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Progress Report No. 2

L.E. Kukacka, A. J. Romano, M. Reich, and others

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16. Abstract Investigations of polymer-impregnated concrete for highway applications made at Brookhaven National Laboratory during the period July 1970 to December 1971 are reported. The work is sponsored by the Federal Highway Administration and the U. S. Atomic Energy Commission.

Samples of normal weight and structural lightweight concretes containing several high-quality aggregates were impregnated with methyl methacrylate and radiation polymerized *in situ*. All the materials produced high-strength (15,000 psi) durable composites, and the results indicate that concretes prepared from locally available materials can be used in the preparation of polymer-impregnated concrete. Comparable results have been obtained with thermal-catalytically polymerized specimens.

Preparation methods for impregnating lightweight insulating-type concretes have been developed and the structural properties of perlite concrete impregnated with methyl methacrylate and polyester-styrene have been measured. Strengths equivalent to or greater than that of conventional concrete have been obtained for materials having final densities ranging from 60 to 75 lb/ft^3.

Techniques are being developed to polymerize monomers at ambient conditions by use of catalyst-promoter systems. To date four monomer systems including methyl methacrylate and polyester-styrene have been completely polymerized at 70°F (21°C). When developed, these techniques will have wide applications in field-type concrete impregnations such as on bridge decks.

Work to determine the feasibility of repairing deteriorated concrete bridge decks by partial impregnation with monomers was initiated. A preliminary field experiment was performed. The results showed promise, and additional work is in progress.

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SUMMARY

A research program to determine the properties of concrete-polymer materials and to find and develop potential highway applications is being performed by the Radiation Division of the Department of Applied Science, Brookhaven National Laboratory (BNL) and the Materials Division, Office of Research, Federal Highway Administration (FHWA). The program is sponsored by the U. S. Department of Transportation, Federal Highway Administration.

The work to date has indicated that great improvements in the structural and durability properties of highway-quality concrete can be obtained by monomer impregnation and <u>in situ</u> polymerization by either radiation or thermal-catalytic means.

Samples of conventional weight and structural-lightweight concretes containing several types of aggregates and with various water/cement ratios were prepared by the FHWA and impregnated at BNL. Tests were performed at both laboratories. Aggregates tested include two crushed limestones, one from the Stones River formation at Riverton, Virginia, and the other from the Plattsmouth member in Kansas; a quartzite gravel from White Marsh, Maryland; a crushed diorite from Chantilly, Virginia; a

sized slag from Baltimore, Maryland; an expanded slate marketed under the trade name of Solite; and a sintered fly ash marketed under the trade name of Edicrete.

After impregnation with methyl methacrylate (MMA) and radiation polymerization, all the materials produced high-strength (>15,000 psi) composites. These results are summarized in Table I. Comparable strengths have also been obtained with thermal-catalytically polymerized specimens.[1-4] The data indicate that concretes prepared from locally available materials can be used in the production of polymer-impregnated concrete (PIC).

In conjunction with this effort, encapsulation methods were evaluated following the vacuum-soak impregnation operation to determine the effectiveness in minimizing monomer drainage and evaporation losses.

The choice of encapsulation method appears to depend upon the initial density of the concrete. Polymerization under water yields results that are at least comparable with those obtained by using forms when high-density ($>140 lb/ft^3$) materials containing limestone, quartzite gravel, or diorite are impregnated. Forms are more effective for lower density materials such as Solite or slag, probably because their use reduces the drainage losses to which low-density materials are more susceptible to negligible values. However, the differences in strength are not large (<15%),

Table 1

Summary of Compressive Strengths and Strength-to-Weight Ratios for FHWA Concrete-Polymer Materials

Monomer, MMA.
Radiation-induced polymerization.

Type of aggregate	Method of encapsulation[a]	Average polymer content		Final density lb/ft^3	Average control compressive strength, psi	Average compressive strength, psi	Average strength-to-weight ratio, S/W[b]
		wt %	vol %				
Diorite	U	5.5	11.5	154	5555	20100	131
White Marsh quartzite gravel	U	5.4	10.9	149	5600	18980	127
Riverton limestone	U	5.6	11.6	152	5690	18280	120
Low strength concrete with Riverton limestone	U	7.1	12.9	146	2230	15530	106
Kansas limestone	F	7.9	15.5	143	5190	23030	161
Slag (3/4-in.)	F	8.6	16.3	138	5220	23690	172
Slag (3/8-in.)	F	10.5	19.0	132	4000	24520	186
Expanded slate	F	16.3	27.8	121	3676	17810	147
Perlite (1:8)	F	61.3	56.8	68	170	7700	113
Perlite (1:8)[c]	F	64.6	57.8	69.8	170	6000	86
Perlite (1:5)	F	57.6	54.4	69.5	250	7395	106
Perlite (1:5)[c]	F	59.9	55.9	72.7	250	6083	84

(a) Encapsulation method which produced the highest compressive strength. U, underwater; F, excess monomer - in forms.
(b) S/W = av compressive strength/av final density.
(c) Impregnated with 50% polyester - 50% styrene.

and therefore the additional cost associated with the use of forms would probably not be warranted. The use of a pre-polymer dip in conjunction with the standard vacuum-soak impregnation method and subsequent rotation of the specimen during polymerization is also an effective method for reducing drainage and evaporation losses. Although the material properties are similar to those obtained with the underwater and in-form techniques, the necessity of rotating large numbers of heavy specimens appears to make this method impractical for all but highly specialized applications.

MMA-impregnated structural lightweight concrete containing slag aggregate produced composites with the greatest strength and strength-to-weight ratio. Average compressive and tensile splitting strengths of 24,520 and 2230 psi, respectively, were obtained for samples containing 3/8-in. maximum size aggregate and 10.5 wt % (19 vol%) MMA. The compressive strength-to-weight ratio was 186. Similar results were obtained with 3/4-in. slag aggregate.

The MMA-impregnation of low-strength (2230 psi) concrete containing Riverton limestone resulted in composites with final strengths of ≈15,500 psi. This corresponds to improvement by a factor of 7. Higher strength (5690 psi) Riverton limestone concrete exhibited a smaller factor of improvement (3.2) and a higher final compressive strength of ≈18,000 psi. Concretes containing other aggregates produced composites with compressive strengths ranging between 15,500 and 23,000 psi.

All the fully impregnated samples exhibited good resistance to rapid freezing and thawing in water. After 1057 cycles, durability factors (D. F.) of between 60 and 99% were measured. Conventional concrete is generally considered satisfactory at a D.F. of 70 at 300 cycles. Flexure tests made on the impregnated normal weight specimens after freeze-thaw exposure indicated strength reductions of as much as 75% for D.F. of 60 but only 27% for the 99% D.F.

Large reductions in chloride ion penetration have also been obtained. Reductions to 1/50 of that in the controls have been measured for cement-paste samples impregnated with MMA and radiation polymerized. Impregnated reinforced concrete showed very little chloride penetration after exposure to brine for 5 weeks.

Preliminary design studies using three dimensional finite element structural analysis methods in conjunction with computer code computations were made for PIC precast bridge decks. The results indicate that thin, durable decks can be suitably designed and fabricated. However, additional structural property data under static and dynamic conditions for the temperature range -40° to 120°F (-40 to 49°C) are required before a detailed design can be undertaken.

Techniques have been developed for producing lightweight insulating-type composites with uniform polymer distributions. Three lightweight aggregates, perlite, vermiculite, and foamed glass, were evaluated and perlite was selected for continued evaluation. Two monomers, MMA and polyester-styrene, were used in these studies.

Structural properties equivalent to or greater than those of high-quality normal weight concrete have been obtained with composites containing 50 to 60 vol % polymer. The densities of these materials range between 60 and 75 lb/ft^3. A test series of non-air-entrained 1:8 perlite concrete specimens impregnated with MMA exhibited average compressive, tensile splitting, and flexural strengths of 7700, 1328, and 1700 psi, respectively. Samples impregnated with polyester-styrene have lower strengths than MMA-impregnated specimens.

Freeze-thaw tests of impregnated lightweight materials are in progress but data are not yet available. Testing in 5% H_2SO_4 has indicated no attack after exposure for 120 days.

Preliminary designs for breakaway luminaires constructed with impregnated perlite concrete have been made and a 5-ft. prototype section has been constructed. Based upon this work, the fabrication of larger sections appears to be technically feasible.

Techniques are being developed to polymerize monomers at ambient conditions by use of catalyst-promoter systems. To date methyl methacrylate, polyester-styrene, 60 wt % styrene - 40 wt % TMPTMA, and 70 wt % methyl methacrylate - 30 wt % TMPTMA have been completely polymerized at 70°F (21°C). When developed, these techniques should have wide application in field-type impregnations such as on bridge decks.

CONCRETE-POLYMER MATERIALS FOR HIGHWAY APPLICATIONS

PROGRESS REPORT NO. 2

1. INTRODUCTION

1.1 Description of AEC Program on Concrete-Polymer Materials

The Concrete-Polymer Materials Program was initiated by the Division of Isotopes Development* of the U. S. Atomic Energy Commission (AEC) in 1967 as a cooperative research and development program between the Department of Applied Science of Brookhaven National Laboratory (BNL) and the U. S. Department of the Interior's Bureau of Reclamation (USBR). The program has been supported by the AEC and the Department of the Interior since that time. In 1969 the Federal Highway Administration (FHWA), U. S. Department of Transportation, initiated support for work at BNL on the use of concrete-polymer materials for highway applications.

The long-range objectives of the program are the investigation and development of concrete-polymer composite materials for use as improved and new materials of construction. At this point at least four distinct types of material are being actively investigated: (1) polymer-impregnated concrete (PIC), consisting of a precast portland cement concrete impregnated by a monomer system that is immediately polymerized; (2) polymer-

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* Reorganized as part of Isotopes Development, Division of Applied Technology as of December 1971.

cement concrete (PCC), consisting of a monomer added to a water-portland cement-aggregate mix that is subsequently polymerized as the concrete hardens; (3) polymer-concrete (PC) consisting of an aggregate mixed with a monomer and subsequently polymerized in place; and (4) precast concrete which is partially impregnated to produce an in-depth polymer coating. For each of these main types, process variations can be introduced to change the properties and characteristics of the materials.

The main effort, and the most successful in improving the structural and durability properties of a portland cement concrete, has been with PIC.

PIC is generally prepared by impregnating precast concrete with a liquid monomer and polymerizing the resin in the hardened concrete by radiation or by thermal-catalytic techniques. The polymer tends to fill the porous void volume of the concrete, which results in significant improvements in strength and durability properties. For a concrete mix that produces specimens with a compressive strength of 5000 psi, compressive strengths >30,000 psi have been measured after impregnation. Great improvements in the tensile strength, modulus of elasticity, modulus of rupture, and hardness are also obtained. Water absorption and permeability are reduced to negligible values, and resistance to chemical attack by distilled water, sulfate brines, and acids is markedly improved. Four topical reports describing the preparation and testing of these materials have been published.[1-4]

1.2 Description of FHWA Program

Because of the favorable results obtained in the AEC Concrete-Polymer Program, the FHWA in conjunction with the AEC and BNL conducted several preliminary tests early in 1969. During the period January 1969 to December 1971 several types of concrete were impregnated at BNL and placed under test at BNL and FHWA. High-strength concretes containing different types of aggregate, low-strength, structural lightweight, and insulating lightweight concretes were investigated. In addition to structural tests, durability tests such as abrasion, scaling, warping, freeze-thaw, and salt penetration are being performed. Tests on partially impregnated sections of highway concrete are also being made. The experimental effort is designed as a materials development program to yield data that can be used for the design of highway-type structures. In support of this effort, preliminary design studies were made to establish the necessary experimental data and to develop design criteria and methods for the use of PIC. Preliminary results indicate that PIC will have application in precast bridge decks and support structures. The potential for the repair of deteriorated bridge decks has also been demonstrated.

Two reports describing work performed in this program through June 1970 have been issued.[5,6] The present report describes work accomplished through December 1971.

1.3 Summary of Previous FHWA Work

The principal findings in the first progress report[5] are summarized below.

Large improvements in the structural and durability properties of highway-quality concrete were obtained by monomer impregnation and in situ polymerization by either radiation or thermal-catalytic means.

Samples of conventional weight concrete with high and low water/cement ratios, and structural lightweight concrete were prepared by the FHWA and impregnated at BNL. Five types of insulating-lightweight concretes (two perlite mixes, vermiculite, foamed glass, and foamed cement) were also tested.

Significant improvements in strength were obtained with high- and low-strength concretes. An average compressive strength of 16,630 psi was obtained for high-quality specimens containing 4.9% MMA. Compared with the control strength of 6445 psi, this corresponds to an improvement factor of 2.6. The impregnation of low-strength concrete produced composites with average compressive and tensile splitting strengths of 10,100 and 1655 psi, respectively. Compared with the controls, these represent improvement factors of $\approx$3. The degree of improvement obtained, although high, was lower than expected and was probably due to excessive monomer evaporation and drainage during polymerization.

Abrasion and skid resistance measurements were made on specimens partially impregnated with polyester-styrene. Compared with the control, the resistance to abrasion was improved by a factor of 2. Little difference in skid resistance was apparent.

The impregnation of structural lightweight concrete with MMA produced composites with the highest strengths of all the FHWA-type materials. Compressive and tensile splitting strengths of 18,160 and 2060 psi respectively, were obtained. These correspond to an improvement factor of $\approx$3.3.

The structural and durability properties of impregnated insulating-type concretes were measured. Specimens containing perlite aggregate produced the greatest improvements in strength and the largest strength-to-weight ratio. Compressive and tensile splitting strengths up to 5000 and 1000 psi, respectively, were obtained for samples of 1:6 perlite concrete. These correspond to an improvement factor of $\approx$20. The density of the composites ranged between 50 and 60 lb/ft^3. All the impregnated materials exhibited structural properties approximately equal to or slightly less than those of the nonimpregnated low-strength or structural lightweight materials of the FHWA-type, with reductions in weight of $\approx$40 to 60%. The data were not readily reproducible, and the specimens exhibited poor freeze-thaw durability. Efforts were underway to prepare high-quality specimens and to develop impregnation techniques that yield composites with a uniform polymer distribution and a hard, continuous polymeric coating. Preliminary results with polyester-styrene appeared encouraging. Specimens with densities of 72 lb/ft^3, strengths of ≈5000 psi, and <3% water absorption were produced.

Preliminary design studies using computer-coded finite element methods were made to determine the feasibility of using PIC for precast bridge decks and breakaway lampposts. On the basis of the limited data on properties, both applications appeared feasible.

1.4 Current FHWA Program

In the current report, data are presented on the effect of aggregate composition and size on the structural properties of FHWA-type materials impregnated with MMA. Data on durability properties such as freeze-thaw and chloride ion penetration are also presented. Measurements of the resistance of partially impregnated specimens to scaling and freeze-thaw have been made.

Improved techniques have been developed for the full and partial impregnation of highway-quality concretes. Techniques for the fabrication and impregnation of insulating-type lightweight concrete specimens have been developed and the structural properties under static and dynamic conditions measured.

A field experiment to investigate the feasibility of repairing deteriorated concrete bridge decks was performed and the results are discussed.

2. MONOMER SURVEY

2.1 Monomer Properties

Two important monomer properties for proper impregnation of concrete are viscosity and cure time. Low viscosity monomers are generally necessary for full impregnation of sound concrete and more viscous monomers are generally preferred for partial impregnation or for deep impregnation of deteriorated concrete. However, in the field where the concrete may not be completely dry, or under other conditions, the viscosity requirements may vary and monomer systems representing wide ranges of viscosity would be highly desirable.

For practical use of polymers in concrete a rapid and complete polymerization (cure time) of the monomer is necessary. For field applications, the ideal polymerization method is one in which the monomer polymerizes at ambient temperature within a predictable time following application. This can be accomplished with some monomer systems by use of catalyst-promoter combinations. For in-plant impregnation of precast concrete, it may be more desirable to use the catalyst-heat or radiation method. In general, a selected monomer system should be versatile with respect to both viscosity and ability to be polymerized.

2.2 Monomers for Highway Applications

Several monomer systems have been selected for FHWA applications on the basis of viscosity and ability to be readily polymerized. These systems are MMA, polyester-styrene, 60 wt% styrene-trimethylolpropane trimethacrylate (TMPTMA), and 70 wt% MMA - 30 wtT TMPTMA. Each system can be polymerized in the presence of concrete with conventional catalysts and heat, by radiation, or by the use of a catalyst-promoter system at ambient conditions. For complete impregnation of precast specimens, MMA polymerized by radiation or heat and catalyst has been used in most of the work in this study. However, since a catalyst-promoter system appears more practical for field impregnation of bridge decks, the major effort has been to develop these systems for the monomers mentioned above.

The most versatile monomer systems for possible FHWA applications are polyester-styrene resins. These resins can be easily cured by catalyst-promoter methods over a range of temperatures (see Table 2). The viscosity of polyester-styrene can be varied by dilution with styrene monomer without seriously affecting the system's desirable properties. The effect of styrene dilution on viscosity and gel time of polyester-styrene mixtures is given in Table 2. The gel times for the system can also be varied by adjusting the concentrations

Table 2

Effect of Temperature and Dilution on Gel Time for a Polyester-Styrene Resin System

Polyester-Resin[a] concentration, wt %	Styrene, wt %	Viscosity, cps at 76°F	Gel time, min[b]			
			40°F	50°F	60°F	75°F
100	0	670	7.4	5.4	4.3	3.2
75	25	68.5	9.5	7.9	6.5	5.0
50	50	10.3	22.5	18.9	15.4	11.0
25	75	2.4	87.4	67.7	53.2	45.5

(a) Marco Co. resin GR 941.

(b) Catalyst, 1.0 wt % methylethyl ketone peroxide;

Promoter, 0.4 wt % cobaltous bromide acetophenone azinate.

of the promoter-catalyst system or by using combinations of catalyst promoter systems other than that shown in Table 2.

Several other monomer systems studied, shown in Table 3, have lower viscosities than polyester resins and therefore may be more suitable for field-type impregnations. Catalyst-promoter systems for ambient temperature polymerization of these monomers have recently been developed at BNL.

The indicated gel and cure times of the monomer systems shown in Table 3 will vary with the concentrations of catalyst and promoter. The ambient temperature will also have a strong effect on these characteristics.

