A	1,040	3
2.1	E	50	PPCC	S+A	1,200	2
2.1	E	50	PRCC	S+A	1,240	2
1.9	L	20	PRCC	A	960	3
1.8	L	20	PRCC	S+A	1,040	2
1.8	L	40	PPCC	S+A	1,020	3
1.8	L	30	PPCC	S+A	980	3
f. Test Age 175 Days						
2.8	L	30	PPCC	A	1,480	3
2.8	L	40	PPCC	A	1,470	3
2.7	E	75	PPCC	S+A	1,560	2
2.6	E	75	PPCC-E	S+A	1,490	3

continued

Table 5. Continued

Strength Ratio	Polymer Type	Polymer Loading % Cement Weight	Concrete Mix	Curing Method	Flexural Strength, psi	Number of Specimens
Column 1	Column 2	Column 3	Column 4	Column 5	Column 6	Column 7
2.6	E	75	PRCC	S+A	1,460	3
2.6	E	100	PRCC	S+A	1,490	3
2.5	L	30	PRCC	A	1,310	3
2.4	L	40	PRCC	A	1,300	3
2.2	E	50	PRCC	S+A	1,260	2
2.2	E	100	PPCC	S+A	1,300	3
2.1	L	40	PPCC	S+A	1,220	3
2.1	L	20	PRCC	S+A	1,190	3
2.0	L	30	PPCC	S+A	1,150	3
2.0	L	20	PRCC	A	1,050	3
2.0	L	40	PRCC	S+A	1,100	3
2.0	E	50	PRCC	S+A	1,180	2
1.9	L	30	PRCC	S+A	1,060	3
g. Test Age 365 Days						
2.8	L	40	PPCC	A	1,570	3
2.8	E	100	PRCC	S+A	1,610	3
2.8	E	75	PPCC-E	S+A	1,610	3
2.7	E	75	PRCC	S+A	1,530	3
2.6	L	30	PPCC	A	1,480	3
2.6	E	50	PPCC	S+A	1,500	2
2.6	E	75	PPCC	S+A	1,520	2
2.5	E	100	PPCC	S+A	1,450	3
2.4	L	40	PRCC	A	1,320	2
2.4	L	30	PRCC	S+A	1,350	3
2.4	L	40	PRCC	S+A	1,360	3
2.4	L	40	PPCC	S+A	1,380	3

continued

Table 5. Continued

Strength Ratio	Polymer Type	Polymer Loading % Cement Weight	Concrete Mix	Curing Method	Flexural Strength, psi	Number of Specimens
Column 1	Column 2	Column 3	Column 4	Column 5	Column 6	Column 7
2.2	E	50	PRCC	S+A	1,260	2
2.1	L	30	PRCC	A	1,170	3
2.1	L	20	PRCC	S+A	1,220	3
2.1	L	30	PPCC	S+A	1,230	3

[a]Strength ratio is computed by dividing the flexural strength of the polymer-modified concrete by the flexural strength of an identical concrete without the polymer.
[b]Polymer types: L = latex; E = epoxy.
[c]Concrete mixes: *PPCC* = polymer-modified portland cement concrete; PRCC = polymer-modified Regulated Set cement concrete.
[d]Curing methods: A = air-cured; S+A = steam-cured for 16 hours, then air-cured for remaining time until test age.
[e]E symbol means that a nonchloride accelerator was used in the mix.

Table 6. Flexural Strengths of Polymer-Modified Concretes by Ranking, 5.9 Mix

a. Test Age 1 Day

Ranking	Flexural Strength, psi	Polymer Type	Polymer Loading % Cement Weight	Concrete Mix	Curing Method	Strength Ratio
Column 1	Column 2	Column 3	Column 4	Column 5	Column 6	Column 7
1	1,300	E[a]	100	PPCC[b]	S+A[c]	3.0[d]
2	1,290	E	75	PPCC	S+A	2.9
3	1,260	E	75	PPCC-E[e]	S+A	2.9
4	1,250	E	100	PRCC	S+A	3.8
5	1,150	E	75	PRCC	S+A	3.5
6	900	E	50	PPCC	S+A	2.0
7	840	E	50	PRCC	S+A	2.5
8	710	L	40	PRCC	S+A	2.2
9	570	L	20	PRCC	S+A	1.7
10	550	L	40	PPCC	S+A	1.2
11	540	L	30	PRCC	S+A	1.6
12	530	L	30	PPCC	S+A	1.2