Table 3

Ambient Temperature Polymerization Conditions for Low-Viscosity Monomers

Monomer mixture	Viscosity cps at 77°F	Promotor, wt %	Catalyst wt %	Gel time, min	Cure time, min
60 wt % styrene - 40 wt % TMPTMA[a]	2.0	0.5% N,N-dimethyl-p-toluidine + 0.5% dimethyl analine	1.0% benzoyl peroxide	15	45
70 wt % MMA - 30 wt % TMPTMA	1.9	1.0% N,N-dimethyl-p-toluidine	1.0% benzoyl peroxide	8	14
MMA[b]	0.5	0.5% N,N-dimethyl-p-toluidine + 0.5% dimethyl aniline	0.5% benzoyl peroxide + 0.5% AIBN[c]	20	60

(a) Trimethylolpropane trimethacrylate

(b) Methyl methacrylate

(c) Azobis isobutyronitrile

3. PREPARATION OF SPECIMENS

Previous work by BNL, USBR, and the FHWA[1-5] showed great improvements in the properties of concrete after impregnation with monomer and in situ polymerization. As part of the continuing FHWA-sponsored materials development program, various concretes, using both high and low water/cement ratios and various aggregates were prepared for impregnation and test to determine the effects on the final strengths of the composite material. The methods of preparation for each of these materials are discussed below.

3.1 Structural-Grade Concrete

Three grades of concrete were prepared for impregnation and evaluation by several test methods: (1) high-strength, low water/cement ratio; (2) a lower-strength, high water/cement ratio concrete made with a good-quality limestone aggregate; and (3) low water/cement ratio lightweight structural concrete made with high-quality lightweight aggregates.

The mix proportions for each of the concretes and the determinations of slump and air content are shown in Tables 4 and 5. In general, specimens of two sizes, 3-in.-diam. x 6-in.-long cylinders and 3x4x16-in. beams, were cast. The cylinders were used in compressive and tensile splitting tests. Flexural

Table 4

Mix Data for Normal Weight Concrete

	Aggregate Type						
	Air-entrained		Non-air entrained				
	Clear Creek gravel[a]	Riverton limestone	Riverton limestone	White Marsh gravel	Diorite	Kansas limestone	Riverton limestone
Cement, lb	10.0	100	100	100	100	100	100
Sand, lb	248.4	230.7	230.9	189.1	214.7	213.3	346.1
Aggregate, lb	332.7	308.6	308.6	332.7	329.4	319.9	425.0
Water, lb	51.0	52.4	52.9	49.17	42.2	48.2	84.3
Water/cement (by wt.)	0.51	0.52	0.53	0.49	0.42	0.48	0.84
Slump, in.	3.2	3.3	3.2	2.5	2.5	2.4	7.8
Air, %	6.6	5.1	2.0	1.7	2.2	2.5	1.5
Wet density, lb/ft^3	139.7	146.5	150.5	148.9	153.9	146.0	147.7

(a) Standard concrete mix used at USBR in concrete-polymer program.[1] Identified as CP-Type concrete.

Table 5

Mix Data for Structural Lightweight Concrete

	Aggregate type			
	Sintered fly ash	Slag, size 3/4-in. to No. 4	Slag, size 3/8-in to No. 4	Solite (expanded shale)
Cement, lb	100	100	100	100
Sand, lb	219.8	197.7	251.0	168.1
Aggregate, lb	166.8	196.5	112.1	128.8
Water, lb	89.1	51.7	55.0	57.3
Water/cement (by wt.)	0.89	0.52	0.55	0.57
Slump, in.	2.7	3.1	2.9	3.2
Air, %	8.0	2.0	3.0	2.0
Wet density, lb/ft^3	117.0	138.7	132.0	121.6

strength and freeze-thaw durability tests were performed with the beams. A portion of each mix was retained at the FHWA for use as controls and a portion was sent to BNL for impregnation and polymerization. Some of the impregnated samples were tested at BNL; the remainder were tested at the FHWA. Impregnation methods for each type of material and test results are discussed in subsequent sections of this report.

3.2 Neat Cement Paste

Specimens of neat cement paste 1x1x4-in. were prepared at the FHWA for use in salt intrusion tests. For these samples, a type I cement and a water/cement ratio of 0.5 were used. Curing was done in a moist cabinet at 70 $^{\circ}$F (21 $^{\circ}$C) for 14 days. The results from these tests are discussed in Section 5.2.5.

3.3 Lightweight Insulating-Type Concrete

Concrete-polymer materials produced by the impregnation of insulating-type concretes are of great interest because of the potential for obtaining a lightweight, high-strength building material. Potential applications include precast bridge decks, wall panels, and breakaway lampposts.

Three lightweight insulating-type materials have been evaluated: perlite, vermiculite, and foamed glass. Mix data for perlite and vermiculite are shown in Table 6, and typical mechanical properties are summarized in Refs. 5 and 7. The structural properties of the materials after impregnation with MMA and polyester-styrene are given in Section 5.4.

Specimens made from vermiculite and foamed glass were obtained from W. R. Grace and Company and Pittsburgh Corning Corporation, respectively. The preparation methods for these materials were given in the first progress report.[5] All the perlite specimens were fabricated at BNL.

Perlite aggregate combined with type II portland cement and water in varying proportions produces an ultra lightweight insulating-type concrete with a density range from 18 to 36 lb/ft^3. The mix designations listed in Table 6 and subsequent sections (example, 1:8 perlite) indicate the proportion of cement to perlite or vermiculite on a volume basis.

Table 6

Mix Data for Insulating-Type Lightweight Concrete

	1:8 Perlite,[a] non-air-entrained	1:8 Perlite	1:6 Perlite	1:5 Perlite	1:8 Vermiculite
Cement, lb	100	100	100	100	100
Aggregate, lb	69.57	69.57	53.62	44.80	68
Water, lb	146.0	145.96	107.95	99.52	274.5
Air entraining agent, oz	0	41.0	31.7	26.4	4.3
Yield, ft^3	7.7	8.7	6.7	5.6	8.93
Wet density, lb/ft^3	40.5	36.6	39.3	44.0	49.6
Dry density, lb/ft^3	27.0	23.0	26.0	30.5	20.0

Note:

(a) Mix proportions by volume; 1 bag cement/8 bags perlite

An air-entraining agent is used to improve the workability with a lower water/cement ratio. The following two-step mixing process was used.

1. Prepare a slurry of cement, water and air-entraining agent. Mix for ½ min in a mortar mixer.

2. Add perlite and mix for an additional 2 min.

Detailed mixing procedures and mix measurements are described in Ref. 8.

After mixing, place the perlite concrete in the forms until each is ≈3/4 full. A stirring rod is then used to "swirl out" entrapped air from the sides of the forms. One or two wiping motions are generally required. The form is then filled and the concrete surface is struck off by using a screed or similar device. Tamping, vibrating, and excessive swirling are avoided. The samples are then cured at room temperature and humidity for 7 to 10 days.

4. METHODS OF IMPREGNATION AND POLYMERIZATION

4.1 Full Impregnation

The basic procedure for fully impregnating precast concrete, described in detail in Refs. 1 and 2, consists of oven-drying the concrete, evacuating the dried sample, soaking it in monomer, wrapping it, and polymerizing it. This procedure was used in the impregnation of high-quality FHWA-type concrete, and the results indicated average compressive strengths of 16,630 psi.[5] The degree of improvement obtained, although high, was lower than expected. Two possible reasons for the difference - concrete composition and poor impregnation due to evaporation and drainage - were given.

During the current report period, experiments were performed to determine the cause of the relatively small strength increase and to develop improved techniques. Experiments to study the effect of aggregate composition on the strength and durability properties of the composite were also performed; the results are discussed in Sections 5.2 and 5.3.

Experiments to develop improved impregnation techniques for FHWA materials are described below.

4.1.1 <u>Encapsulation Techniques</u>

One of the steps in the basic procedure in the laboratory for fully impregnating precast concrete has been to wrap the monomer-saturated specimens in polyethylene sheet or aluminum foil to reduce evaporation and drainage losses during the polymerization reaction. Evaporation is a problem when high vapor-pressure monomers such as MMA are used. Another mode of monomer loss is monomer drainage which takes place on standing between the time the specimen is impregnated and the time when the monomer is polymerized. This effect becomes appreciable when low density concretes are impregnated.[5]

In an attempt to reduce monomer evaporation and drainage to negligible values, the following encapsulation methods have been tested:

1. Encapsulation of the specimen in a form during impregnation and polymerization.

2. Polymerization with the monomer-saturated specimens inundated in water.

3. Impregnation with monomer followed by a pre-polymer dip, wrapping, and rotation during polymerization.

Each of these methods is discussed in subsequent sections of this report.

4.1.1.1 <u>In Forms</u>

A series of experiments was performed in which oven-dried specimens were placed in close-fitting glass forms prior to evacuation and saturation with monomer. With use of this technique, the specimens were completely immersed in monomer throughout the polymerization reaction. After polymerization, the forms and the excess polymer were removed. Specimens of high-strength concrete containing Riverton crushed limestone or White Marsh gravel were tested. In addition, specimens of USBR prepared high-pressure steam-cured CP-type concrete and fog-cured non-air-entrained concrete were evaluated.[4] Mix data for these specimens were given in Table 4. All the specimens were oven-dried at 221°F (105°C), impregnated with MMA by the vacuum-soak technique, and radiation polymerized. Experimental data for the samples are given in Table 7. All the specimens impregnated in the forms exhibited higher polymer loadings and higher compressive strengths than the corresponding samples which had been wrapped in foil prior to polymerization. The Riverton crushed limestone and White Marsh gravel specimens had compressive strengths of 19,030 and 21,810 psi, respectively. The strengths are similar to those obtained by underwater polymerization (see Section 4.1.1.2) and are the highest obtained to date with these aggregates. Similar results were obtained with specimens containing crushed diorite aggregate. These data are tabulated in Section 5.2. Data for lightweight insulating-type concretes are given in Section 5.4.

Table 7

High-Strength Concrete Impregnated in Glass Forms

Monomer, MMA.
Specimen size, 3-in.-diam x 6-in.-long cylinders.
All specimens oven-dried at 221°F (105°C) prior to impregnation
Radiation-induced polymerization.

Specimen No.	Specimen type	Encapsulation method[c]	Polymer loading, %	Compressive strength, psi
2.1.3-32	CP-type concrete, high-pressure steam-cured	F	8.7	27,260
2.1.3-10[a]	CP-type concrete, high-pressure steam-cured	W	7.1	23,200
7-65	CP-type concrete without air-entraining agent	F	10.0	24,400
7-61[b]	CP-type concrete without air-entraining agent	W	6.2	18,980
95836	FHWA concrete containing Riverton limestone aggregate	F	5.3	19,030
95393-401[a]	FHWA concrete containing Riverton limestone aggregate	W	5.1	14,210
95821	FHWA concrete containing White Marsh gravel aggregate	F	4.8	21,810
95360[a]	FHWA concrete containing White Marsh gravel aggregate	W	4.2	15,900

(a) Average of five specimens.

(b) Average of three specimens.

(c) F, impregnated in glass forms by using vacuum-soak technique
W, impregnated by using vacuum-soak technique and wrapped in foil.
CP-type concrete made at USBR.[1]

Experiments have also been performed in which the concrete specimens were impregnated directly in the forms in which they were originally cast. Initial experiments were conducted using 3-in.-diam x 6-in.-long cylinders of CP-type concrete contained in glass and cardboard forms. Tests were also performed with 6-in.-diam x 12-in.-long cylinders containing White Marsh gravel. The latter were contained in disposable metal forms.

All specimens were dried at 221°F (105°C), impregnated with MMA by use of the vacuum-soak technique, and radiation polymerized. The results indicated an average polymer loading and compressive strength of 3.8% and 12,000 psi, respectively, both considerably lower than expected. Visual examination of the samples revealed that the center portion of the cylinders had not been impregnated. Subsequent work has shown the cause to be inadequate drying before impregnation.

Two 6-in.-diam x 12-in.-long cylinders in disposable metal forms were impregnated after being dried to constant weight. Two drying temperatures, 230°F (110°C) and 302°F (150°C), were used. Because of the small surface area exposed, drying times of 13 and 7 days, respectively, were required. A control experiment was also conducted in which a similar specimen was removed from the form prior to drying. As expected, a much shorter time was required to reach constant weight (1 day at

302°F [150°C]). The results from these experiments are given in Table 8. Specimen No. 432, which was dried at 302°F (150°C) while contained in the fabrication form, exhibited a compressive strength of 18,950 psi, or approximately that of the comparison sample (No. 431) that had been removed from the form prior to drying. Specimen No. 433, dried at 230°F (110°C), had a compressive strength of only 15,800 psi. In view of the smaller loss of weight during drying and the lower polymer loading, this specimen may not have been completely dried prior to impregnation.

The results of this study indicate that using a fabrication form to contain a specimen during impregnation is not practical for massive objects because of the severe drying conditions required.

4.1.1.2 Under Water

The feasibility of using water to reduce monomer evaporation and drainage from concrete specimens has been investigated. Preliminary data indicated that the compressive strengths of specimens radiation-polymerized while immersed in water were essentially the same as those of specimens wrapped in polyethylene and irradiated in air. The polymerization rate for specimens irradiated under water at 185°F (85°C) was three times greater than that for specimens

Table 8

High-Strength Concrete Impregnated in Fabrication Forms

Monomer, MMA.
Specimen size, 6-in.-diam x 12-in.-long cylinders.
Radiation-induced polymerization.
FHWA-type concrete containing White Marsh gravel aggregate.

Specimen No.	Impregnation method	Weight loss on drying, %	Polymer loading, %	Compressive strength, psi
431	Dried outside form at 302°F (150°C) and impregnated in form	4.8	5.1	18,600
432	Dried in form at 302°F (150°C) and impregnated in fabrication form	5.1	5.4	18,950
433	Dried in form at 230°F (110°C) and impregnated in fabrication form	4.3	4.3	15,800

irradiated at 68°F (20°C) either in water or in air.[2]

Additional experiments have recently been performed. MMA-saturated specimens were immersed in ≈2 ft of water immediately after removal from the impregnator, and polymerization was initiated with gamma radiation. During the reaction, a small amount of monomer was observed floating on the surface of the water; after polymerization, white powdery PMMA was apparent on the surfaces of the specimens. Sectioning of the specimens revealed that the samples were completely impregnated and little evaporation loss from the surfaces was apparent. The measured polymer loadings were greater than those normally obtained for specimens of similar density which were wrapped and irradiated in air.

A program was started to determine the effects of the presence of water during the polymerization reaction on the structural and durability properties of the composite. Specimens of FHWA-type concrete were impregnated with MMA and polymerized by radiation while in contact with water. Solite specimens and samples containing slag, Riverton limestone, White Marsh gravel, and diorite aggregate were tested. These data (tabulated in Sections 5.2 and 5.3) indicate in general that under water polymerization has no detrimental effect on the properties and may be advantageous because of reductions in monomer loss due to evaporation and drainage.

The results of the under water polymerization method were at least comparable to those from using forms when high-density ($\approx$140 lb/ft^3) materials containing limestone, White Marsh gravel, and diorite were impregnated. Forms were more effective for lower density materials such as Solite (density, $\approx$104 lb/ft^3), and specimens containing slag (density, $\approx$135 lb/ft^3). Low-density materials are more susceptible to drainage losses, and these can be reduced to negligible values by using forms. However, the differences in strength are not large (<15%), and therefore the additional cost associated with the use of forms would probably not be warranted.

4.1.1.3 Pre-polymer Dip and Rotation

The use of a pre-polymer dip in conjunction with the standard vacuum-soak impregnation method and subsequent rotation of the specimen during polymerization has also been evaluated as a means of reducing drainage losses. Experimental data from these tests are given in Table 9. In general, although the strengths were similar to those obtained with the under water and form techniques, the necessity of rotating large numbers of heavy specimens would appear to make this method impractical. However, for special applications, such as the impregnation of pipe prepared by the roller suspension process, the technique appears to be readily adaptable.

Table 9

Comparison of Encapsulation Techniques - Strength Determinations

Monomer, MMA.
Radiation-induced polymerization.
Specimen size, 3-in.-diam. x 6-in.-long cylinders.
All concrete samples fog-cured 7 days.
All specimens dried to constant weight at 230°F (110°C).
Vacuum-soak impregnation.

Sample no.	Encapsulation method	Type of Aggregate[a]	Dry density lb/ft^3	Polymer loading, %	Polymer content vol %	Compressive strength, psi	Tensile splitting strength, psi	Improvement[b] %
Control	-	RL	-	0	0	5690	700	-
Control	-	WM	-	0	0	5580	600	-
95838	Excess monomer, in forms	RL	142	5.1	9.8	18970	-	233
40	"	RL	142	5.1	9.8	-	1555	120
36[c]	"	RL	145	5.3	10.4	19030	-	234
21	"	WM	142	4.8	9.2	21810	-	290
22	"	WM	142	5.4	10.4	-	2135	255
34	Under water	RL	147	5.3	10.6	-	1890	170
46	"	RL	144	5.9	11.5	18280	-	221
16	"	WM	142	5.4	10.4	20500	-	267
18	"	WM	143	5.3	10.3	-	1870	211
45	Wrapped and rotated	RL	141	5.8	11.1	-	1500	114
47	"	RL	147	5.7	11.4	17470	-	207
19	"	WM	142	5.5	10.6	21870	-	291
20	"	WM	143	5.2	10.1	-	1995	232

(a) RL = Riverton limestone; WM = White Marsh gravel.

(b) % = [(test-control)/control] 100.

(c) Tested at BNL.

4.2 Partial Impregnation

4.2.1 Laboratory Studies

Partially impregnated concrete is designed for durability rather than high strength, and as a result less monomer is required than for fully impregnated concrete. The polymer should effectively seal off the surface and penetrate to a sufficient depth to prevent separation of the impregnated layer and cause premature failure. Preliminary techniques for the impregnation of high-strength concrete specimens from the top surface to depths of 3/8 and 3/4 in. were described in the previous progress report.[5] A ponding technique was used for partial impregnation with MMA, and pressurization was required when polyester-styrene was used. For the latter, the dried concrete samples were sealed with silicon rubber into a metal frame. The seal prevented the monomer from leaking past or diffusing into the specimen through the sides. After the rubber had been cured, the frame was covered and sealed. The monomer, containing 1.0 wt % benzoyl peroxide initiator was introduced through the top. After soaking under 100 psig air, for a predetermined time, the samples were removed from the frame and polymerized in an oven at $167^{o}F$ ($75^{o}C$). Test data obtained during the current report period are given in Section 5.5. Examination of the specimens indicated that viscous monomer systems such as polyester-styrene are best suited for this application because the penetration depths are more easily controlled, voids in the penetrated portion remain filled, and monomer losses due to evaporation and drainage during the time between impregnation and complete polymerization are lower.