b. Test Age 3 Days

1	770	L	40	PPCC	A	2.2
2	610	L	40	PRCC	A	2.5
3	590	L	30	PPCC	A	1.7
4	440	L	30	PRCC	A	1.8
5	430	L	20	PRCC	A	1.8

c. Test Age 7 Days

1	1,380	E	75	PPCC	S+A	2.7
2	1,330	E	100	PRCC	S+A	3.5
3	1,300	E	100	PPCC	S+A	2.4

continued

Table 6. Continued

Ranking	Flexural Strength, psi	Polymer Type	Polymer Loading % Cement Weight	Concrete Mix	Curing Method	Strength Ratio
Column 1	Column 2	Column 3	Column 4	Column 5	Column 6	Column 7
4	1,290	E	75	PRCC	S+A	3.4
5	1,230	E	75	PPCC-E	S+A	2.4
6	1,020	E	50	PRCC	S+A	2.7
7	860	E	50	PPCC	S+A	1.7
8	780	L	40	PPCC	A	2.2
9	710	L	40	PRCC	S+A	1.9
10	700	L	40	PRCC	A	2.5
11	640	L	40	PPCC	S+A	1.2
12	620	L	30	PPCC	A	1.7
13	610	L	30	PPCC	S+A	1.2
14	580	L	30	PRCC	S+A	1.5
15	540	L	20	PRCC	A	1.9
16	530	L	30	PRCC	A	1.9
17	520	L	30	PRCC	S+A	1.4

d. Test Age 28 Days

1	1,280	E	75	PPCC	S+A	2.4
2	1,270	E	100	PRCC	S+A	2.6
3	1,250	E	75	PRCC	S+A	2.6
4	1,240	E	100	PPCC	S+A	2.5
5	1,240	E	75	PPCC-E	S+A	2.3
6	1,030	L	40	PPCC	A	2.5
7	910	L	30	PPCC	A	2.2
8	900	E	50	PRCC	S+A	1.9
9	830	E	50	PPCC	S+A	1.5
10	800	L	40	PRCC	A	1.7
11	780	L	40	PRCC	S+A	1.6

continued

Table 6. Continued

Ranking	Flexural Strength, psi	Polymer Type	Polymer Loading % Cement Weight	Concrete Mix	Curing Method	Strength Ratio
Column 1	Column 2	Column e	Column 4	Column 5	Column 6	Column 7
12	740	L	30	PRCC	A	1.6
13	740	L	20	PRCC	S+A	1.5
14	710	L	20	PRCC	A	1.5
15	710	L	30	PRCC	S+A	1.4
16	700	L	40	PPCC	S+A	1.3
17	650	L	30	PPCC	S+A	1.2
e. Test Age 91 Days						
1	1,460	E	75	PPCC	S+A	2.6
2	1,450	E	75	PPCC-E	S+A	2.6
3	1,430	E	100	PRCC	S+A	2.5
4	1,350	E	75	PRCC	S+A	2.3
5	1,330	L	40	PPCC	A	2.7
6	1,300	E	100	PPCC	S+A	2.3
7	1,240	E	50	PRCC	S+A	2.1
8	1,200	E	50	PPCC	S+A	2.1
9	1,170	L	30	PPCC	A	2.3
10	1,100	L	40	PRCC	A	2.2
11	1,040	L	30	PRCC	A	2.1
12	1,040	L	20	PRCC	S+A	1.8
13	1,020	L	40	PPCC	S+A	1.8
14	980	L	30	PPCC	S+A	1.8
15	970	L	30	PRCC	S+A	1.7
16	960	L	20	PRCC	A	1.9
17	930	L	40	PRCC	S+A	1.6

continued

Table 6. Continued

Ranking	Flexural Strength, psi	Polymer Type	Polymer Loading % Cement Weight	Concrete Mix	Curing Method	Strength Ratio
Column 1	Column 2	Column 3	Column 4	Column 5	Column 6	Column 7
			f. Test Age 175 Days			
1	1,560	E	75	PPCC	S+A	2.7
2	1,490	E	75	PPCC-E	S+A	2.6
3	1,490	E	100	PRCC	S+A	2.6
4	1,480	L	30	PPCC	A	2.8
5	1,470	L	40	PPCC	A	2.8
6	1,460	E	75	PRCC	S+A	2.6
7	1,310	L	30	PRCC	A	2.5
8	1,300	L	40	PRCC	A	2.4
9	1,300	E	100	PPCC	S+A	2.2
10	1,260	E	50	PRCC	S+A	2.2
11	1,220	L	40	PPCC	S+A	2.1
12	1,190	L	20	PRCC	S+A	2.1
13	1,180	E	50	PPCC	S+A	2.0
14	1,150	L	30	PPCC	S+A	2.0
15	1,100	L	40	PRCC	S+A	2.0
16	1,060	L	30	PRCC	S+A	1.9
17	1,050	L	20	PRCC	A	2.0
			g. Test Age 365 Days			
1	1,610	E	100	PRCC	S+A	2.8
2	1,610	E	75	PPCC-E	S+A	2.8
[illegible]	1,570	L	40	PPCC	A	2.8
4	1,530	E	75	PRCC	S+A	2.7
5	1,520	E	75	PPCC	S+A	2.6
6	1,500	E	50	PPCC	S+A	2.6

continued

Table 6. Continued

Ranking	Flexural Strength, psi	Polymer Type	Polymer Loading % Cement Weight	Concrete Mix	Curing Method	Strength Ratio
Column 1	Column 2	Column 3	Column 4	Column 5	Column 6	Column 7
7	1,480	L	30	PPCC	A	2.6
8	1,450	E	100	PPCC	S+A	2.5
9	1,380	L	40	PPCC	S+A	2.4
10	1,360	L	40	PRCC	S+A	2.4
11	1,350	L	30	PRCC	S+A	2.4
12	1,320	L	40	PRCC	A	2.4
13	1,260	E	50	PRCC	S+A	2.2
14	1,230	L	30	PPCC	S+A	2.1
15	1,220	L	20	PRCC	S+A	2.1
16	1,170	L	30	PRCC	A	2.1

[a]Polymer types: L = latex; E = epoxy

[b]Concrete mixes: PPCC = polymer-modified portland cement concrete; PRCC = polymer-modified Regulated Set cement concrete.

[c]Curing methods: A = air-cured; S+A = steam-cured for 16 hours, then air-cured for remaining time until test age.

[d]Strength ratio is computed by dividing the flexural strength of the polymer-modified concrete by the flexural strength of an identical concrete without the polymer.

[e]E symbol means that a nonchloride accelerator was used in the mix.

Table 7. Strength Ratios for Young's Moduli of Polymer-Modified Concretes, 5.9 Mix

a. Test Age 1 Day

Strength Ratio	Polymer Type	Polymer Loading % Cement Weight	Concrete Mix	Curing Method	Young's Modulus, 10^6 psi	Number of Specimens
Column 1	Column 2	Column 3	Column 4	Column 5	Column 6	Column 7
1.4[a]	L[b]	20	PRCC[c]	S+A[d]	2.07	3
1.4	E	50	PRCC	S+A	2.08	2
1.4	L	30	PRCC	S+A	2.03	3
1.3	L	40	PRCC	S+A	1.91	3
1.1	E	100	PRCC	S+A	1.70	3
1.1	E	100	PPCC	S+A	1.87	3
0.8	E	75	PPCC	S+A	1.44	2
0.8	E	75	PRCC	S+A	1.21	3
0.6	L	40	PPCC	S+A	1.09	3

b. Test Age 3 Days

Strength Ratio	Polymer Type	Polymer Loading % Cement Weight	Concrete Mix	Curing Method	Young's Modulus, 10^6 psi	Number of Specimens
1.1	L	40	PPCC	A	2.00	3
1.0	L	40	PRCC	A	1.73	3
1.0	L	30	PRCC	A	1.60	3
0.9	L	30	PPCC	A	1.75	3
0.9	L	20	PRCC	A	1.53	3

c. Test Age 7 Days

Strength Ratio	Polymer Type	Polymer Loading % Cement Weight	Concrete Mix	Curing Method	Young's Modulus, 10^6 psi	Number of Specimens
1.7	L	20	PRCC	S+A	3.08	3
1.4	L	40	PRCC	S+A	2.52	3
1.4	L	20	PRCC	A	2.23	3
1.4	E	75	PPCC-E[e]	S+A	1.95	3
1.3	L	40	PPCC	A	2.63	3
1.3	E	50	PRCC	S+A	2.42	2

continued

Table 7. Continued

Strength Ratio	Polymer Type	Polymer Loading % Cement Weight	Concrete Mix	Curing Method	Young's Modulus, 10^6 psi	Number of Specimens
Column 1	Column 2	Column 3	Column 4	Column 5	Column 6	Column 7
1.2	E	75	PRCC	S+A	2.30	3
1.2	E	100	PRCC	S+A	2.19	3
1.2	L	40	PRCC	A	2.03	3
1.2	E	100	PPCC	S+A	1.77	3
1.1	L	30	PRCC	S+A	2.03	3
1.1	L	30	PRCC	A	1.83	3
1.0	E	75	PPCC	S+A	1.41	2
1.0	L	40	PPCC	S+A	1.38	2
1.0	L	30	PPCC	A	2.04	3
d. Test Age 28 Days						
1.5	L	40	PRCC	S+A	3.05	3
1.5	L	30	PPCC	A	2.67	5
1.5	L	40	PPCC	A	2.66	3
1.4	E	75	PRCC	S+A	2.86	4
1.2	L	30	PRCC	S+A	2.53	5
1.2	L	20	PRCC	S+A	2.52	4
1.2	L	20	PPCC	A	2.16	1
1.2	E	50	PRCC	S+A	2.58	3
1.1	E	75	PPCC-E	S+A	2.49	1
1.0	L	20	PRCC	A	2.38	4
1.0	L	40	PRCC	A	2.35	3
1.0	E	100	PRCC	S+A	2.12	4