During the current report period the pressurization technique was changed to improve control and reproducibility of the depth of penetration. Water absorption measurements made prior to impregnation make it possible to calculate the amount of monomer required for any depth of penetration. The calculated quantity of monomer is placed on the surface to be impregnated and pressure is applied. After all the monomer has soaked into the concrete, polymerization is initiated. A soak time of ≈5 hr under 100 psig pressure was required to obtain a 3/4-in. penetration with a 67.5 wt % styrene - 32.5 wt % polyester mixture (viscosity 9 cps).* A sectioned specimen impregnated to a depth of 3/4 in. is shown in Figure 1. Compared with the earlier procedure of soaking followed by drainage of excess monomer, the revised procedure results in greater control and reproducibility of the depth of penetration.

Work to develop impregnation procedures requiring less severe conditions is under way. Emphasis is being placed on

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*Formulated by diluting Plaskon 941 (65 wt % polyester - 35 wt % styrene). Composition: 50 wt % styrene - 50 wt % Plaskin 941.

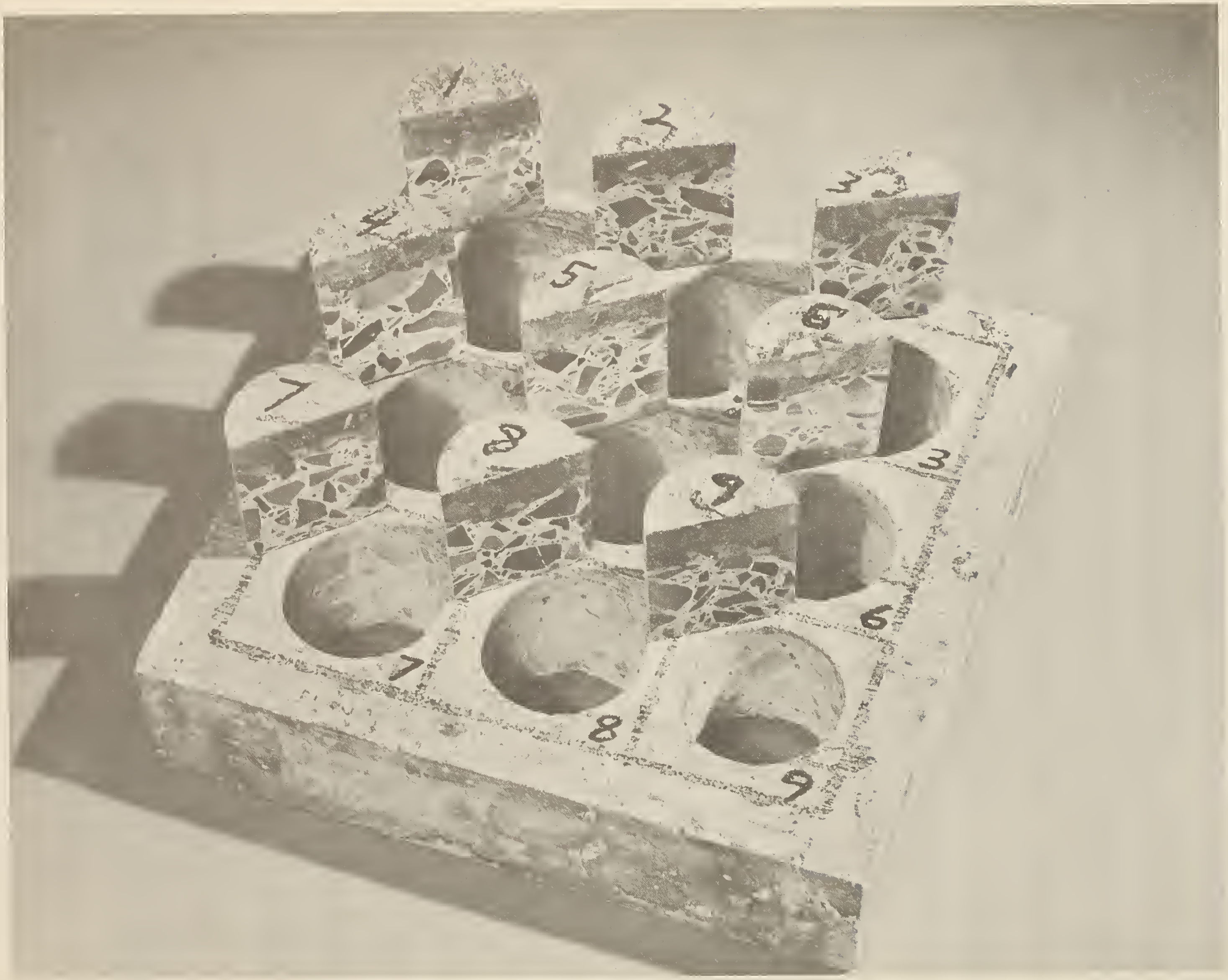

Figure 1

Cross sections of core samples taken from a highway-quality concrete slab partially impregnated with 67.5 wt % styrene - 32.5 wt % polyester on one surface to a depth of 3/4 in.

impregnation at lower pressures, including evacuating and then applying atmospheric pressure as well as by drying and then soaking with monomer. Methods of drying are also under investigation. A number of low viscosity systems, MMA, 70 wt % MMA - 30 wt % TMPTMA, 60 wt % styrene - 49 wt % TMPTMA, and 90% styrene - 10% polyester, are being investigated. These systems have viscosities <2 cps, and ambient-temperature polymerization methods are being developed (see Section 2.2).

4.2.2 Field Studies

Preliminary experiments were performed to determine the feasibility of repairing deteriorated bridge decks in situ by partial impregnation and polymerization. In conjunction with the FHWA and the Kansas State Highway Department, two bridges in Kansas were selected as test sites. Two types of failure, deteriorated mortar and delaminated concrete, were studied.

The experiments with deteriorated mortar were conducted on Bridge No. 24-52 10.6 on Highway 24 near Tonganoxie, Kansas. This bridge is about 418 ft long, 28 ft wide, and 15 in. thick. Several years ago it had been overlaid with 4 in. of asphalt. The hubguards along both sides of the bridge were also badly deteriorated in certain areas.

At the time, the most appropriate monomer system for this application was judged to be polyester-styrene. The advantages of this system are that it can be polymerized at ambient temperature in a relatively short time and the viscosity of the basic resin system can be varied by dilution with styrene monomer to produce mixtures having different diffusion rates through concrete.

The three polyester-styrene mixtures described below were used in the field tests. All proportions are given in wt %.

(1) 50% styrene monomer
50% polyester resin, trade name Marco GR37X
0.5% cobalt naphthenate (accelerator)
0.5% methyl ethyl ketone (MEK) peroxide (catalyst)

(2) 75% styrene monomer
25% polyester resin, Marco GR37X
1.0% cobalt naphthenate
1.0% MEK peroxide

(3) 90% styrene monomer
10% polyester resin, Marco GR37X
1.0% cobalt naphthenate
1.0% MEK peroxide

The first attempt to impregnate the deteriorated concrete areas beneath the asphalt was made by drilling several 1-in.-diam x 7½-in.-long holes in the deck and filling them with the 90% styrene - 10% resin mixture. Since this material had the lowest viscosity (≈1.8 cps), it was expected to readily diffuse into the concrete rubble. However, the holes remained filled and very little resin appeared to penetrate the deck. It was later determined that the rubble beneath the asphalt was practically saturated with water, which therefore may have prevented diffusion of the resin at atmospheric pressure. Dust from the drilling that was left on the sides of the holes may also have prevented the monomer from soaking into the deck.

In a subsequent experiment, the asphalt layer over a 31 x 31-in. area was removed. The exposed concrete was highly deteriorated for a depth of ≈6 in. and could be scooped up by hand. In some areas the reinforcing steel was exposed. Before the rubble in the exposed area was allowed to dry, 2 gal of the 90% styrene - 10% resin mixture were applied to the surface. Within several minutes the resin had been absorbed. This was followed with 1 gal of the more viscous (≈10 cps) 50% styrene - 50% resin mixture, which was also readily absorbed by the rubble. A polymer-concrete consisting of 80 wt % sand and 20 wt % of the 50% styrene - 50% resin mixture was then trowled onto the surface, to produce a 2-in.-thick overlay.

Test cores were cut from the center of the treated section. The results indicated a 2-in.-thick hard coherent top layer, due mainly to the polymer-concrete. With increasing depth, the coherence of the impregnated deteriorated cement diminished. All the cores had an odor of styrene. Cores taken farther away from the center showed progressively less polymer impregnation. Perimeter cores could not be recovered because of crumbling. The failure to form a cohesive material throughout can be attributed to either the presence of water or insufficient polymer impregnation.

Delaminated concrete was studied on a bridge located on Interstate 470 over 29th Street, Topeka, Kansas. The main problem here was delamination of the concrete at the level of the top mat of reinforcing steel. After locating several delaminated regions with use of an impact hammer and the chain-drag test, two 1-in.-diam x 3-in.-deep holes were drilled 4 in. apart. A 50% styrene - 50% polyester resin mixture was poured into one hole until the horizontal crack appeared to be full and the resin mixture flowed into the adjacent hole.

Another hole was drilled in a large delaminated area and filled with a 90% styrene - 10% polyester resin mixture, fed into the hole through an 18-in.-long, 0.5-in.-i.d. metal pipe. About 1 gal of resin was added. Pressure from a bicycle pump was then used to force more resin into the deck. After polymerization, soundings made by the impact hammer and chain-drag technique indicated that the delaminated regions had been filled.

Conclusions and recommendations based on these tests are listed below.

1. The impregnation of deteriorated concrete and delaminated bridge decks appears feasible, although extensive development work is required. Monomer systems that will penetrate the sound concrete sublayer under atmospheric pressure conditions and can be completely polymerized at ambient temperature should be developed.

2. The effects of moisture on the above variables should be determined and drying techniques developed, if necessary.

3. It appears feasible to repair delaminated bridge decks by pumping monomers into the void regions and polymerizing *in situ*. Impregnation techniques and equipment should be developed and field-tested.

4. Polymer-concrete overlays on repaired bridge decks warrant continued study. The long-term durability of the overlays should be determined.

Work in each of these areas has been initiated and is in progress.

4.3 Polymerization Methods

4.3.1 Radiation-Induced Polymerization

It is well known that free-radical polymerizations can be initiated by ionizing radiation. Monomers that polymerize by this mechanism include MMA, styrene, and polyester-styrene.

Radiation-initiated polymerization has several unique advantages that make it of interest in the Concrete-Polymer Materials Program. Probably the most significant is that the initiation step is independent of temperature, so that polymerization can take place at ambient temperature, which minimizes evaporation of the monomer. In effect, the gamma rays act as the catalyst for the reaction and chemical initiators need not be added to the monomer prior to impregnation. This prolongs the monomer's shelf-life and eliminates the problems involved in the handling and storage of monomer-catalyst systems. Essentially unlimited re-use of excess catalyst-free monomer is possible if proper inhibitor concentrations are maintained.

The radiation process also has several disadvantages. Large amounts of biological shielding are required, and radiation-initiated polymerization rates are slower than those obtained by other methods. The radiation process seems better suited to the "in-plant" treatment of thin precast sections than to field-type processes. However, detailed design and economic studies for each specific application are required before a decision pertaining to the feasibility of using a radiation-process can be made.

4.3.2 Thermal-Catalytic Polymerization

The most widely accepted method for conducting free-radical-initiated polymerization reactions is to use a chemical initiator (described commercially as a catalyst) and heat the solution to an elevated temperature. At such temperatures, the chemical catalyst decomposes to form free radicals which in turn initiate the polymerization reaction. The decomposition temperature varies with the type of catalyst. In general, the higher the decomposition temperature of the catalyst, the longer the shelf-life of the catalyst-monomer mixture and the greater the safety. The vapor pressure of the monomer must also be considered when selecting a catalyst. The decomposition temperature of the catalyst must be less than the boiling point of the monomer.

A catalyst used extensively in the FHWA Concrete-Polymer Materials Program is benzoyl peroxide. The temperatures for initiating reactions with MMA range between 158° and 194°F (70° and 90°C), and complete polymerizations are obtained in several hours. Although the shelf-life for catalyst-monomer systems is reasonably long if temperature control is maintained, the possibility of a premature reaction always exists. In addition, the chemical catalyst or free radicals may interact with materials in the concrete. For example, complete polymerization of MMA could not be obtained in FHWA-high water/cement ratio concrete when benzoyl peroxide catalyst was used. For this reason, a study was made to select a catalyst that would function satisfactorily in this environment. Experiments have indicated that complete polymerization can be obtained by use of azo-type catalysts such as azobis isobutyronitrile and α-t-butylazoisobutyronitrile.

Since heat is required for the thermal-catalytic process, it appears that the technique will be most readily used as an "in-plant" process. Specialized field applications such as on bridge decks also seem feasible, since heat sources for drying the concrete prior to impregnation could probably be developed.

4.3.3 Catalyst-Promoter Techniques

A polymerization technique that does not require temperatures above ambient is the chemical catalyst-promoter system. A promoter or accelerator is a chemical material that induces decomposition of the catalyst. The polymerization rates or cure times can be controlled to some extent by varying the catalyst and/or the accelerator concentrations, or by varying the temperature. Normally, as the temperature is increased the polymerization rate increases. An accelerator, where applicable, eliminates the need for a radiation source or for elevated temperatures. The reaction can take place readily at room temperature. However, the proportions of catalyst and accelerator must be carefully controlled to avoid premature polymerization.

The monomer system most readily polymerized with a catalyst-promoter system is polyester-styrene. Techniques for polymerizing materials such as MMA, MMA-TMPTMA, and styrene-TMPTMA are being developed. This work was discussed in Section 2.2. When developed, catalyst-promoter systems will have wide application in field-type impregnations such as the repair of bridge decks.

5. TEST RESULTS

The structural and durability properties of concretes of varying composition that have been fully impregnated with MMA or polyester-styrene are being measured at BNL and the FHWA. The properties of specimens partially impregnated on one surface with polyester-styrene mixtures are also being measured. These are continuing tests, and only partial results are available (as of February 1972). The data are summarized below. Methods for the fabrication and impregnation of the test specimens were given in Section 3 and 4, respectively. When applicable, tests at the FHWA were made in accordance with ASTM procedures. Special tests are described in Reference 5.

5.1 BNL Testing Methods

5.1.1 Compression Tests

All compression tests on 3 in.-diam x 6-in.-long cylinders were made in accordance with ASTM Procedure C 39. Prior to testing, the ends of all unimpregnated specimens were covered with a high-strength (10,000 psi) capping compound and the ends of the impregnated cylinders were ground with a surface grinder. In both procedures the ends were parallel to within 0.002 in. All tests were made at a loading rate of 2000 psi/min. Strain measurements were made with use of type

SR-4 wire strain gauges attached to the specimens with epoxy cement. The gauge length used was always more than three times the size of the largest aggregate in the specimen. The loading rate for modulus of elasticity determinations was also 2000 psi/min. In all cases the measurements were recorded to failure.

5.1.2 Tension Tests

Both direct tensile and tensile splitting tests were used to determine the tensile strengths of impregnated and control concrete. Tensile splitting tests were performed in accordance with ASTM C 496. In the direct tensile tests the 3-in.-diam x 6-in.-long specimens were glued by use of an epoxy resin into steel cup-shaped end caps having a depth of at least 3/4 in. (see Figure 2). Strain measurements were made as described above for the compression tests. A load rate of 100-200 psi/min was used for the tensile splitting test and a rate of 700 psi/min was used for the direct tension test.

5.1.3 Fatigue Test

Fatigue tests on 2x2x20-in.-long beams of insulating-type perlite concrete impregnated with MMA and polyester-styrene were performed with use of a modified Instron 10,000-lb Universal Testing machine. The apparatus is shown in Figure 3. The beams were tested in cantilever with a moment arm of 13 in. Test

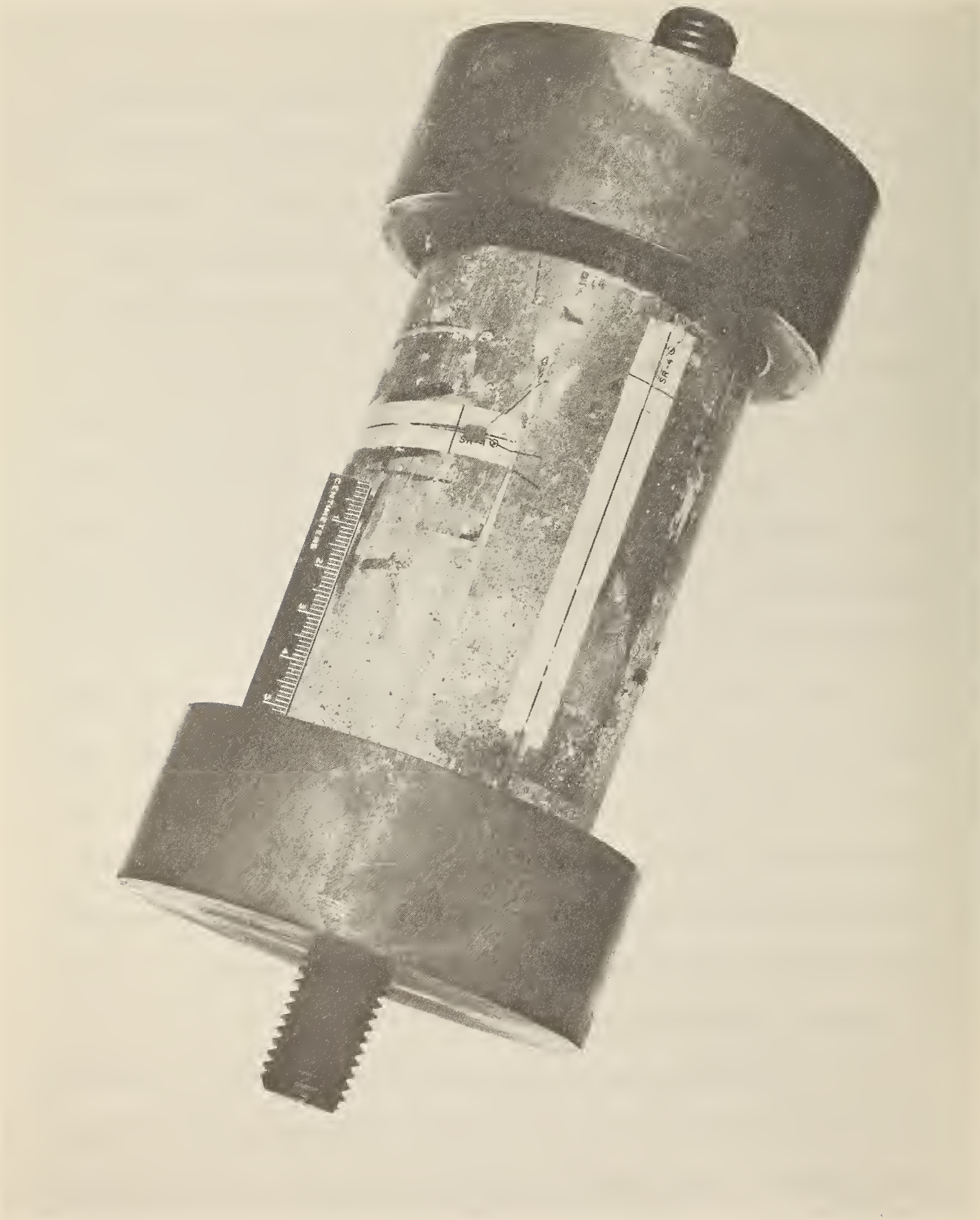

Figure 2

Impregnated concrete specimen in test configuration prior to direct tensile testing.

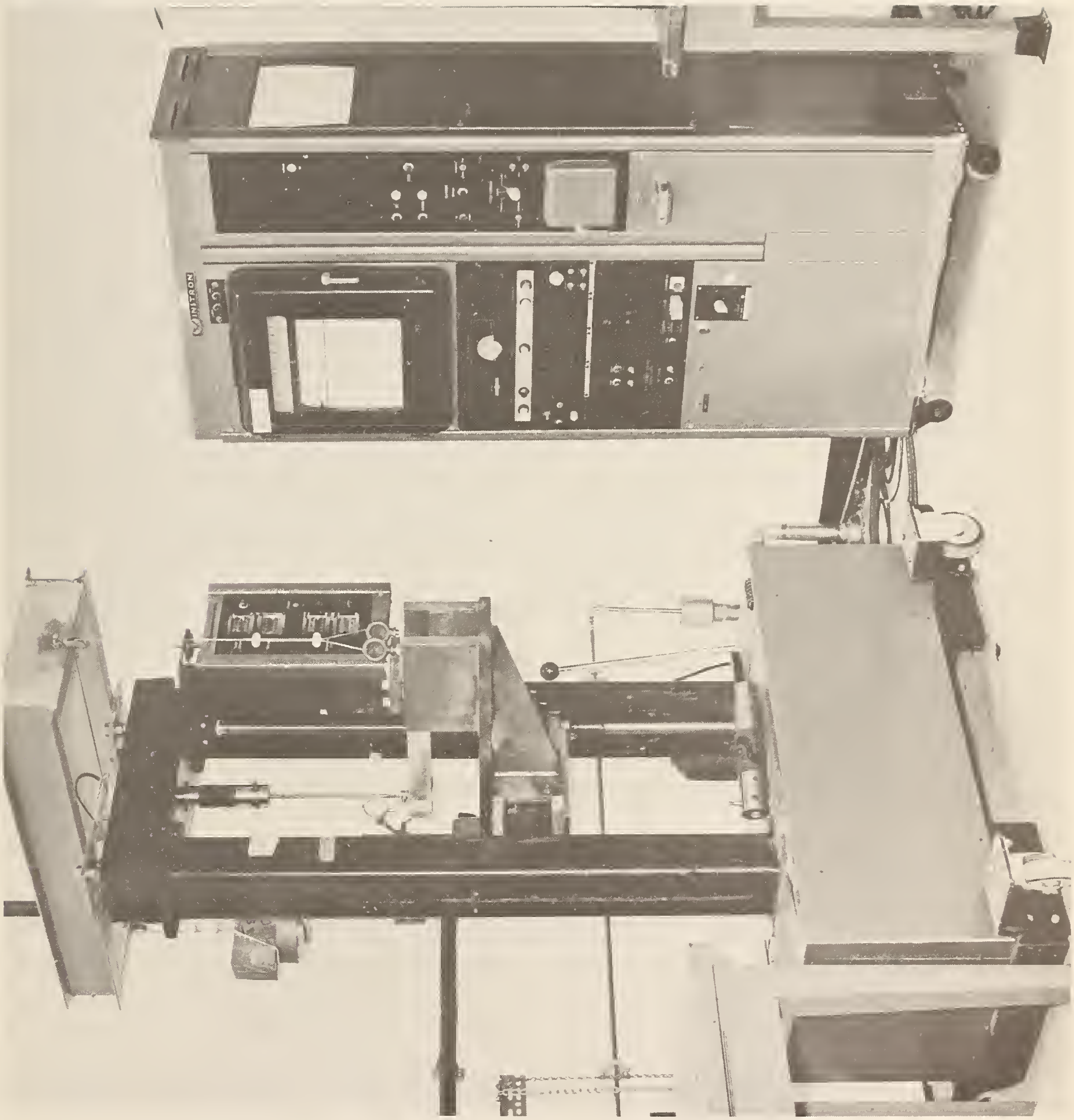

Figure 3

Equipment used for performing fatigue tests on impregnated insulating-type perlite concrete beams.

loads varying between 0.4 and 0.7 of the modulus of rupture were used. Cyclic rates were varied between 5 and 14 cycles/min.

5.2 Normal Weight Concrete

Previous work with Riverton limestone aggregate gave strength results that were lower than expected when compared with data obtained from the USBR for CP-type concrete. Several possible explanations were given for the lower results including the degree of impregnation and the porosity of the aggregate.

Early in this report period a screening test was performed in which concretes containing other aggregates were compared with Riverton limestone concrete. Samples of CP-type concrete made at the USBR and of FHWA concrete made from Riverton limestone or White Marsh gravel were impregnated with MMA by use of the standard vacuum-soak technique and radiation polymerized. These and all subsequent specimens were irradiated at a ^{60}Co intensity of 3.0×10^5 rads/hr to a total dose of $\approx 5 \times 10^6$ rads. All samples were impregnated at the same time and handled in a random manner. The results, given in Table 10, showed that samples made from CP-type concrete had higher strengths than the highway-type composites. The results from samples tested at the USBR differed appreciably from those tested at the FHWA, and these differences have not yet been resolved. It was evident, however, that the samples containing Riverton limestone had lower strengths than those containing White Marsh gravel.

Table 10

Summary of Results from Normal Weight Concrete Screening Tests

Strengths of Clear Creek Gravel, White Marsh Gravel, and Riverton Limestone Concretes

Monomer, MMA.
Radiation-induced polymerization.
All specimens dried to constant weight at 302°F (150°C).
Vacuum-soak impregnation.

Specimen no.	Aggregate	Dry density, lb/ ft^3	Polymer loading, %	Polymer content vol %	Compressive strength,(a) psi		Tensile splitting strength,(a) psi		Flexural strength,(b) psi	
CP-4A-11D(c)	CP	135	6.8	12.5	18,740		---		---	
12E	"	134	7.0	12.7	---		2016		---	
14D	"	134	6.9	12.6	---		1563		---	
CP-4B-11B	"	136	6.6	12.2	---		1981		---	
12C	"	135	6.8	12.5	18,370		---	Av. = 1853	---	
13F	"	137	6.4	11.9	22,200	Av = 20,106	---	S = ± 206	---	
11C(c)	"	136	6.6	12.2	21,710	S = ± 1606	---	V = 11.1%	---	
12F	"	136	6.7	12.4	19,510	V = 8.0%				
CP-1A-5(d)	"	137	5.7	10.6	---		---		2500	
95393	Riverton	143	5.1	9.9	12,870		---		---	
394	limestone	144	5.2	10.2	12,700		---		---	
395	"	144	5.0	9.8	12,940		---		---	
397	"	143	5.4	10.5	---		1504		---	
398	"	143	5.3	10.3	---		1456		---	
399	"	142	5.3	10.2	---		1015		---	
400(c)	"	143	5.1	9.9	16,340		---	Av. = 1312	---	
401(c)	"	143	5.1	9.9	16,200		---	S = ± 221	---	Av. = 1440
410	"	147	5.0	10.0	---	Av = 14,210	---	V = 16.8%	1550	S = ± 86
412	"	146	5.0	9.9	---	S = ± 1684	---		1430	V = 6%
417	"	146	4.6	9.1	---	V = 11.9%	---		1340	

Table 10 (cont'd.)

Specimen No.	Aggregate	Dry density lb/ ft^3	Polymer loading, %	Polymer content vol %	Compressive strength,(a) psi		Tensile splitting strength,(a) psi		Flexural strength,(b) psi	
95360	White Marsh	140	5.0	9.5	14,530		---		---	
61	Gravel	140	4.8	9.1	16,610		---		---	
62	"	143	4.5	8.7	12,370		---		---	
64	"	143	4.8	9.3	---		1490		---	
65	"	142	5.0	9.6	---		1539		---	
66	"	142	4.7	9.1	---		1734		---	
67(c)	"	142	4.8	9.3	17,110		---	Av. = 1588	---	
68(c)	"	142	4.9	9.4	18,950		---	S = ± 105.	---	
77	"	143	5.1	9.9	---	Av. = 15,914	---	V = 6.6%	2200	Av. = 2040
78	"	144	5.8	11.3	---	S = ± 2110	---		2060	S = ± 139
80	"	144	5.1	10.0	---	V = 13.3%	---		1860	V = 6.8%

(a) Specimen size, 3-in.-diam. x 6-in.-long cylinders.

(b) Specimen size, 3 x 4 x 16-in. bars.

(c) Tested at USBR.

(d) Data (average of 3 specimens) from Reference 1

Av. = average, S = standard deviation, V = coefficient of variation.

The results of water absorption measurements made on the fine and coarse aggregates used in the three concretes studied are as follows.

	Water absorption, %		
Aggregate type	Clear Creek	Riverton limestone	White Marsh gravel
Coarse aggregate	0.9	0.4	0.5
Sand	0.6	0.8	0.8[a]

The results from this low-quality concrete series are given in Table II. The compressive and tensile splitting strengths of samples prepared by the standard vacuum-soak and wrapping in foil technique were determined and compared with those of samples prepared by the vacuum-soak technique and then curing under water or in forms. Considerable improvement was obtained in all cases, although the wrapping method is apparently the least effective. Average compressive and tensile splitting strengths of 15,527 psi and 1515 psi were obtained by the underwater method. These results are comparable to those for fully impregnated high strength highway-type PIC. The higher strengths achieved with these low-strength samples, as compared with those reported previously,[5] are probably due to the reductions in drainage losses, and therefore higher polymer loadings,

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[a] This sand also used in Riverton limestone concrete.

Monomer, MMA.
Specimens oven-dried at 230°F (110°C).
Vacuum-soak impregnation.
Radiation-induced polymerization.
Specimen size, 3-in.-diam x 6-in.-long cylinders.
Aggregate, Riverton limestone.

Table 11

Compressive and Tensile Splitting Strengths for Low-Strength Concrete

Sample No.	Encapsulation method	Dry density, lb/ ft^3	Polymer loading, %	Polymer content, vol %	Compressive Strength, psi		Tensile splitting strength, psi		Difference %[(a)]
Controls[(b)]	-	-	0	0	2230		395		-
95618	Vacuum-soak	135	7.4	13.6	12,510		-		
622	"	136	7.5	13.9	12,280		-		
623	"	137	7.1	13.2	11,340		-		441
95624	"	135	7.3	13.4	-	Av. = 12,043	1965	Av. = 1737	
625	"	136	7.4	13.7	-	S = ± 506.	1775	S = 204	
626	"	136	7.4	13.7	-	V = 4.2%	1470	V = 11.7%	340
95318	Under water	135	7.8	14.3	17,030		-		
319	"	135	7.8	14.3	16,030		-		
317[(c)]	"	137	7.4	13.8	14,600		-		
321[(c)]	"	137	7.7	14.3	14,450		-		596
95320	"	135	8.0	14.7	-	Av. = 15,527	1545	Av. = 1515	
323	"	135	7.8	14.3	-	S = ± 1064	1425	S = ± 242.5	
322[(c)]	"	137	7.3	13.6	-	V = 6.9%	1210	V = 16.%	
324[(c)]	"	135	7.6	13.9	-		1880		283
96331	Excess monomer,	136	7.5	13.9	14,160		-		
332	in forms	136	7.2	13.3	15,110		-		
326[(c)]	"	135	6.7	12.3	15,700		-		
327[(c)]	"	136	6.6	12.2	16,200		-		586
96325	"	136	6.9	12.7	-	Av. = 15,292	1560	Av. = 1324	
329	"	135	7.7	14.1	-	S = ± 985.5	1460	S = ± 191.	
328[(c)]	"	137	6.5	12.1	-	V = 6.0%	1100	V = 14.4%	
330	"	137	6.7	12.5	-		1177		235

(a) Average of samples shown. % ≅[(test-av. control)/av. control] 100.
(b) Average of 3 samples for each strength shown.
(c) Tested at BNL.

Av = average, S = standard deviation, V = coefficient of variation achieved by using the improved impregnation and encapsulation techniques. It is also of interest, particularly from economic considerations, that the polymer loading of the low-strength concrete is ≈ 40% greater than that in the high-strength material.

High-strength Riverton limestone concrete samples impregnated with MMA have already been discussed and test results have been presented in Tables 7, 9, and 10. These data are summarized below:

1. With samples prepared by use of the standard vacuum-soak technique (see Table 10), average compressive and tensile splitting strengths of 14,210 psi and 1312 psi, respectively, were measured. An average flexure strength of 1440 psi was also measured.
2. Samples processed by the three encapsulation methods shown in Table 9 gave higher results, 17,470 to 19,030 psi for compression and 1500 to 1890 psi for tensile splitting.

A series of 3 x 4 x 16-in. bars and 3-in.-diam x 6-in.-long cylinders has been impregnated with MMA for use in flexure and freeze-thaw testing, and for compressive stress-strain measurements now being made at the FHWA. Since one of the functions of the polymer is to improve the bond between the cement and aggregate phases, reduced penetration or adhesion to the aggregate could produce a composite of lower strength. On this basis, the low porosity limestone aggregate was thought to be the main contributor to the lower strength of concrete-polymer containing Riverton limestone.

To reduce the effects of nonuniform impregnation, improved encapsulation technqiues for use with FHWA-type concretes were developed (see Section 4.1). Tests were performed to determine whether the properties of the composite were affected by the type of aggregate used. High-quality, normal weight concretes were made with several types of aggregate, including Riverton linestone, White Marsh gravel, Kansas limestone, and crushed diorite gravel. The results of these tests are discussed below.

5.2.1 Riverton Limestone Aggregate

Low-strength (high water/cement ratio, low cement factor, and short curing time) concrete samples containing Riverton limestone aggregate were impregnated with MMA, radiation polymerized, and evaluated to determine the degree to which low-strength concrete could be improved. The samples were dried at 302°F (150°C) after three days of curing to stop hydration. Previous work[5] had indicated that, compared with an average control compressive strength of 3320 psi, an average strength of 10,100 psi was obtained for specimens containing 5.8% MMA.

Freeze-thaw tests at the FHWA were performed in accordance with ASTM specification C 290-67, "Rapid Freezing and Thawing In Water." The tests with PIC were terminated after 1057 cycles and flexure strength measurements were subsequently made. These data are given in Table 12. All specimens exhibited excellent durability, the specimens impregnated in forms having higher durability factors (average, 81%) than those processed under water (average, 67.7%). The results of flexure strength measurements indicated a sizable reduction in strength after 1057 freeze-thaw cycles. Compared with an initial PIC flexure strength of 2210 psi, average strengths of 955 and 704 psi were measured for the specimens processed in forms and under water, respectively. This large reduction in flexural strength with a decrease in durability factor is quite comparable to the reported decrease in dynamic modulus of elasticity.[14]

5.2.2 White Marsh Aggregate

Samples of high-quality concrete containing White Marsh quartzite gravel were prepared for testing by the FHWA and BNL. Compressive, tensile splitting, and flexural strengths were measured in one series and creep measurements were made in another.

Several 3-in.-diam x 6-in.-long cylinders and 3 x 4 x 16-in. bars were impregnated with MMA by the standard vacuum-soak

Table 12

Summary of Freeze-Thaw Test Results for Normal Weight Concrete

Monomer, MMA.
Specimens oven-dried at 230°F (110°C).
Vacuum-soak impregnation.
Radiation-induced polymerization.
Sample size, 3x4x16-in. bars.

Specimen no.	Aggregate type	Encapsulation method	Dry density, lb/ft^3	Polymer loading, %	Polymer content, vol %	Durability factor after 1057 cycles,[a] %	Flexure strength after freeze-thaw test, psi
95854[b]	Riverton limestone	Under water	147	5.7	11.3	-	2210[b]
95851	"	"	146	5.8	11.5	80.7	868
95409	"	"	146	5.8	11.5	54.7	540
95852	"	Excess monomer, in forms	146	4.0	7.9	82.8	915
95853	"	"	145	4.0	7.8	79.2	995
95828[b]	White Marsh	Under water	145	5.0	9.8	-	2725[b]
95826	"	"	144	5.5	10.8	86.2	965
95376	"	"	142	5.5	10.6	63.7	-
95827	"	Excess monomer, in forms	144	4.8	9.4	99.0	1980
95829	"	"	145	4.0	7.9	100.0	1675
96278[b]	Diorite	Under water	149	5.4	10.9	-	2760[b]
96279[b]	"	"	151	5.4	11.1	-	2740[b]
96275	"	"	149	5.5	11.1	80.6	640
96276	"	"	158	5.6	11.2	90.2	1000
96277	"	"	149	5.4	10.9	96.5	1255
96286[b]	"	Excess monomer, in forms	150	5.2	10.6	-	2085[b]
96287[b]	"	"	150	4.2	8.6	-	2240[b]
96283	"	"	150	3.9	8.0	69.9	820
96284	"	"	150	4.5	9.2	53.9	570
96288	"	"	149	4.3	8.7	60.3	800

(a) Measured in accordance with ASTM C290-67, "Rapid Freezing and Thawing in Water."