continued

Table 7. Continued

Strength Ratio	Polymer Type	Polymer Loading % Cement Weight	Concrete Mix	Curing Method	Young's Modulus, 10^6 psi	Number of Specimens
Column 1	Column 2	Column 3	Column 4	Column 5	Column 6	Column 7
e. Test Age 91 Days						
1.6	L	40	PPCC	A	2.98	3
1.3	L	20	PRCC	A	3.00	3
1.2	L	40	PRCC	A	2.82	3
1.1	L	40	PRCC	S+A	3.09	3
1.1	L	30	PRCC	A	2.68	3
1.1	E	75	PRCC	S+A	3.00	3
1.1	L	30	PPCC	A	2.06	3
1.0	L	20	PRCC	S+A	2.77	3
1.0	L	30	PRCC	S+A	2.70	3
0.9	E	50	PRCC	S+A	2.52	2
0.9	E	100	PRCC	S+A	2.37	3
f. Test Age 175 Days						
1.5	L	30	PPCC	A	2.84	3
1.4	L	20	PRCC	A	2.96	3
1.4	L	40	PRCC	A	2.79	3
1.4	L	40	PPCC	A	2.65	3
1.3	L	40	PRCC	S+A	3.24	3
1.3	E	50	PRCC	S+A	3.20	2
1.2	E	75	PRCC	S+A	2.81	3
1.2	L	20	PRCC	S+A	3.15	3
1.2	L	30	PRCC	A	2.38	3
1.1	L	30	PRCC	S+A	2.78	3
1.0	E	100	PRCC	S+A	2.54	3

continued

Table 7. Continued

Strength Ratio	Polymer Type	Polymer Loading % Cement Weight	Concrete Mix	Curing Method	Young's Modulus, 10^6 psi	Number of Specimens
Column 1	Column 2	Column 3	Column 4	Column 5	Column 6	Column 7
g. Test Age 365 Days						
1.8	L	30	PRCC	A	3.62	3
1.8	E	50	PRCC	S+A	3.90	2
1.8	L	40	PRCC	A	3.62	3
1.6	L	40	PPCC	A	3.04	3
1.6	L	30	PPCC	A	2.96	3
1.6	L	30	PRCC	S+A	3.57	3
1.4	L	20	PRCC	S+A	3.18	3
1.3	L	40	PRCC	S+A	2.91	2
1.3	E	75	PRCC	S+A	2.86	3
1.3	L	20	PRCC	A	2.54	3
1.0	E	100	PPCC	S+A	2.74	3
1.0	E	100	PRCC	S+A	2.21	3

[a] Strength ratio is computed by dividing the Young's modulus of the polymer-modified concrete by the Young's modulus of an identical concrete without the polymer.
[b] Polymer types: L = latex; E = epoxy.
[c] Concrete mixes: PPCC = polymer-modified portland cement concrete; PRCC = polymer-modified Regulated Set cement concrete.
[d] Curing methods: A = air-cured; S+A = steam-cured for 16 hours, then air-cured for remaining time until test age.
[e] E symbol means that a nonchloride accelerator was used in the mix.

Table 8. Young's Moduli for Polymer-Modified Concretes by Ranking, 5.9 Mix

a. Test Age 1 Day

Ranking	Young's Modulus, 10^6 psi	Polymer Type	Polymer Loading % Cement Weight	Concrete Mix	Curing Method	Strength Ratio
Column 1	Column 2	Column 3	Column 4	Column 5	Column 6	Column 7
1	2.08	E[a]	50	PRCC[b]	S+A[c]	1.4[d]
2	2.07	L	20	PRCC	S+A	1.4
3	2.03	L	30	PRCC	S+A	1.4
4	1.91	L	40	PRCC	S+A	1.3
5	1.87	E	100	PPCC	S+A	1.1
6	1.70	E	100	PRCC	S+A	1.1
7	1.44	E	75	PPCC	S+A	0.8
8	1.21	E	75	PRCC	S+A	0.8
9	1.09	L	40	PPCC	S+A	0.6

b. Test Age 3 Days

1	2.00	L	40	PPCC	A	1.1
2	1.75	L	30	PPCC	A	0.9
3	1.73	L	40	PRCC	A	1.0
4	1.60	L	30	PRCC	A	1.0
5	1.53	L	20	PRCC	A	0.9

c. Test Age 7 Days

1	3.08	L	20	PRCC	S+A	1.7
2	2.63	L	40	PPCC	A	1.3
3	2.52	L	40	PRCC	S+A	1.4
4	2.42	E	50	PRCC	S+A	1.3
5	2.30	E	75	PRCC	S+A	1.2
6	2.23	L	20	PRCC	A	1.4

continued

Table 8. Continued

Ranking	Young's Modulus, 10^6 psi	Polymer Type	Polymer Loading % Cement Weight	Concrete Mix	Curing Method	Strength Ratio
Column 1	Column 2	Column 3	Column 4	Column 5	Column 5	Column 7
7	2.19	E	100	PRCC	S+A	1.2
8	2.04	L	30	PPCC	A	1.0
9	2.03	L	40	PRCC	A	1.2
10	2.03	L	30	PRCC	S+A	1.1
11	1.95	E	75	PPCC-E[e]	S+A	1.4
12	1.83	L	30	PRCC	A	1.1
13	1.77	E	100	PPCC	S+A	1.2
14	1.41	E	75	PPCC	S+A	1.0
15	1.38	L	40	PPCC	S+A	1.0

d. Test Age 28 Days

1	3.05	L	40	PRCC	S+A	1.5
2	2.86	E	75	PRCC	S+A	1.4
3	2.67	L	30	PPCC	A	1.5
4	2.66	L	40	PPCC	A	1.5
5	2.58	E	50	PRCC	S+A	1.2
6	2.53	L	30	PRCC	S+A	1.2
7	2.52	L	20	PRCC	S+A	1.2
8	2.49	E	75	PPCC-E	S+A	1.1
9	2.38	L	20	PRCC	A	1.0
10	2.35	L	40	PRCC	A	1.0
11	2.16	L	20	PPCC	A	1.2
12	2.12	E	100	PRCC	S+A	1.0

continued

Table 8. Continued

Ranking	Young's Modulus, 10^6 psi	Polymer Type	Polymer Loading % Cement Weight	Concrete Mix	Curing Method	Strength Ratio
Column 1	Column 2	Column 3	Column 4	Column 5	Column 6	Column 7
e. Test Age 91 Days						
1	3.09	L	40	PRCC	S+A	1.1
2	3.00	L	20	PRCC	A	1.3
3	3.00	E	75	PRCC	S+A	1.1
4	2.98	L	40	PPCC	A	1.6
5	2.82	L	40	PRCC	A	1.2
6	2.77	L	20	PRCC	S+A	1.0
7	2.70	L	30	PRCC	S+A	1.0
8	2.68	L	30	PRCC	A	1.1
9	2.52	E	50	PRCC	S+A	0.9
10	2.37	E	100	PRCC	S+A	0.9
11	2.06	L	30	PPCC	A	1.1
f. Test Age 175 Days						
1	3.24	L	40	PRCC	S+A	1.3
2	3.20	E	50	PRCC	S+A	1.3
3	3.15	L	20	PRCC	S+A	1.2
4	2.96	L	20	PRCC	A	1.4
5	2.84	L	30	PPCC	A	1.5
6	2.81	E	75	PRCC	S+A	1.2
7	2.79	L	40	PRCC	A	1.4
8	2.78	L	30	PRCC	S+A	1.1
9	2.65	L	40	PPCC	A	1.4
10	2.54	E	100	PRCC	S+A	1.0
11	2.38	L	30	PRCC	A	1.2

continued

Table 8. Continued

Ranking	Young's Modulus, 10^6 psi	Polymer Type	Polymer Loading % Cement Weight	Concrete Mix	Curing Method	Strength Ratio
Column 1	Column 2	Column 3	Column 4	Column 5	Column 6	Column 7
g. Test Age 365 Days						
1	3.90	E	50	PRCC	S+A	1.8
2	3.62	L	30	PRCC	A	1.8
3	3.62	L	40	PRCC	A	1.8
4	3.57	L	30	PRCC	S+A	1.6
5	3.18	L	20	PRCC	S+A	1.4
6	3.04	L	40	PPCC	A	1.6
7	2.96	L	30	PPCC	A	1.6
8	2.91	L	40	PRCC	S+A	1.3
9	2.86	E	75	PRCC	S+A	1.3
10	2.74	E	100	PPCC	S+A	1.0
11	2.54	L	20	PRCC	A	1.3
12	2.21	E	100	PRCC	S+A	1.0

[a]Polymer types: L = latex; E = epoxy
[b]Concrete mixes: PPCC = polymer-modified portland cement concrete; PRCC = polymer-modified Regulated Set cement concrete.
[c]Curing methods: A = air-cured; S+A = steam-cured for 16 hours, then air-cured for remaining time until test age.
[d]Strength ratio is computed by dividing the Young's modulus of the polymer-modified concrete by the Young's modulus of an identical concrete without the polymer.
[e]E symbol means that a nonchloride accelerator was used in the mix.