(b) Impregnated specimen not exposed to freeze-thaw test.

impregnation method. Half of the specimens were encapsulated in forms during impregnation and radiation-induced polymerization and half were radiation polymerized under water. The test results are shown in Table 13. Specimens prepared by the under water method showed improvements in compressive strength up to 240% as compared with the unimpregnated controls. Although the specimens prepared by the in-form method showed significant improvement over the controls (163%), the compressive strengths were less than those of samples prepared under water. Similar results were obtained from tensile splitting and flexural strength tests. The results for specimens tested at BNL were in good agreement with those obtained at the FHWA.

A series of 6-in.-diam x 12-in.-long cylinders was impregnated with MMA for creep test measurements. As part of the effort, several 3-in.-diam x 6-in.-long cylinders were prepared for compressive and tensile splitting strength measurements. The excess monomer, in-form method of encapsulation was used. The results given in Table 14 for compressive and tensile splitting strengths are in close agreement with those in Table 13 for samples prepared by the same method. Compressive and tensile splitting strengths of 16,432 and 1479 psi were obtained in the creep test series, compared with 16,477 and 1480 psi

Table 13

Compressive, Tensile, Splitting, and Flexural Strengths for Concrete Containing White Marsh Gravel

Monomer, MMA
Specimens oven-dried at 230°F (110°C)
Vacuum-soak impregnation
Radiation-induced polymerization
Specimen sizes, as shown

Sample No.	Encapsulation method	Dry density, lb/ft^3	Polymer loading %	Polymer content vol %	Compressive strength(a) psi	Tensile splitting strength(a) psi	Flexural strength(b) psi	Difference %
Controls(d)	---	---	0	0	5580	600	610	-
96296	Under water	139	5.9	11.1	19510 Av. = 18,977	---	---	
298	" "	139	5.9	11.1	18110 S = ± 799	---	---	
300	" "	139	5.7	10.8	18290 V = 4.2%	---	---	
301(e)	" "	141	5.6	10.7	20000	---	---	240
96295	" "	140	5.7	10.8	---	1865 Av. = 1677	---	
297	" "	139	5.8	11.0	---	1760 S = ± 168	---	
299	" "	139	5.7	10.8	---	1675 V = 10%	---	
302(e)	" "	140	5.6	10.7	---	1410	---	180
95826	" "	144	5.5	10.8	---	---	965	
828	" "	145	5.0	9.9	21200(f)	---	2725 279(f)	203
96304	Excess monomer,	141	5.0	9.6	15850 Av. = 16,477	---	---	
307	in forms	140	4.7	8.9	15670 S = ± 838	---	---	
310	"	139	5.3	10.0	16590 V = 5.1%	---	---	
306(e)	"	139	4.3	8.1	17800	---	---	163
96303	"	141	5.0	9.6	---	1635 Av. = 1480	---	
305	"	138	5.3	9.9	---	1640 S = ± 197	---	
309	"	139	5.2	9.8	---	1420 V = 13.3%	---	
308(e)	"	140	4.6	8.7	---	1227	---	147
95827	"	144	4.8	9.4	---	---	1980	
829	"	145	4.0	9.9	---	---	1675	199

(a) Sample size, 3-in.-diam x 6-in.-long cylinders.

(b) Sample size, 3 x 4 x 16-in. bars.

(c) Average of samples shown. % = [(test - av control)/ av control 100.]

(d) Average of three samples for each mechanical strength shown.

(e) Tested at BNL.

(f) Result from 3 x 4 x 16-in. sample ends. Tested at the FHWA

Av = Average, S = Standard deviation, V = Coefficient of variation.

Table 14

Strength Data for Creep Test Specimens
Containing White Marsh Gravel

Monomer, MMA.
Vacuum-soak impregnation.
Encapsulation method, excess monomer in forms.
Radiation-induced polymerization.
Specimens oven-dried at 230°F (110°C) to constant weight.

Sample No.	Sample size	Dry density, lb/ft³	Polymer loading, %	Polymer content vol %	Compressive strength psi	Tensile splitting strength, psi	Difference, %
4 controls	3-in.-diam x 6-in.-long	---	0	0	5,667	753	
96099	"	139	4.0	7.6	17,780 Av. = 16,432	---	
101	"	141	4.4	7.7	16,200 S = ± 790	---	
103	"	140	3.6	6.8	15,930 V = 4.8%	---	
105	"	140	4.8	9.1	15,820	---	190
098	"	141	3.1	5.9	---	Av. = 1479 1425	
100	"	139	4.1	7.7	---	S = ± 39 1535	
102	"	139	5.0	9.4	---	V = 2.7% 1485	
104	"	142	4.2	8.1	---	1470	97
3 controls	6-in.-diam x 12-in. long	---	0	0	---	465	
96084	"	140	5.0	9.5	---	Av. = 1100 1020	
085	"	140	5.2	9.9	---	S = ± 99 1040	
086	"	140	5.2	9.9	---	V = 9% 1240	137
			Creep Specimens				
96076	6-in.-diam x 12-in. long	139	4.7	8.9			
077	"	139	4.9	9.2			
078	"	139	5.2	9.8			
079	"	138	5.4	10.1			
080	"	139	5.2	9.8			
081	"	140	5.2	9.9			
082	"	139	5.2	9.8			

(a) Sample size, 3-in.-diam x 6-in.-long cylinder.

(b) Sample size, 3 x 4 x 16-in. bars.

(c) Average of samples shown. % = [(test - av control)/av control] 100.

(d) Average of three samples for each mechanical strength shown.

(e) Tested at BNL.

(f) Result from 3 x 4 x 16-in. sample ends. Tested at the FHWA.

Av. = average, S = standard deviation, V = coefficient of variation.

respectively in the first series. Lower tensile splitting strengths (1100 psi) were measured for the 6-in.-diam x 12-in.-long cylinders. Similar size effects have been observed at the USBR.[4] Creep tests are currently under way at the FHWA.

Freeze-thaw durability tests were performed on four 3 x 4 x 16-in. bars (see Table 12). The difference between the durability factors for samples prepared by each of the two encapsulation methods was more pronounced for the White Marsh aggregate than for the Riverton limestone. Average durability factors of 99.5% and 75.0% were measured for the in-form and underwater methods, respectively.

After 1057 cycles of freezing and thawing, an average flexural strength of 1827 psi was measured for two specimens processed in forms. A specimen polymerized in contact with water had a flexural strength of 965 psi as compared with a strength of 2725 psi for an impregnated but unexposed specimen. All the results are higher than those obtained for the Riverton limestone specimens processed in a similar manner.

5.2.3 Diorite Aggregate

Samples of high-strength, high-density ($\approx$ 147 lb/ft^3) concrete containing diorite coarse aggregate were impregnated with MMA by using the vacuum-soak technique. Two methods of encapsulation, under water and excess monomer in forms, were used.

Cylindrical specimens, 3-in.-diam x 6-in.-long and 6-in.-diam x 12-in.-long, were tested for compressive strength and tensile splitting. Beams measuring 3 x 4 x 16 in. were used for flexure and freeze-thaw testing.

Experimental data and test results are given in Table 15. The average compressive strengths of the samples were the same for each encapsulation method, ≈20,000 psi. However, for the tensile splitting and flexure strengths, the underwater polymerization method appears more effective. The average tensile splitting and flexure strengths for samples prepared by the underwater method were 1786 psi and 2616 psi, respectively; for the in-form method, they were 1324 psi and 2096 psi.

The results of freeze-thaw testing of several 3x4x16-in. bars prepared by one or the other encapsulation methods are given in Table 12. In contrast to the results for Riverton limestone and White Marsh PIC, the diorite samples polymerized underwater gave higher durability factors (average, 90%) than those of samples encapsulated in forms (average, 61%). In addition, the average post-exposure flexural strength of the samples processed underwater was greater, in agreement with the aforementioned trend. However, this may be partially due to differences in the average strengths of the unexposed samples,

Table 15

Compressive, Tensile, Splitting, and Flexural Strengths for Concrete Containing Diorite Aggregate

Monomer, MMA.
Specimens oven-dried at 230°F (110°C).
Vacuum-soak impregnation.
Radiation-induced polymerization.
Sample sizes, as shown.

Specimen No.	Encapsulation method	Dry density, lb/ft³	Polymer loading, %	Polymer content, vol %	Compressive strength[a] psi		Tensile splitting strength[a] psi		Flexural strength[b] psi		Difference[c] %
controls (6)	-	-	0	0	5,555		660		720		-
96254	Under water	145	5.9	11.6	19,410		-		-		-
255	"	145	5.9	11.6	18,580	Av=20,058	-		-		-
253[e]	"	147	5.7	11.4	19,580	S=±949	-		-		
256[e]	"	146	5.6	11.1	20,480	V=4.7%	-		-		
236[d, e]	"	142	5.8	11.2	21,100		-		-		-
237[d, e]	"	143	5.5	10.7	21,200		-		-		260
257	"	145	5.9	11.6	-		1560		-		
258	"	146	5.7	11.3	-		1480		-		
259[e]	"	146	5.6	11.1	-		1960	Av=1786	-		
260[e]	"	149	5.6	11.3	-		1867	S=±230	-		
235[d]	"	144	6.1	11.9	-		1705	V=12.9%	-		
240[d]	"	142	5.8	11.2	-		1685		-		
238[d] [e]	"	145	5.4	10.6	-		1770		-		
239[d] [e]	"	144	5.7	11.2	-		2260		-		170
278	"	149	5.4	10.9	-		-		2762	Av=2616	
279	"	151	5.4	11.1	-		-		2738	S=±194	
280[e]	"	151	5.4	11.1	-		-		2285	V= 7.4%	
281[e]	"	152	5.3	10.9	-		-		2680		263
96261	Excess monomer,	144	5.4	10.6	19,920		-		-		
263	in forms	144	5.7	11.2	17,680	Av=19,992	-		-		
262[e]	"	146	5.1	10.1	21,400	S=±1142	-		-		
263[e]	"	148	4.8	9.7	20,350	V=5.7%	-		-		
241[d, e]	"	145	4.8	9.4	20,600		-		-		
242[d, e]	"	145	5.3	10.4	20,600		-		-		260
264	"	147	5.4	10.8	-		1625		-		
266	"	146	5.5	10.9	-		1575	Av=1324	-		
265[e]	"	148	5.0	10.0	-		1580	S=±255	-		
267[e]	"	147	5.0	10.0	-		1267	V=19.2%	-		
245[d]	"	142	6.3	12.2	-		925		-		
246[d]	"	143	5.7	11.1	-		980		-		
243[d] [e]	"	146	5.0	9.9	-		1415		-		
244[d] [e]	"	142	5.6	10.8	-		1222		-		101
96286	"	150	5.2	10.6	-		-		2085	Av=2096	
287	"	150	4.2	8.6	-		-		2238	S=±219	
282[e]	"	151	3.6	7.4	-		-		1745	V=10.4%	
285[e]	"	149	3.5	7.1	-		-		2315		191

(a) Specimen size, 3-in.-diam x 6-in.-long cylinders.

(b) Specimen size, 3x4x16-in. bars.

(c) Based on average of strengths shown. [% = [test - av control/av control]100.]

(d) 6-in.-diam x 12-in.-long cylinders.

(e) Tested at BNL.

Av = average, S = standard deviation, V = coefficient of variation.

which were 2750 psi and 2165 psi for the underwater and in-form methods, respectively. Therefore, both series exhibited reductions in strength of ≈65% during exposure to 1057 cycles of freezing and thawing.

5.2.4 Kansas Limestone Aggregate

Laboratory experiments were performed in which high strength concrete containing Kansas limestone aggregate was fully impregnated to determine the maximum improvement in properties that could be expected with this absorptive limestone.

Concrete specimens, 3-in.-diam x 6-in.-long cylinders, were impregnated with MMA by using the vacuum-soak technique. The underwater and in-form encapsulation methods were used. Experimental data and the results of compressive and tensile splitting tests are given in Table 16. Although the in-form method resulted in specimens with higher polymer loadings and strengths, considerable enhancement of the structural properties was obtained with both methods. The average compressive and tensile splitting strengths of samples encapsulated in forms were 23,034 psi and 1691 psi, respectively, higher than those measured on samples of PIC containing Riverton limestone aggregate.

Table 16

Compressive and Tensile Splitting Strengths for
Concrete Containing Kansas Limestone Aggregate

Monomer, MMA.
Specimens oven-dried at 230°F (110°C).
Vacuum-soak impregnation.
Radiation-induced polymerization.
Sample size, 3-in.-diam x 6-in.-long cylinders.

Specimen No.	Encapsulation method	Dry density lb/ft^3	Polymer loading %	Polymer content vol %	Compressive strength[a] psi		Tensile splitting strength[a] psi		Difference[a] %
Controls	---	---	0	0	5,190		570		---
96575[b]	Under water	131	7.3	12.9	15,000	Av. = 18,124	---		
77[b]	" "	132	7.3	13.1	19,300	S = ±1874			
79	" "	131	7.5	13.3	19,806	V = 10.3%			
84	" "	133	7.7	13.9	18,391		---		249
96580	" "	132	7.6	13.6	---		1514	Av. = 1470	
83	" "	133	7.4	13.4	---		1510	S = ± 60	
87[b]	" "	132	7.3	13.1	---		1385	V = 4.1%	157
96576[b]	Excess monomer in forms	133	8.7	15.7	23,600	Av. = 23,034	---		
85	" "	133	8.5	15.3	23,171	S = ± 490	---		
86	" "	132	8.9	15.9	23,116	V = 2.1%	---		
88[b]	" "	133	8.3	14.9	22,250		---		344
96578[b]	" "	132	8.3	14.8	---		1530	Av. = 1691	
81	" "	134	8.6	15.6	---		1832	S = ±124	
82	" "	132	8.8	15.7	---		1712	V = 7.3%	196

(a) Average of samples shown. % = [(av test samples - controls)/controls] 100.

(b) Tested at BNL; all others tested at the FHWA

Av. = average, S = standard deviation, V = coefficient of variation.

A freeze-thaw durability tests was performed on one 3 x 4 x 16-in. specimen (No. 96590) containing 7.3% MMA and polymerized in water. After 708 cycles, a durability factor of 84% was calculated. This is also in agreement with the results obtained with Riverton limestone.

5.2.5 Special Durability Tests

Six 1 x 1 x 5-in. cement paste bars were impregnated with MMA for use in salt intrusion tests. The vacuum-soak impregnation method was used. The bars were encapsulated in aluminum forms and polymerization was initiated by radiation. The impregnation data and test results are shown in Table 17. Experiments performed at the FHWA, in which hardened cement paste specimens were exposed to a solution of deicing salt (1.2 N $CaCl_2$) for a 2-month period, indicated that prior polymer impregnation is effective in decreasing the penetration of chloride ion. Impregnation resulted in a decrease in the quantity of chloride ion in the surface layer (to 1/8 in.) of the paste to 1/5 of that found in control specimens, and to only 1/50 of that in controls at levels below the top 1/8-in. layer. The tests indicate that blocking the access of chloride ion to the interior of the concrete by polymer impregnation[12] is a possible method of preventing steel corrosion and surface scaling in bridge decks and concrete pavements.

Table 17

Salt Intrusion of Neat Cement Paste

Monomer, MMA
Radiation-induced polymerization.
Specimens, 1x1x5-in. cement past bars.
Specimens oven-dried at 220°F (105°C) prior to impregnation.

Specimen designation	Polymer content[a] %	Exposure time to $CaCl_2$ solution, days	% Chloride content[b] at indicated depth in specimen			
			0-0.125 in.	0.125-0.250 in.	0.250-0.357 in.	0.375-0.500 in.
P-16	29	11[c]	0.208	0.014	0.017	0.015
P-10	25	30[c]	0.326	0.012	0.008	0.014
P-14	29	62	0.151	0.025	0.062	0.016
P-12	29	62	0.291	0.009	0.006	
P- 2	33	62	0.263	0.010	0.007	
P- 4	25	62	0.250	0.009	0.005	
P- 3	0	5[c]	0.067	0.892	0.767	
P-13	0	9[c]	0.992	0.881	0.739	0.674
P-15	0	21[c]	1.240	1.135	1.008	0.866
P- 9	0	30	1.017	0.948	0.851	0.761
P-11	0	30	1.117	1.007	0.918	
P- 1	0	62	2.312	1.841	1.451	

(a) Expressed as percentage of original dry cement.

(b) Expressed as Cl^-, percentage of original dry cement.

(c) Exposure time was < 62 days because of leakage.

On the basis of these results, four 6 x 32 x 5½-in. slabs of reinforced concrete containing Riverton limestone aggregate were impregnated with MMA, polymerized by radiation while under water, and returned to the FHWA for testing under brine solutions. Impregnation data are shown in Table 18. After five weeks of exposure no evidence of corrosion of the reinforcing steel is evident as determined by the electrical potential developed.[13]

Table 18

Summary of Impregnation Data for
Reinforced Concrete Slabs Being Tested in Brine

Monomer, MMA
Vacuum-soak impregnation.
Radiation-induced polymerization, under water.
Specimen size, 26 x 32 x 5.5 in.
Specimen dried at 230°F (110°C).

Sample No.	W/C[a]	Dry density, lb/ft^3	Weight loss on drying, %	Polymer loading, %	Polymer content, vol %
23-92	0.4	143	3.3	5.3	9.4
83-91	0.4	154	3.8	5.7	10.9
19-93	0.5	131	5.8	9.2	15.0
111-94	0.5	137	6.5	8.7	14.7

(a) Water to cement ratio by weight.

5.3 Structural Lightweight Concrete

Concretes containing three types of lightweight aggregate, slag, sintered fly ash, and expanded slate, were evaluated.

The mix composition of each type of concrete is given in Table 5.

Earlier work[5] showed that the impregnation of structural lightweight concrete with MMA produced composites with the highest compressive and tensile splitting strengths of all the FHWA-type materials tested. Because of their low density (100 to 130 lb/ft^3) and high porosity, lightweight concretes are easily saturated with monomer. However, to obtain the maximum polymer loading and therefore high strength, care must be exercised to minimize drainage losses during polymerization.