Table 9. Water Absorption of Polymer-Modified Concretes, 5.9 Mix

Polymer Type	Polymer Loading (% Cement Weight)	Concrete Mix	Curing Method	Absorption (%)	Control Absorption (%)	Ratio: Polymer-Modified to Control
Column 1	Column 2	Column 3	Column 4	Column 5	Column 6	Column 7
E[a]	50	PPCC[b]	S+A[c]	6.1	9.6	0.64
E	75	PPCC	S+A	3.9	9.6	0.41
E	100	PPCC	S+A	3.5	9.6	0.36
E	50	PRCC	S+A	5.5	10.7	0.51
E	75	PRCC	S+A	3.7	10.7	0.35
E	100	PRCC	S+A	3.3	10.7	0.31
L	30	PPCC	S+A	5.9	9.6	0.61
L	40	PPCC	S+A	5.3	9.6	0.55
L	20	PRCC	S+A	5.2	10.7	0.49
L	30	PRCC	S+A	6.7	10.7	0.63
L	40	PRCC	S+A	4.1	10.7	0.38
L	30	PPCC	A	4.5	9.1	0.49
L	40	PPCC	A	3.8	9.1	0.42
L	20	PRCC	A	7.2	11.4	0.63
L	30	PRCC	A	6.5	11.4	0.57
L	40	PRCC	A	5.3	11.4	0.46

[a]Polymer types: L = latex; E = epoxy

[b]Concrete Mixes: PPCC = polymer-modified portland cement concrete; PRCC = polymer-modified Regulated Set cement concrete.

[c]Curing methods: A = air-cured; S+A = steam-cured for 16 hours, then air-cured for remaining time until test age.

Table 10. Incremental Costs for Ingredients of Polymer-Modified Concrete

(a) Incremental Costs per Cubic Yard

Ingredient	Weight of Ingredient, lb	Ingredient Cost Per Pound	Incremental Cost of Ingredient	Item
Epi-rez 5077	416[a]	$0.85	$353.60	1
Epon 815	416	0.77	320.32	2
Ancamine T-1	83.2[b]	1.33	110.66	3
Latex 464	444[c]	0.61	270.84	4
Antifoam B	6.4[d]	0.77	4.93	5
Type III Cement	555[e]	0.002	1.11	6
Regulated Set Cement	555	0.004	2.22	7

(b) Total Incremental Cost of Selected Mixes

Polymer-Modified Mix	Total Incremental Cost Per Cubic Yard[f]
5.9 PPCC with Epi-rez 5077 epoxy (Items 1 + 3 + 6)	$465.37[g]
5.9 PPCC with Epon 815 epoxy (Items 2 + 3 + 6)	432.09[g]
5.9 PRCC with Epi-rez 5077 epoxy (Items 1 + 3 + 7)	466.48[g]
5.9 PRCC with Epon 815 epoxy (Items 2 + 3 + 7)	433.20[g]
5.9 PPCC with Latex 464 (Items 4 + 5 + 6)	276.88
5.9 PRCC with Latex 464 (Items 4 + 5 + 7)	277.99

[a] Epoxy loading of 75% requires 416 lb.

[b] Ratio of curing agent to epoxy is 5:1; 416/5 = 83.2 lb.

[c] Latex loading of 40% requires 222 lb of solids but latex 464 is 50% solids, 50% water, so total weight is 444 lb.

[d] Antifoam B: 0.0144 x latex weight (444 lb) = 6.4 lb.

[e] 5.9 mix requires 555 lb of cement.

[f] All cost figures shown are 1976 costs.

[g] Costs do not include intangible costs for compaction and for cleaning of equipment.

Table 11. Ratios of Splitting Tensile and Flexural Strengths to Compressive Strengths