5.3.1 Slag Aggregate

Samples of structural lightweight concrete containing slag aggregate (density, ≈125 lb/ft^3) were impregnated with MMA. Two aggregate sizes, 3/8-in. and 3/4-in. maximum, were evaluated. Duplicate samples were prepared with use of the under water and in-form encapsulation methods. Compressive, tensile splitting, and flexural strengths were measured.

The impregnation data and test results for specimens containing the 3/8-in. maximum size aggregate are given in Table 19.

The average flexural strength of the specimens processed by the under water method was greater than that of those processed by the in-form method (2687 vs. 1958 psi). The compressive and tensile splitting strength measurements, however, favored the in-form method. Strengths as high as 26,100 psi and 2630 psi, respectively, were measured for samples containing a polymer loading of 11.7% MMA (10.5 wt %). The opposite trend in the case of the flexure bars is not yet understood. Similar results were obtained with concrete containing 3/4-in. slag aggregate (see Table 20). The average flexural strength of samples processed by the under water method was higher (2422 psi) than that of samples processed in forms (1872 psi). However, the average compressive strength

Table 19

Compressive, Tensile Splitting, and Flexural Strengths for Concrete Containing 3/8-in. Slag Aggregate

Monomer, MMA.
Radiation-induced polymerization.
All specimens dried to constant weight at 220°F (105°C).
Vacuum-soak impregnation.

Specimen no.	Encapsulation method	Dry density, lb/ft^3	Polymer loading, %	Polymer content, vol %	Compressive strength[a] psi	Tensile Splitting strength[a] psi	Flexure strength[b] psi	Difference[c] %
Control	-	-	0	0	4,000	465	650	
96197	Under water	119	12.6	20.4	21,140	-	-	
208	"	118	12.7	20.4	21,160 Av=21,850	-	-	
198[d]	"	119	12.3	19.9	23,000 S =±769	-	-	
201[d]	"	119	12.4	20.0	22,100 V = 3.5%	-	-	446
194	"	119	12.5	20.2	-	1880 Av=1920	-	
206	"	118	12.7	20.4	-	1855 S =±63	-	
202[d]	"	118	12.4	19.9	-	1925 V =3.3%	-	
204[d]	"	117	12.5	19.9	-	2020	-	315
218	"	122	12.9	21.4	20,120[e]	-	2612 Av=2687	
219	"	122	12.9	21.4	21,830[e]	-	2762 S =±75	424[e], 313
96199	Excess monomer, in forms	118	12.1	19.4	23,700 Av=24,520	-	-	
209		119	11.9	19.2	24,080 S =±1082	-	-	
195[d]	"	119	11.5	18.6	24,200 V =4.4%	-	-	
196[d]	"	119	11.7	18.9	26,100	-	-	513
200	"	117	12.2	19.4	-	1905 Av=2231	-	
207	"	118	11.9	19.1	-	1900 S =±332.5	-	
193[d]	"	119	10.8	17.5	-	2490 V =14.9%	-	
203[d]	"	118	11.7	18.8	-	2630	-	380
217	"	122	12.9	21.4	19,170[e]	-	1892 Av=1957	
220	"	122	10.6	17.6	19,950[e]	-	2023 S =±65.5	389[e], 201

(a) Specimens, 3-in.-diam x 6-in.-long cylinders.
(b) Specimens, 3x4x16-in.-bars.
(c) Based upon average of strengths shown. % = [(test - av control)/av control]100.
(d) Tested at BNL.
(e) Results from 3x4x16-in. sample ends tested at the FHWA.

Av = average, S = standard deviation, V = coefficient of variation.

Table 20

Compressive, Tensile Splitting, and Flexural Strengths for Concrete Containing 3/4-in. Slag Aggregate

Monomer, MMA.
Radiation-induced polymerization.
All specimens dried to constant weight at 220°F (105°C).
Vacuum-soak impregnation.

Specimen no.	Encapsulation method	Dry density, lb/ft³	Polymer loading, %	Polymer content, vol %	Compressive strength[a] psi	Tensile splitting strength[a] psi	Flexural strength[b] psi	Difference[c] %
Control	-	-	0	0	5,220	533	705	-
96165	Under water	127	10.3	17.8	21,050 Av=22,062	-	-	6
170	"	126	10.5	18.0	21,500 S =±893	-	-	
175[d]	"	126	10.0	17.1	22,300 V = 4%	-	-	
177[d]	"	126	10.1	17.3	23,400	-	-	323
168	"	128	10.5	18.3	-	1655	-	
174	"	126	10.4	17.8	-	1850 Av=1872	-	
162[d]	"	127	10.3	17.8	-	1855 S =±169	-	
163[d]	"	127	10.2	17.6	-	2130 V = 9%	-	259
182	"	131	10.3	18.3	21,210[e]	-	2320 Av=2422	
188	"	131	10.3	18.3	21,830[e]	-	2325 S =±102 V = 4.2%	312[e], 243
96167	Excess monomer,	126	10.1	17.3	22,300	-	-	
169	in forms	125	9.9	16.8	22,420 Av=23,692	-	-	
171[d]	"	126	9.5	16.3	23,850 S =±1571	-	-	
176[d]	"	128	9.0	15.7	26,200 V = 6.6%	-	-	354
164	"	128	9.7	16.9	-	2195	-	
173	"	126	9.6	16.4	-	1445 Av=1862	-	
161[d]	"	127	8.9	15.4	-	1940 S =±270	-	
172[d]	"	128	9.0	15.7	-	1870 V = 14.5%	-	257
185	"	132	8.9	16.0		-	1842 Av=1872	
189	"	131	8.2	14.6		-	1902 S =±30	312[e], 165

(a) Specimens, 3-in.-diam x 6-in.-long cylinders.
(b) Specimens, 3x4x16-in. bars.
(c) Based upon average of strengths shown. % = [(test - av control)/av control]100.
(d) Tested at BNL.
(e) Results from 3x4x16-in. sample ends tested at the FHWA.

Av = average, S = standard deviation, V = coefficient of variation.

(23,692 psi) of the samples encapsulated in forms was higher than that for the samples processed under water (22,062 psi). The tensile splitting strengths were essentially equal ($\approx$1870 psi).

The impregnation of lightweight concrete containing slag aggregate produces composites with the highest strengths obtained to date in the FHWA program. The initial high porosity of this material and its high strength after impregnation are advantages in considering it for field impregnation applications; however, the greatly increased polymer loading may be a determining factor when monomer cost is considered.

Samples of PIC containing slag aggregate were tested for freeze-thaw durability in accordance with ASTM C 290-67. Test results after 1057 cycles are given in Table 21. Samples encapsulated in forms had higher durability factors and flexural strengths after testing than those polymerized under water. No significant difference was noted between the specimens containing 3/8-in. and 3/4-in. aggregate and processed by the same method. One of the 3/4-in. aggregate samples that was processed under water (specimen 96183) cracked after 660 cycles. During the freeze-thaw testing surface scaling was apparent. Exposure times at which scaling was first observed are shown in Table 21.

Table 21

Summary of Freeze-Thaw Test Results for Structural Lightweight Concrete

Monomer, MMA.
Specimens oven-dried at 220°F (105°C).
Vacuum-soak impregnation.
Radiation-induced polymerization.
Samples, 3x4x16-in. bars.

Specimen no.	Aggregate type	Encapsulation method	Dry density, lb/ft^3	Polymer loading, %	Polymer content, vol %	Durability factor after 1057 cycles,[a] %	Flexure strength after freeze-thaw test, psi	Scaling first observed, cycles
(b)	3/8-in. slag	Under water	122	12.9	21.4	-	2685[b]	-
96216	"	"	122	12.9	21.4	89.7	275	238
96222	"	"	122	13.0	21.6	56.2	220	291
(b)	"	Excess monomer,	122	11.8	19.6	-	1955[b]	-
96215	"	in forms	122	11.6	19.2	91.3	1150	215
96221	"	"	122	12.1	20.1	97.8	920	660
(b)	3/8-in. slag	Under water	131	10.3	18.4	-	2425[b]	-
96183	"	"	131	10.3	18.4	(c)	0	-
96184	"	"	131	10.3	18.4	66.0	605	454
(b)	"	Excess monomer,	132	8.6	15.4	-	1870[b]	-
96186	"	in forms	131	8.2	14.6	88.6	1145	400
96187	"	"	131	9.1	16.2	94.3	1175	454
(b)	Expanded	Under water	106	20.0	28.8	-	2180[b]	-
96055	Slate	"	104	20.7	29.3	67.3	630	454
96063	"	"	107	19.6	28.5	54.2	145[d]	-
96061[e]	"	Excess monomer,	105	18.0	25.7	-	1510[e]	-
96054	"	in forms	105	18.8	26.8	89.5	950	-
96062	"	"	108	16.9	24.8	(c)	0	-

[a] In accordance wtih ASTM C290-67, "Rapid Freezing and Thawing in Water."

[b] Average of two impregnated samples not exposed to freeze-thaw test.

[c] Sample cracked on freezing after 660 cycles.

[d] Sample cracked on freezing.

[e] Sample not exposed to freeze-thaw test.

5.3.2 Expanded Slate Aggregate

Samples containing expanded slate aggregate and with a density of ≈105 lb/ft^3 were impregnated with MMA by using the vacuum-soak technique. The three methods of encapsulation described in Section 4.1.1 were used. Impregnation data and results of compressive, tensile splitting, and flexural strength tests are given in Table 22. The average compressive strength of samples prepared by the under water method was ≈15,000 psi, and was lower than the 18,500 psi obtained for specimens prepared by the in-form and rotation methods. The average tensile splitting strength for each method of encapsulation was about 1870 psi. The limited number of samples tested in flexure makes it difficult to observe any trends. However, the average flexural strength of 2,180 psi measured for samples encapsulated under water is in general agreement with that of polymer-impregnated normal weight concrete.

Samples of impregnated concrete containing expanded slate aggregate and processed by the under water and in-form encapsulation methods were tested for freeze-thaw durability as described earlier. The results of the tests are shown in Table 21. Because two of the samples cracked prematurely, data are limited but indicate durability factors ranging

Table 22

Compressive, Tensile Splitting and Flexural Strengths for Concrete Containing Expanded Slate Aggregate

Monomer, MMA.
Radiation-induced polymerization.
Specimens oven-dried at 220°F (105°C) to constant weight.
Specimen size, as noted below.
Vacuum-soak impregnation.

Sample No.	Encapsulation method	Dry density, lb/ft^3	Polymer loading, %	Polymer content, vol %	Compressive strength,[a] psi	Tensile splitting strength,[a] psi	Flexure strength,[b] psi	Difference[c] %
Controls	-	-	0	0	3,676	450	587	-
96038	Wrapped and	103	17.9	25.1	18,560	-	-	405
043	rotated	104	18.9	26.7	19,180	-	-	421
050	"	102	19.0	26.3	-	1810	-	302
051	"	104	18.1	25.6	-	1920	-	326
96039	Under water	107	17.9	26.0	14,090	-	-	283
040	"	103	18.5	25.9	16,130	-	-	338
049	"	103	18.9	26.4	-	2015	-	347
052	"	103	19.3	27.0	-	1766	-	292
056	"	105	20.4	29.1	15,440[d]	-	2200	320[d], 274
064	"	107	19.6	28.5	16,270[d]	-	2165	342[d], 268
96041	Excess monomer,	104	20.1	28.4	19,100	-	-	419
042	in forms	105	21.1	30.1	18,530	-	-	404
047	"	103	17.7	24.8	-	1850	-	311
048	"	105	19.8	28.2	-	1910	-	324
061	"	105	19.0	25.7	15,820[d]	-	1510	330[d], 157

(a) Sample size, 3-in.-diam x 6-in.-long.

(b) Sample size, 3x4x16-in.

(c) Difference, % = [(test sample - control)/control]100.

(d) Results from 3x4x16-in. sample ends tested at the FHWA.

between 54 and 90% and show a slight advantage for the in-form method of encapsulation. The results obtained for the polymer-impregnated expanded slate aggregate concrete were, in general, more erratic and lower than those for the slag aggregate.

5.3.3 Sintered Fly-ash Aggregate

Sintered fly-ash aggregate is of interest to the FHWA because of its great abundance and the desirability of using a waste material. Eight samples of concrete containing sintered fly-ash aggregate were impregnated with MMA by using the vacuum-soak method. Five 2-in. cubes were encapsulated by wrapping in foil and rotating, and three other specimens, 3-in.-diam x 6-in.-long cylinders, were encapsulated by using the in-form method. Impregnation data and the results of mechanical testing are given in Table 23.

The average compressive strength measured for the cubes was 14,448 psi. However, the limited data obtained from the cylinders showed a higher compressive strength, 23,460 psi, and an average tensile splitting strength of ≈2000 psi. These results are comparable to the data obtained for the other structural lightweight materials.

Table 23

Compressive and Tensile Splitting Strengths for Concrete Containing Sintered Fly Ash Aggregate

Monomer, MMA.
Radiation-induced polymerization.
Specimens oven-dried at 220°F (105°C) to constant weight.
Vacuum-soak impregnation.

Sample No.[a]	Encapsulation method	Dry density, lb/ft^3	Polymer loading, %	Polymer content, vol %	Compressive strength, psi		Tensile splitting strength, psi
1	Excess monomer, in form	102	18.2	25.2	23,460		-
2	"	101	18.1	24.8	-		2190
3	"	101	17.9	24.6	-		1805
5	Wrapped, rotated	104	13.3	18.8	16,820		-
6	"	104	14.4	20.3	17,420		-
7	"	104	14.0	19.8	15,320	Av=14,448	-
8	"	104	14.4	20.3	11,100		-
9	"	105	13.2	18.8	11,580		-

[a] Samples 1-3, 3-in.-diam x 6-in.-long cylinders; samples 5-9, 2-in. cubes.

5.4 Insulating-Type Lightweight Concrete

Previously reported work[5] indicated that composites with compressive and tensile splitting strengths up to 5000 and 1000 psi, respectively, could be produced by MMA impregnation of insulating-type concretes of a dry density ranging between 20 and 30 lb/ft^3. On this basis, perlite, vermiculite, and foamed-glass concretes were selected for additional study.

During this report period, efforts were made to prepare high-quality specimens and to develop impregnation techniques that would yield composites with uniform polymer distribution and with hard, continuous polymeric coatings. The structural and durability properties of MMA and polyester-styrene impregnated specimens prepared by use of these techniques were measured. Tests of compressive, tensile splitting, and flexural strengths, fatigue, and freeze-thaw durability were performed.

5.4.1 Comparison of Insulating Concretes

Early in the report period, concrete specimens made from each of the three aggregates discussed above were impregnated with MMA using the standard vacuum-soak technique and radiation polymerized. The mix proportions and fabrication methods for the specimens are given in Section 3.2. Although considerable scatter was evident, the test results from the series (see Table 24) were in agreement with earlier

Table 24

Test Results for Various Insulating-type Concretes

Monomer, MMA + 20% PMMA dip.
Radiation-induced polymerization.
Vacuum-soak impregnation.
Specimens rotated during irradiation.
Specimens dried at 212° F (100°C) prior to impregnation.
Specimen size, 3-in. diameter x 6-in. long cylinders.

Specimen	Aggregate	Initial density, lb/ft^3	Polymer content, Wt %	Polymer content, Vol%	Final density, lb/ft^3	Compressive strength, psi	Modulus of elasticity[(a)], 10^6 psi	Strength[(b)], Final density
1:6-10	Perlite	28.3	54.6	46.2	62.3	4570	-	67.5
1:6-12	Perlite	28.4	54.5	46.2	62.4	3850	0.20	
1:8-1	Perlite	21.1	54.7	34.6	46.5	2530	0.37	52.0
1:8-2	Perlite	21.8	57.6	40.3	51.5	2560	-	
3V-1	Vermiculite	35.9	51.2	51.0	73.3	3260	-	55.0
3V-2	Vermiculite	33.2	52.6	50.0	70.0	4630	-	
4V-1	Vermiculite	30.7	55.1	51.1	68.3	5350	-	63.1
4V-2	Vermiculite	31.8	54.8	52.4	70.4	3410	-	
G-1	Foamed glass	25.5	54.3	41.2	55.8	2750	-	44.2
G-2	Foamed glass	27.2	52.5	40.8	57.2	2240	-	

(a) Compression.

(b) Average of two samples

work. The perlite 1:6 (cement/aggregate by volume) test samples gave the highest strength-to-weight ratio. The vermiculite test samples also had high strengths but were significantly heavier than the perlite 1:6 specimens. The foamed-glass composite gave the lowest strength-to-weight ratio.

During the impregnation of insulating-type concrete, monomer losses due to evaporation and drainage are considerable and it is difficult to produce specimens with uniform polymer distributions. In an attempt to reduce the drainage losses to negligible values, specimens were encapsulated in forms during impregnation and polymerization. This method was discussed in Section 4.1.1.

Several 3x4x16-in. beams of a 1:6 vermiculite-concrete mix were encapsulated in forms, impregnated with MMA, and radiation polymerized. Severe swelling and cracking of the samples occurred. Flexural strength measurements made on the four specimens having the most uniform appearance and the least number of cracks indicated an average flexural strength of 750 psi and a flexural modulus of elasticity of 0.55×10^6 psi. The average polymer concentration and final density were 62 wt % and 68 lb/ft^3, respectively. The flexural strengths were lower than those obtained earlier with use of the normal vacuum-soak procedure[5] and were considerably lower than those obtained with similarly processed perlite concrete (see Table 27).

Additional work indicated that crack-free vermiculite specimens could be produced by eliminating the evacuation process to reduce the monomer loading and initiating polymerization with a lower radiation intensity ($\approx 1.4 \times 10^5$ rads/hr). A 1:6 vermiculite test beam processed by this method had a polymer concentration of 53 wt %, a final density of 56 lb/ft^3, and a flexural strength of 1045 psi. Seven 3-in.-diam x 6-in.-long cylinders of 1:8 vermiculite concrete that were impregnated with MMA by use of this procedure had an average compressive strength of 2970 psi, a polymer concentration of 58.8 wt %, and a density of 51 lb/ft^3.

These test results indicate that vermiculite and foamed-glass concrete impregnated with MMA are of poorer quality and have lower strengths than perlite concrete. Further work with insulating-type concrete was therefore focused on the use of perlite, although some samples of vermiculite were made for comparison purposes.

5.4.2 Perlite Concrete Screening Tests

Screening tests to evaluate techniques for the impregnation of perlite concretes were performed. Parameters investigated include method of encapsulation, monomer viscosity, radiation intensity, and concrete density.

Encapsulation studies were performed with a series of perlite concrete specimens prepared as follows.

1. Cast in forms, cured, removed from forms for impregnation by use of vacuum-soak technique.

2. Cast in forms, cured, impregnated in forms by use of vacuum-soak technique.

3. Cast in forms that had been treated with release agents, cured, impregnated in forms by use of vacuum-soak technique.

4. Samples prepared as in (1), placed in glass forms and impregnated by use of the vacuum-soak technique.

Specimens impregnated in carboard cartons uncoated with a release agent (procedure 2) were difficult to remove from the containers after polymerization. Teflon and polyurethane were found to be effective release agents when used with polyester-styrene impregnated specimens (procedure 3) but were ineffective with MMA. The best results were obtained by use of a secondary can or glass form (procedure 4).

Samples of 1:6 and 1:8 perlite concrete were impregnated with 60% styrene - 40% polyester* (viscosity $\approx$15 cps) and radiation polymerized while in pretreated cardboard

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* Formulated by diluting Plaskon 941 (65% polyester - 35% styrene). Composition, 38.5% styrene - 61.5% Plaskon 941.

forms. Nonuniform polymer loadings, irregular surface finishes, and poor release action were encountered with several of these samples because the polyurethane layer was thin in some areas. However, eleven samples with uniformly smooth surfaces were tested at the FHWA. The test results (see Table 25) indicate that compressive and tensile splitting strengths up to a maximum of 4040 psi and 755 psi respectively could be obtained with a 1:8 perlite-polyester-styrene composite. Measurements of 1:6 perlite composites were very erratic, probably due to the polymer contents which ranged from 24.3 to 52.1 vol %. With adequate impregnation techniques, strengths greater than those obtained with the 1:8 mixture could undoubtedly be obtained.

Another series of perlite samples was impregnated with MMA. These specimens were removed from the fabrication forms and placed in glass forms prior to impregnation. The test results (Table 26) indicate that the strength properties are strongly affected by the polymer content. Compressive and tensile splitting strengths up to a maximum of 5560 and 1385 psi, respectively, were obtained for 1:8 perlits samples containing 65 wt % PMMA (final density, 61 lb/ft^3). The 1:6 perlite mix produced composites with maximum compressive and tensile splitting strengths of 8080 and 1455 psi, respectively.

Table 25

Strengths of Perlite Concrete Impregnated in Cardboard Forms

Monomer, 60% styrene - 40% polyester.[a]
Vacuum-soak impregnation in cardboard forms.
Radiation-induced polymerization.
Specimen size, 3-in. diam. x 6-in. long cylinders
Radiation intensity, 5×10^5 rads/hr.

Specimen No.	Initial density lb/ft^3	Polymer Content Wt %	Polymer Content Vol%	Final density lb/ft^3	Compressive strength, psi	Tensile splitting strength, psi
1:6-1	24.8	62.2	52.1	65.3	-	785
5	25.6	42.6	24.3	44.6	-	360
6	26.3	52.8	37.8	55.8	2360	-
8	24.5	44.8	25.5	44.3	1300	-
9	26.5	55.3	42.1	59.4	-	685
1:8-2	20.6	67.7	55.5	64.0	-	695
4	19.8	69.0	56.7	64.1	-	495
6	20.6	68.0	56.1	64.4	4040	-
8	25.6	60.7	50.6	65.1	-	755
9	19.4	69.0	55.1	62.4	3820	-
10	20.2	67.9	54.6	62.8	4040	-

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[a] Viscosity $\approx$ 15 cps. Formulated by diluting Plaskon 941.
Composition, 38.5% styrene - 61.5% Plaskon 941.

Table 26

Strengths of Perlite Concrete Impregnated in Glass Forms

Monomer, MMA.
Vacuum-soak impregnation.
Encapsulation in glass forms.
Radiation-induced polymerization.
Specimen size, 3-in. diameter x 6-in. long cylinders.
Specimens dried at 167° F (75° C) prior to impregnation.
Radiation intensity, 5 x 10^5 rads/hr.

Specimen No.	Initial density, lb/ft^3	Polymer Content Wt %	Vol%	Final density, lb/ft^3	Compressive strength, psi	Tensile splitting strength, psi
1:6- 4	25	62.7	56.8	66.8	7070	-
5	26	61.9	57.4	68.4	-	1315
6	27	58.5	51.7	65.1	6200	-
10	27	56.7	48.1	62.4	-	575
11	26	56.6	46.1	60.0	4200	-
13	26	61.2	55.8	67.0	-	1455
14	26	62.5	58.8	69.3	8080	-
15	26	61.7	56.8	67.8	-	1430
1:8- 1	22	63.4	51.7	60.0	5090	-
2	21	65.7	54.7	61.3	-	1365
4	22	58.6	42.4	53.2	2970	-
5	23	58.4	44.0	55.4	-	625
6	22	59.2	43.4	54.0	3650	-
8	22	64.8	54.9	62.5	-	1385
14	21	65.6	52.9	61.1	5560	-
15	21	65.0	52.9	60.0	-	1280
16	21	65.0	53.1	60.3	-	1240

Several 1:8 perlite beams were impregnated with MMA and radiation polymerized while encapsulated in secondary forms containing excess monomer. Once again, nonuniform polymer loadings, irregular surface appearance, and some degree of cracking were apparent. The large amount of monomer being polymerized in each form caused high heat fluxes to be generated and as a result a sponge-like polymer was formed. Flexural strength measurements were made on the samples that had the most uniform appearance. The average flexural strength measured for three 3x4x16-in. beams having an average polymer content of 58 wt % and a final density of 51 lb/ft^3 was ≈800 psi.

During these experiments it was observed that, as with vermiculite, the radiation intensity had an effect on polymer content and appearance of the samples. At high intensities the surfaces were covered with a popcorn-type polymer which was probably caused by the rapid polymerization rate and subsequent heat generation. As a result, a series of 1:6 perlite beams was impregnated with MMA and radiation polymerized at lower intensities (1.5 to 3.0×10^5 rads/hr) than that normally used (5.0×10^5 rads/hr). Three encapsulation techniques, forms, rotation, and wrapping in foil, were used. The results of flexural strength tests, given in Table 27, indicate that composites with high and reproducible flexural

Table 27

Effect of Radiation Intensity and Encapsulation Method

on the Flexural Strength of Perlite Concrete

Monomer, MMA.
Vacuum-soak impregnation.
Specimens oven-dried at 212°F (100°C)
Perlite 1:6 concrete, BNL batch No. 6.

Sample No.	Encapsulation Method	Radiation intensity 10^5 rads/hr	Polymer content, Wt %	Polymer content, Vol%	Final density, lb/ft^3	Flexural Strength,[b] psi	
60601[a]	In forms	3.0	53	47.4	60	1825	
602[a]	In forms	3.0	54	44	60	2145	Av = 2058
611A	Rotated	2.0	56	46.5	61	2100	
611B	Rotated	2.0	56	46.5	61	2175	S = ±147
612A	Rotated	2.0	53	42.6	59	1860	
612B	Rotated	2.0	54	46.5	61	2100	V = 7.1%
615A	Wrapped in foil	1.5	52	41.1	58	1950	
615B	Wrapped in foil	1.5	54	44	60	2230	
618	Wrapped in foil	1.5	54	44.8	61	2140	

(a) Sample size, 3 x 4 x 16 in.; all others 2 x 2 x 6 in.

(b) Average flexural modulus of elasticity, 0.25 x 10^6 psi.

Av = average, S = Standard deviation, V = coefficient of variation strengths (average, 2058 psi) can be produced regardless of the encapsulation method.

The underwater encapsulation method (described in Section 4.1.1) was also used. Specimens produced by this method did not have the strength or the esthetic appearance obtained by use of the forms. An average flexural strength of 1285 psi was obtained for specimens containing 56 wt % polymer and having a final density of 64 lb/ft^3.

The results from the screening tests indicate that samples with high polymer loadings, uniform polymer distribution, and good surface appearance can be produced by use of the following techniques.

1. Cast specimens in metal forms; cure and dry.
2. Impregnate in the form by using a viscous ($\approx$50 cps) monomer in conjunction with the vacuum-soak process.
3. Radiation-polymerize in the forms at a maximum radiation intensity of 3×10^5 rads/hr.

5.4.3 Perlite Concrete Impregnated with MMA or Polyester-Styrene

Although the screening test results were extremely encouraging, further attempts were made to reduce the variation in strength that occurred. Since well-impregnated specimens were being produced, the development of techniques for fabricating uniform perlite cylinders was emphasized. Parameters investigated included (1) removal of the perlite fines, (2) exclusion of the air entraining agent, (3) addition of steel and glass fibers, and (4) mechanical vibration or tamping.

Elimination of the air-entraining agent seems to have the most promise, although additional work on mechanical vibration or tamping appears warranted.

Specimens of 1:8 and 1:6 non-air-entrained perlite concrete were prepared, impregnated with a 20% PMMA solution while in metal forms, and radiation polymerized. The results are given in Table 28. The exclusion of the air-entraining agent produced composites with high final densities but with improved strength properties and lower polymer contents. Improvements in surface appearance were also observed. However, the 1:6 perlite samples were not completely impregnated, probably because of the high specimen density and high monomer viscosity.

Based upon these and earlier results, a series of non-air-entrained specimens of 1:8 perlite concrete and air-entrained 1:5 perlite specimens were prepared for evaluation by the FHWA and BNL. Perlite 1:5 was selected because its

Table 28

Compressive and Tensile Splitting Strengths of

Non-Air-Entrained Perlite Concrete

1:6 & 1:8 Perlite
Monomer, 20% PMMA solution (viscosity, ≈60 cps)
Radiation-induced polymerization
Impregnation and polymerization in forms
Specimens dried at 230°C (110°C)
Specimen size, 3-in-diam x 6-in-long cylinders

Sample No.	Density, lb/ft^3 dry	Density, lb/ft^3 final	Polymer content wt.%	Polymer content vol.%	Compressive strength, psi	Tensile splitting strength psi
1:6-A-1	39	73.4	46.9	46.7	---	1550
1:6-A-2	39.6	77.4	49.0	51.5	---	1570
1:6-A-3	38.6	70.0	44.8	42.5	---	1110
1:8-A-1	32	71.3	55.2	53.4	7920	---
1:8-A-2	32	71.9	55.6	53.8	7480	---
1:8-A-3	32	71.7	55.4	53.9	8200	---
1:8-A-4	32	71.8	55.5	54.1	---	1510
1:8-A-5	31	70.2	55.9	53.3	---	1570
1:8-A-6	32	71.8	55.5	54.1	---	1550

dry density was higher than that of 1:6 but similar to that of non-air-entrained 1:8. Tests to be performed in the series include compressive, tensile splitting and flexural strengths, fatigue, impact testing, and freeze-thaw durability. Duplicate sets of specimens from each material were impregnated with polyester-styrene and MMA.

The results of the compressive, tensile splitting, and flexural strength measurements for the 1:5 and 1:8 specimens are given in Tables 29 and 30 and the impregnation data for the remaining samples are given in Tables 31 and 32. In general, the strength results for any given composite are fairly uniform. Samples made with MMA had the highest strengths and in most cases the specimens impregnated with polyester-styrene had the smallest strength variations.

Fatigue test data are given in Table 33 and Figure 4. Compared with data given in ASTM publication STP-169A for normal weight structural grade concrete, all the impregnated insulating-type lightweight specimens had a shorter fatigue life. Although the data exhibit considerable scatter, reductions in fatigue life with increasing load are apparent for the 1:5 perlite samples. MMA-impregnated specimens had slightly better properties than specimens impregnated with polyester-styrene. The results from the 1:8 perlite are too scattered to permit any conclusions.

Table 29

Summary of Results for MMA-impregnated Perlite Concrete Test Series

Monomer, 20% PMMA solution (viscosity=70 cps)
Vacuum-soak impregnation
Encapsulation method excess monomer in forms
Radiation-induced polymerization
All specimens dried to constant weight at 230°F (110°C)
All specimens tested at BNL

Sample No.	Aggregate mix ratio	Dry density, lb/ft³	Polymer Content Wt %	Polymer Content Vol%	Final density, lb/ft³	Compressive strength,(a) psi		Tensile splitting strength,(a) psi		Flexural strength,(b) psi	
Control(c)	1:8 w/o AEA(d)	-	0	0	-	170		40		8	
8N105	"	26.0	62.4	58.7	69.2	6720	Av = 7700	-		-	
107	"	25.2	63.1	58.7	68.4	7975	S = ±713	-		-	
108	"	25.3	63.7	60.3	67.9	8400	V = 9.3%	-		-	
8N109	"	25.6	62.5	58.1	68.4	-		1148	Av = 1328	-	
110	"	25.6	63.5	60.7	70.3	-		1585	S = ±187	-	
112	"	25.7	62.6	58.6	68.9	-		1250	V = 14.1%	-	
8N125	"	28.1	57.6	51.2	66.4	-		-		2560	Av = 1700
126	"	27.2	58.6	52.8	65.8	-		-		1434	S = ±568
127	"	26.0	61.0	55.8	67.3	-		-		1012	V = 33.4%
128	"	28.0	58.3	53.3	67.3	-		-		1793	
Control(c)	1:5	-	0	0	-	250		50		10	
50108	"	29.2	58.5	56.0	70.5	7480	Av = 7395	-		-	
109	"	31.2	55.3	52.4	69.8	6770	S = ±479	-		-	
141	"	29.4	59.9	59.7	73.4	7935	V = 6.5%	-		-	
50101	"	28.8	58.5	55.2	69.5	-		1270	Av = 1151	-	
102	"	29.0	58.3	55.3	69.7	-		1293	S = ±184	-	
140	"	30.7	58.2	58.2	73.5	-		891	V = 16%	-	
50110	"	27.1	58.4	51.8	65.3	-		-		2720	
111	"	33.3	51.1	47.3	68.1	-		-		2485	Av = 2620
138	"	28.0	59.3	52.6	68.8	-		-		2520	S = ±119
150	"	27.6	58.4	55.5	66.3	-		-		2755	V = 4.5%

(a) Specimen size, 3-in. diameter x 6-in. long cylinders.

(b) Specimen size, 2 x 2 x 10-in. bars.

(c) Perlite Institute Catalog No. 30.

(d) Without air entraining agent.

Av = average, S = standard deviation, V = coefficient of variation.

Table 30

Summary of Results for Polyester Styrene-Impregnated Perlite Concrete Test Series

Monomer, 50% polyester - 50% styrene[a].
Vacuum-soak impregnation.
Encapsulation method, excess monomer, in forms.
Radiation-induced polymerization.
All specimens dried to constant weight at 230°F (110°C)
All specimens tested at BNL.

Sample No.	Aggregate mix ratio	Dry density, lb/ft^3	Polymer Content Wt %	Polymer Content Vol%	Final density, lb/ft^3	Compressive strength,[b] psi		Tensile splitting strength,[b] psi		Flexural strength,[c] psi	
Control[d]	1:8 w/o AEA[e]	-	0	0	-	170		40		8	
8N101	"	25.8	64.7	60.6	73.1	6580	Av = 6000	-		-	
102	"	25.6	64.6	60.0	72.5	6620	S = ±849	-		-	
103	"	25.6	60.6	50.5	65.0	4800	V = 14.1%	-		-	
8N104	"	26.2	63.4	58.2	71.6	-		762	Av = 820	-	
106	"	25.3	65.2	60.9	72.9	-		849	S = ±41	-	
111	"	25.3	65.6	62.0	73.7	-		848	V = 5%	-	
8N122	"	21.7	66.1	54.4	64.2	-		-		1090	Av = 1218
124	"	22.4	67.1	58.5	68.0	-		-		1053	S = ±207
150	"	23.9	64.4	55.6	67.3	-		-		1510	V = 17%
Control[d]	1:5	-	0	0	-	250		50		10	
50121	"	31.4	58.9	57.7	76.4	6030	Av = 6083	-		-	
122	"	29.5	61.0	59.2	75.7	5980	S = ±113	-		-	
123	"	31.8	58.1	57.5	75.9	6240	V = 1.9%	-		-	
50120	"	28.3	62.2	59.8	75.0	-		762	Av = 749	-	
142	"	30.5	59.1	56.5	74.7	-		736	S = ±13	-	
50132	"	27.9	58.7	50.9	67.7	-		-		1640	Av = 1406
134	"	27.1	60.2	52.6	68.2	-		-		1528	S = ±277
136	"	30.2	57.1	51.6	70.5	-		-		1522	V = 19.7%
137	"	25.5	63.6	57.2	70.1	-		-		933	

(a) Monomer mixture formulated by diluting Plaskon 941; composition, 23% styrene - 77% Plaskon 941.

(b) Specimen size, 3-in. diameter x 6-in. long cylinders.

(c) Specimen size, 2 x 2 x 10-in. bars.

(d) Perlite Institute Catalog 30.

(e) Without air entraining agent.

Av = average, S = standard deviation, V = coefficient of variation.

Table 31

MMA Impregnation Data for Perlite Concrete

1:5 Perlite.
Monomer, 20% PMMA solution and 50% polyester - 50% styrene[a].
Vacuum-soak impregnation in forms.
Radiation-induced polymerization.
Specimens dried at 230° F (110°C)

Sample No.	Sample size (nominal)	Density, lb/ft^3 Dry	Density, lb/ft^3 Final	Polymer content Wt %	Polymer content Vol%
	PMMA[b]				
50117	3x3x16-in.	29.2	65.7	55.5	49.6
50118	"	25.8	64.2	59.8	52.1
50119	"	26.3	65.2	59.6	52.8
50112	2x2x20-in.	24.7	68.1	63.8	59.0
50113	"	26.0	68.8	62.2	58.2
50125	"	27.3	65.9	58.5	52.3
50151	2x2x4 -in.	33.5	69.8	52.0	49.3
50152	"	33.4	70.3	52.4	50.0
	Polyester-styrene[c]				
50114	3x3x16-in.	28.8	68.3	57.8	50.6
50115	"	28.0	69.9	59.9	53.7
50116	"	27.5	68.0	59.5	51.9
50126	2x2x20-in.	28.4	58.5	51.3	38.5
50127	"	27.6	57.0	51.5	37.7
50129	"	29.5	68.0	56.6	49.4
50131	2x2x4 -in.	26.2	68.5	61.7	54.2
50153	"	26.6	67.5	60.5	52.4
50154	"	26.6	66.5	60.0	51.2

[a] Vol % based upon a polymer density of 1.18 g/cc.