Polymer — Modified Concretes						Plain Concrete	
Polymer Type, Loading, Mix, and Curing Method	Compressive Strength, psi	Splitting Tensile Strength, psi	Flexural Strength, psi	Ratio: Column 3 to Column 2	Ratio: Column 4 to Column 2	Ratio: Tensile to Compressive	Ratio: Flexural to Compressive
Column 1	Column 2	Column 3	Column 4	Column 5	Column 6	Column 7	Column 8
(a) Test Age 7 Days							
E[a], 75%[b], 5.9 PRCC[c], S+A[d]	7,220	1,100	1,290	0.15	0.18	0.07[e]	0.12[e]
E, 75%, 5.9 PPCC, S+A	5,990	1,180	1,380	0.20	0.23	0.08	0.13
L, 40%, 5.9 PPCC, A	4,960	720	780	0.14	0.16	0.08	0.14
(b) Test Age 28 Days							
E, 75%, 5.9 PRCC, S+A	8,390	1,060	1,250	0.13	0.15	0.07	0.12
E, 75%, 5.9 PPCC, S+A	6,910	1,050	1,280	0.15	0.18	0.07	0.12
L, 40%, 5.9 PPCC, A	7,060	930	1,030	0.13	0.15	0.07	0.12
(c) Test Age 91 Days							
E, 75%, 5.9 PRCC, S+A	8,540	1,260	1,350	0.15	0.16	0.07	0.11
E, 75%, 5.9 PPCC, S+A	7,080	1,280	1,460	0.18	0.21	0.07	0.12
L, 40%, 5.9 PPCC, A	8,150	950	1,330	0.12	0.16	0.07	0.12
(d) Test Age 175 Days							
E, 75%, 5.9 PRCC, S+A	9,320	1,170	1,460	0.13	0.16	0.07	0.11
E, 75%, 5.9 PPCC, S+A	6,620	1,400	1,560	0.21	0.24	0.07	0.12
L, 40%, 5.9 PPCC, A	8,950	950	1,470	0.11	0.16	0.07	0.11
(e) Test Age 365 Days							
E, 75%, 5.9 PRCC, S+A	10,150	1,250	1,530	0.12	0.15	0.07	0.11
E, 75%, 5.9 PPCC, S+A	7,690	1,340	1,520	0.17	0.20	0.07	0.12
L, 40%, 5.9 PPCC, A	10,110	970	1,570	0.10	0.16	0.07	0.11

[a]Polymer types: L = latex; E = epoxy.
[b]Polymer loading is expressed as a percentage of the weight of the cement.
[c]Concrete mixes: PPCC = polymer-modified portland cement concrete; PRCC = polymer-modified Regulated Set cement concrete.
[d]Curing methods: A = air-cured; S+A = steam-cured for 16 hours then air-cured for remaining time until test age.
[e]From Table 2 of Reference 13.

Appendix A

POLYMERS AND ASSOCIATED MATERIALS

Polymer	Source	Cost Per Pound[a]
Epi-rez 5077	Celanese Resins, Los Angeles, California	$0.85
Epon 815	Shell Chemical Company, New York, New York	0.77
Ancamine T-1	Pacific Anchor Chemical Company, Richmond, California	1.33
Latex 464	Dow Chemical Company, Midland, Michigan	0.61
Antifoam B	Dow Corning Corporation, Midland, Michigan	0.77
Regulated Set Cement	Huron Cement Company, Southfield, Michigan	0.025
Type III Portland Cement	Southwestern Portland Cement Company, Los Angeles, California	0.023

[a]1976 costs.

Appendix B

STRENGTHS OF CONTROL MIXES

Tables B-1 through B-4 present the compressive strengths, Young's moduli, splitting tensile strengths, and flexural strengths of the control concrete mixes.

Table B-1. Compressive Strengths of Control Mixes

Curing	Mix Designation	Compressive Strengths (psi)						
		1 Day	3 Days	7 Days	28 Days	91 Days	175 Days	365 Days
(a) Type III Portland Cement Concrete								
Steam + Air (S+A)	5.9	1,830	2,300	2,690	3,350	3,590	3,660	3,700
	6.9	2,750	3,740	4,220	5,080	–	–	–
	8.0	3,860	4,850	5,350	5,690	–	–	–
Air (A)	5.9	570	1,400	2,220	2,710	2,960	3,030	3,130
(b) Regulated Set Cement Concrete								
Steam + Air (S+A)	5.9	1,380	1,800	2,080	2,470	2,700	2,740	2,760
	6.9	1,940	2,420	2,810	3,390	–	–	–
	8.0	2,600	3,110	3,580	4,100	–	–	–
Air (A)	5.9	790	1,410	2,270	2,810	3,070	3,120	3,150

Table B-2. Young's Moduli of Control Mixes

Curing	Mix Designation	Young's Moduli (10^6 psi)						
		1 Day	3 Days	7 Days	28 Days	91 Days	175 Days	365 Days
(a) Type III Portland Cement Concrete								
Steam + Air (S+A)	5.9	1.72	–	1.42	2.34	2.75	2.75	2.75
Air (A)	5.9	1.70	1.85	1.95	1.80	1.88	1.89	1.89
(b) Regulated Set Cement Concrete								
Steam + Air (S+A)	5.9	1.50	–	1.84	2.04	2.75	2.51	2.22
Air (A)	5.9	–	1.64	1.62	2.43	2.38	2.06	2.00

Table B-3. Splitting Tensile Strengths of Control Mixes

Curing	Mix Designation	Splitting Tensile Strength (psi)						
		1 Day	3 Days	7 Days	28 Days	91 Days	175 Days	365 Days
(a) Type III Portland Cement Concrete								
Steam + Air (S+A)	5.9	280	–	400	410	410	400	400
Air (A)	5.9	250	310	340	350	340	340	330
(b) Regulated Set Cement Concrete								
Steam + Air (S+A)	5.9	270	–	400	440	440	440	410
Air (A)	5.9	–	250	320	340	350	370	370

Table B-4. Flexural Strengths of Control Mixes

Curing	Mix Designation	Flexural Strength (psi)						
		1 Day	3 Days	7 Days	28 Days	91 Days	175 Days	365 Days
(a) Type III Portland Cement Concrete								
Steam + Air (S+A)	5.9	440	–	510	540	560	580	580
Air (A)	5.9	330	350	360	410	500	520	570
(b) Regulated Set Cement Concrete								
Steam + Air (S+A)	5.9	330	–	380	490	580	560	570
Air (A)	5.9	–	240	280	460	500	530	560

Appendix C

TYPICAL MIX DESIGNS AND MIXING AND CURING PROCEDURES FOR POLYMER-MODIFIED CONCRETES

MIXING DESIGN AND PROCEDURE FOR 5.9 PPCC WITH EPOXY

The following quantities of material per cubic yard of portland cement concrete with 75% epoxy loading should be used:

Coarse aggregate	1,172 pounds
Fine aggregate	1,620 pounds
Type III cement	555 pounds (5.9 sacks)
Water	388 pounds* (W/C = 0.70)
Epoxy (0.75 x 555)	416 pounds
Ancamine T-1 (416 ÷ 5)	83 pounds

The mixing procedure is as follows:

1. Mix aggregates, cement, and water for 3 minutes.
2. Allow mixed concrete to stand for 1 hour, mixing occasionally for 10 seconds to maintain fluidity.
3. Mix epoxy and curing agent and allow to stand for 10 minutes prior to adding to concrete.
4. Add mixed epoxy and curing agent to concrete and mix for 3 minutes.
5. Place polymer-modified concrete in forms; hand-packing combined with vibration gives best results.

It should be noted that when an accelerator is used (according to the manufacturer's instructions), step 2 can be reduced to 15 minutes; when Regulated Set cement is used instead of Type III portland cement, step 2 can be eliminated.

MIXING DESIGN AND PROCEDURE FOR 5.9 PPCC WITH LATEX

The following quantities of material per cubic yard of portland cement concrete with 40% latex loading should be used:

Coarse aggregate	1,172 pounds
Fine aggregate	1,620 pounds
Type III cement	555 pounds (5.9 sacks)
Water	388 pounds** (W/C = 0.70)
Latex solids (0.40 x 555)	222 pounds
Latex (50% water)	444 pounds (solids + water)
Antifoam B (0.0144 x 444)	6.4 pound

*Assuming saturated, surface-dry aggregates.

**Assuming saturated, surface-dry aggregates.

It should be noted that the 222 pounds of water in the latex total must be included in the 388 pounds of water needed.

The mixing procedure is as follows:

1. Mix latex and Antifoam B.
2. Mix aggregates, cement, water, and latex for 3 minutes.
3. Place the latex-modified concrete in the form; it compacts easily with vibration.

Mixing and placing procedures are the same when Regulated Set cement is used instead of Type III portland cement.

CURING PROCEDURES

1. Epoxy-modified concretes require steam-curing. The structure can be covered with a hood and steam supplied by a portable steam generator (such as in prestressing yards), or, as an alternative, wet burlap can be placed over the structure and then covered with an "electric blanket" type of heating unit. Curing should continue for at least 16 hours, but longer time — up to 2 days — will provide even higher strengths.

2. Latex-modified concretes require no special curing; as soon as practicable, form work should be removed and ambient air allowed to reach as much of the structure as possible.

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SWEDEN Chalmers Univ of Technology (Dr I R Malinowski) Gothenburg, VBB (Library), Stockholm
TIDEWATER CONSTR. CO Norfolk VA (Fowler)
TRW SYSTEMS CLEVELAND, OH (ENG. LIB.), REDONDO BEACH, CA (DAI)
UNITED KINGDOM Assoc Portland Cement Mfg (W O Nutt) Croyden England, Cement & Concrete Assoc. (Library), Wexham Springs, Slough, Cement & Concrete Assoc. (Lit. Ex), Bucks, Cement & Concrete Assoc. (R. Rowe), Wexham Springs, Slough B, D. New, G. Maunsell & Partners, London, Shaw & Hatton (F. Hansen), London, Taylor, Woodrow Constr (014P), Southall, Middlesex, Univ. of Bristol (R. Morgan), Bristol
WESTINGHOUSE ELECTRIC CORP. Annapolis MD (Oceanic Div Lib, Bryan), Library, Pittsburgh PA
WISS, JANNEY, ELSTNER, & ASSOC Northbrook, IL (J. Hanson)
WM CLAPP LABS - BATTELLE DUXBURY, MA (LIBRARY), DUXBURY, MA (RICHARDS)
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