[b] Vol % based upon an estimated polymer density of 1.25 g/cc.

[c] Monomer mixture formulated by diluting Plaskon 941; composition, 23% styrene - 77% Plaskon 941.

Table 32

Polyester-Styrene Impregnation Data for Perlite Concrete

1:8 Perlite without air entraining agent.
Monomers, 50% polyester - 50% styrene[(a)] and 20% PMMA solution.
Vacuum-soak impregnation in forms.
Radiation-induced polymerization.
Specimens dried at 230°F (110°C).

Sample No.	Sample size (nominal)	Density, lb/ft^3 Dry	Density, lb/ft^3 Final	Polymer content Wt %	Polymer content Vol%
		PMMA[(b)]			
8N114	3x4x16-in.	21.9	58.1	62.3	49.6
8N115	"	21.7	59.2	63.3	50.9
8N116	"	21.5	58.6	63.3	50.4
8N129	2x2x20-in.	27.6	64.1	56.9	49.6
8N130	"	26.0	63.5	59.0	50.9
8N131	"	23.1	64.5	64.1	56.1
8N133	2x2x4 -in.	23.9	67.5	64.6	59.2
8N154	"	23.9	67.5	64.6	59.2
8N155	"	23.9	67.9	64.7	59.7
		Polyester-styrene[(c)]			
8N113	3x4x16-in.	20.5	69.5	70.5	62.8
8N115	"	19.3	68.4	71.7	62.9
8N118	"	22.8	67.4	66.1	57.2
8N119	2x2x20-in.	20.5	63.8	67.8	52.2
8N120	"	21.6	62.4	65.3	52.3
8N123	"	23.4	68.6	65.8	57.9
8N151	2x2x4 -in.	21.3	66.2	67.8	57.6
8N152	"	20.5	64.1	68.6	55.3
8N153	"	20.7	63.6	67.4	55.0

(a) Monomer mixture formulated by diluting Plaskon 941; composition, 23% styrene - 77% Plaskon 941.

(b) Vol % based upon a polymer density of 1.18 g/cc.

(c) Vol % based upon an estimated polymer density of 1.25 g/cc.

Table 33

Summary of Fatigue Test Results for Impregnated Perlite Concrete

Monomers, 50% polyester - 50% styrene and 20% PMMA solution.
Vacuum-soak impregnation in forms.
Radiation-induced polymerization.
Specimens dried to constant weight at 230°F (110°C).

Sample No.[c]	Monomer	Final density, lb/ft^3	Polymer content, Wt %	S_{av},[a] psi	S_{max},[b] psi	$\frac{S_{max}}{S_{av}}$	Cyclic rate, cycles/min	Cycles to failure
8N129	PMMA	64.1	56.9	1700	1190	0.70	8.5	3,380
8N130	"	63.5	59.0	"	977	0.57	10	1,823
8N133	"	67.5	64.6	"	765	0.45	14	38,965
50112	"	68.1	63.8	2620	972	0.45	5	126,554
50113	"	68.8	62.2	"	1830	0.70	5	409
50125	"	65.9	58.5	"	1400	0.57	6	82,879
8N119	P-S	63.8	67.8	1220	854	0.70	8	51,830
50126	"	58.8	51.3	1410	987	0.70	9.5	288
50127	"	57.0	51.5	"	635	0.45	13	75,884
50129	"	68.0	49.4	"	811	0.57	11	14,879

(a) Modulus of rupture, average of 3 samples.

(b) Maximum stress applied during test.

(c) Sample numbers starting with 8 indicate 1:8 Perlite. Numbers starting with 5 indicate 1:5 Perlite.

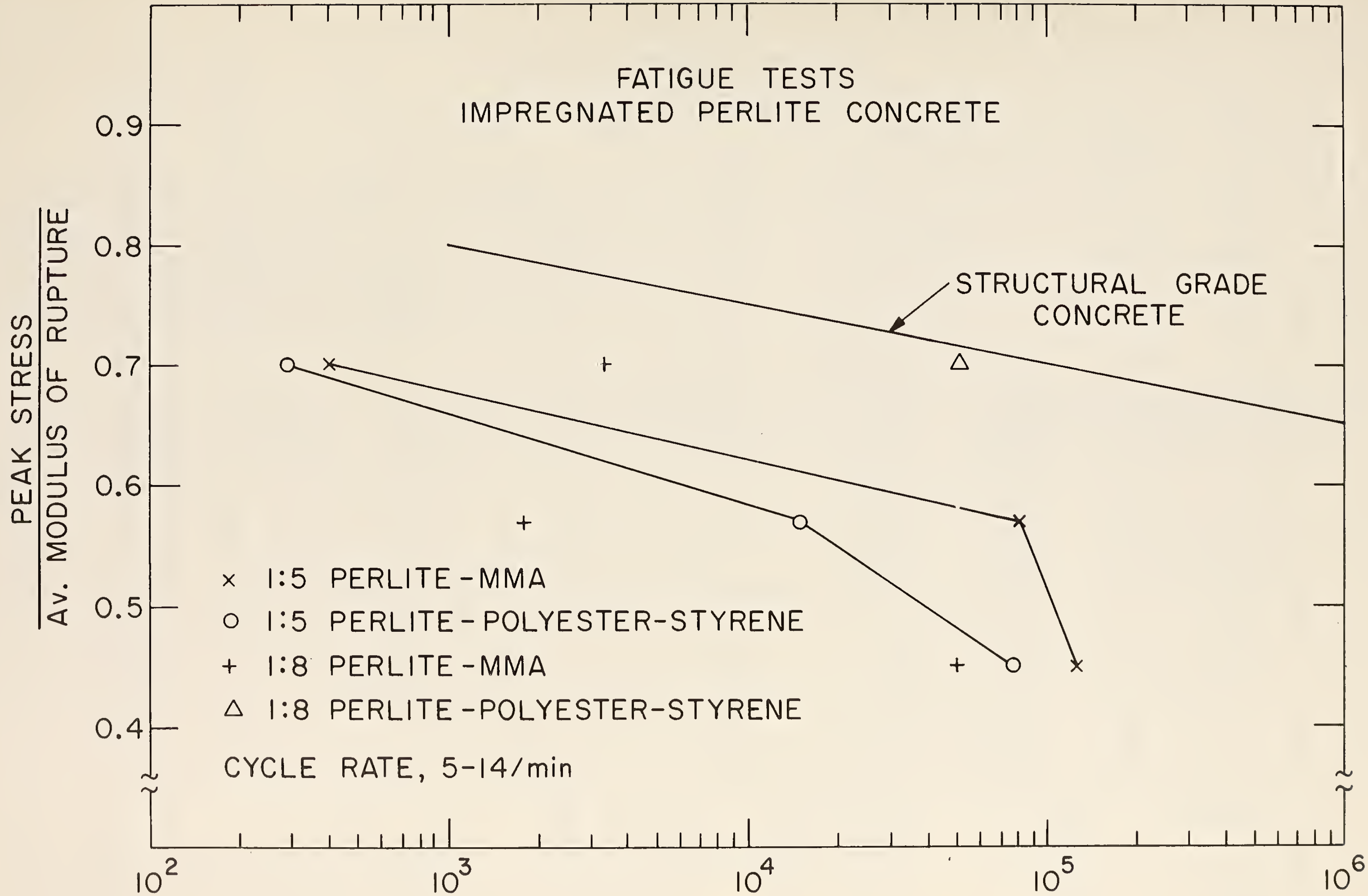

FIGURE 4

Fatigue test results for impregnated perlite concrete.

In next year's program, experiments will be performed in which a plasticizer will be added to the two monomers prior to impregnation. In these experiments, only the 1:5 perlite concrete will be tested.

Impact and freeze-thaw testing of other samples is under way.

5.4.4 Perlite Ferro-Cement Concrete

Because of their high strength and light weight, panels made from polymer-impregnated perlite concrete appear to have applications in prefabricated housing and other types of construction.

Experiments have been performed to determine whether the tensile and flexural properties of perlite concrete could be enhanced by the addition of reinforcing wire mesh. Improved fatigue life would also be expected.

Perlite insulating-type ferro-cement panels, fabricated of 1:6 perlite concrete and 1/2 x 1/2-in., 0.04-in.-diam wire, were impregnated with MMA and radiation polymerized. Flexural strength measurements were made at BNL on the 1x4x16-in. panels. The results are shown in Table 34.

Although there seems to be no increase in flexural strength ($\approx$1820 psi) with increased wire concentration, there is a nearly linear increase in flexural modulus of elasticity,

Table 34

Flexural Strength Results for

Perlite Ferro-Cement

1:6 perlite.
Monomer, PMMA solution, ≈ 50 cps viscosity.
Specimen size, 1x4x16-in.
Wire size, ½x½-in. with 1/8-in.-diam. spacers
Radiation-induced polymerization
Vacuum-soak impregnation in forms
Specimens dried at 230°F (110°C)

Sample No.	Number tested	Layers of wire	Dry density, lb/ft^3	Final composition vol. % [(a)]			Final density lb/ft^3	Flexural strength,[(b)] psi	
				Perlite	Polymer	Metal		Fracture[(c)]	Modulus of elasticity
FE-0	1	0	26.3	53	47	0	60.7	1822	0.38×10^6
FE-1	3	1	30.6	55.5	44	0.5	66.4	1833	0.43×10^6
FE-2	3	2	36.5	55.8	43	1.2	74.8	1870	0.53×10^6
FE-3	2	3	43.8	55.7	42	2.3	84.5	1764	0.57×10^6

(a) Volume concentration based upon a polymer density of 1.18 g/cc.
(b) Average of the number tested.
(c) Defined as the occurrence of the first crack.

from 0.38 to 0.57 x 10^6 psi. The highest concentration of metal used in the samples tested was 2.3 vol %. Normal weight ferro-cement usually contains ≈5 vol % steel. However, increasing the metal content of the composite would also significantly increase its final density. Previous work[4] indicated that compared with a flexural strength of ≈600 psi for normal ferro-cement, impregnation with 60% styrene - 40% TMPTMA increased the strength to 1900 psi.

In all tests, failure was defined as the occurrence of the first crack, even though the maximum load was significantly higher in the case of the samples containing wire. At maximum load, considerable damage and deflection has already occurred, and the pull-out strength of the steel is probably the overriding factor. Additional work is required with this material.

5.4.5 Fabrication of Prototype Lampposts

Several sections of prototype lampposts were fabricated with use of perlite insulating-type concrete. It was originally planned to evaluate these sections as part of the luminairé program discussed in Section 7.2. Some of the shapes cast (see Figure 5) are a 36-in. length of 1:8 perlite pipe with a 9-in. o.d. and a 1¼-in.-thick wall, a 12-in. section of 1:6 perlite pipe, and a 5-ft length of 1:6 perlite tapered tube. The latter was to simulate a portion of a lamppost. A similar length of tapered tube was also made with non-air-entrained 1:8 perlite. The results from these preliminary attempts were encouraging and it appears that fabrication of lamppost sections is technically feasible. Vibrating and tamping equipment to minimize the number of voids should be used in future work. The use of non-air-entrained concrete is also recommended.

The 36-in. length of pipe was impregnated and coated with polyester-styrene (see Figure 5) as follows: (1) After drying the pipe at 230°F (110°C), the outer surface was wrapped with aluminum foil. (2) The monomer, containing promotor and catalyst, was introduced onto the inner surface of the pipe while it was rotated mechanically. The monomer was readily absorbed by the concrete and polymerized in about 40 minutes. (3) The inner surface of the pipe was later coated with polyester-styrene. This method of impregnation seems readily adaptable to lamppost sections.

Durability testing of this section of perlite pipe is in progress to determine the potential application of the material as a lightweight sewer pipe. After exposure to 5% H_2SO_4 for 120 days, the sample, which contains 65 wt % polyester-styrene, shows no evidence of attack. This is shown in Figure 6.

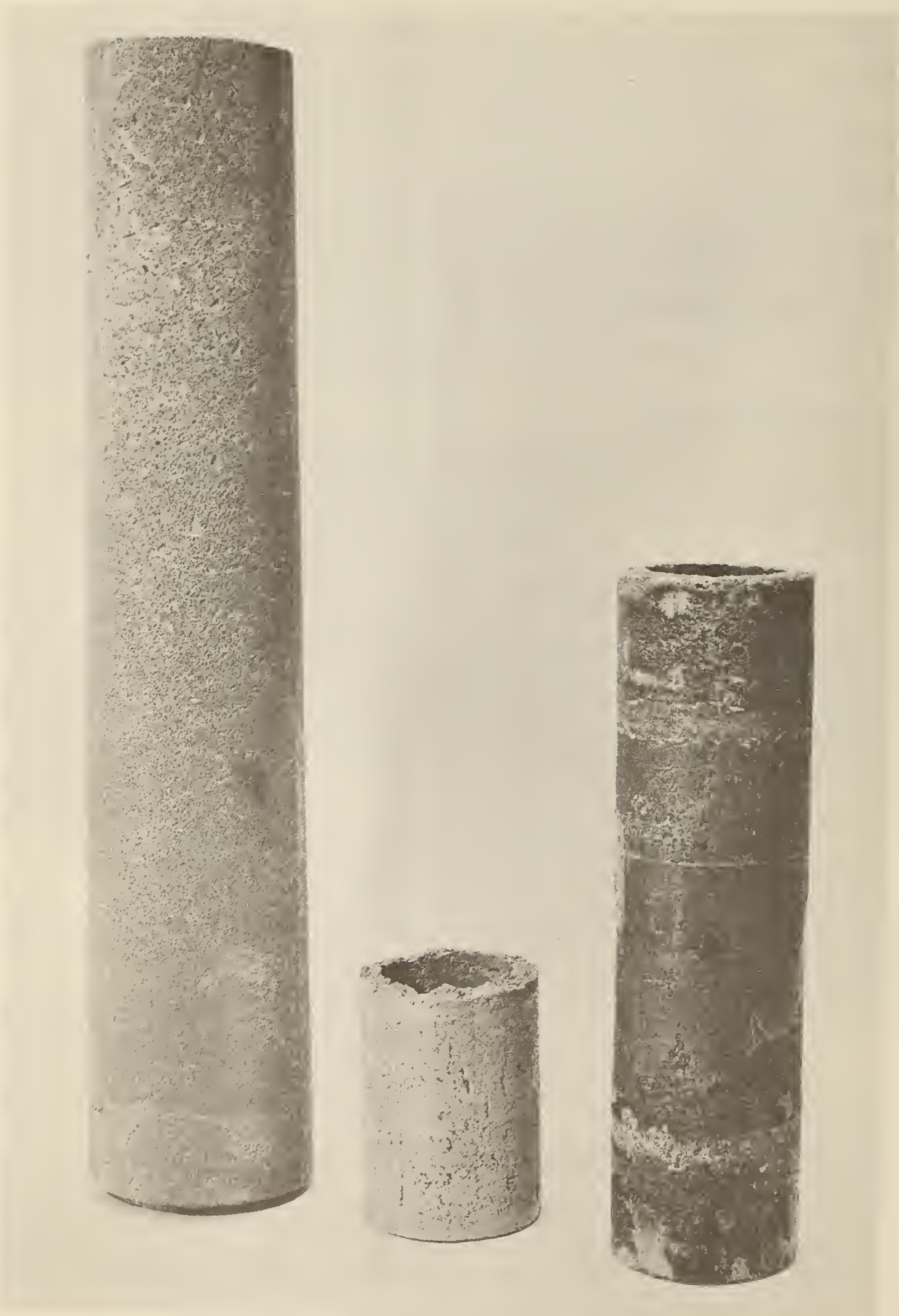

FIGURE 5
Prototype lamppost and pipe
fabricated from perlite concrete.

FIGURE 6

Impregnated perlite concrete pipe after exposure to 5% H_2SO_4 for 120 days.

5.5 Partial Impregnation

Partially impregnated bars and slabs made from concrete containing Riverton limestone aggregate were prepared for abrasion, warping, scaling, and freeze-thaw testing. The techniques used for impregnation and polymerization were disucssed in Section 4.2. A detailed description of the equipment used was presented earlier.[5]

Twelve bars and slabs impregnated with 67.5% styrene - 32.5% polyester* were polymerized thermally at 167°F (75°C) with use of 1% benzoyl peroxide initiator. Two depths of penetration, 3/4 in. and 3/8 in., were attempted. The impregnation data are given in Table 35. Visual examination of sample No. 95646, which was broken during handling, indicated that the desired 3/4-in. depth of penetration had been attained.

The freeze-thaw scaling tests performed at the FHWA on four 14 x 14 x 3-in. slabs were made by forming a dike of mortar about 1 in. wide and 3/4 in. high around the perimeter of the top surface of the slab. About ¼ in. of water was then placed on the top surface and the slab was placed in a freezer overnight. Each morning (5 days/week) the slabs were removed from the freezer and calcium chloride was sprinkled on the

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*Formulated as follows: 50% styrene - 50% Plaskon 941; viscosity of mixture, ≈9 cps at 77°F (25°C).

Table 35

Partial Impregnation of Reiverton Limestone Concrete With Polyester-Styrene

Monomer, 67.5% styrene - 32.5% polyester[a]
Thermal-catalytic polymerization using 1% benzoyl peroxide at 167°F (75°C).
Samples oven dried at 220°F (105°C) prior to impregnation
Impregnation technique, no vacuum, pressurize to 100 psig after introducing monomer. Hold overnight.

Sample no.	Size	Nominal depth of penetration, in.	Amount of monomer added, g	Polymer loading, %	Estimated polymer loading in penetrated depth, %
95633	14x14x3-in.	3/4	500	2.2	8.8
95634	"	3/4	500	2.2	8.8
95632	"	3/8	250	0.9	7.2
95635	"	3/8	250	1.0	8.0
95646[b]	6x24x3-in.	3/4	190	1.0	4.0
95647	"	3/4	190	1.1	4.4
95648	"	3/4	190	1.1	4.4
95645	"	3/8	95	0.5	4.0
95639	3x24x3-in.	3/4	190	1.7	6.8
95640	"	3/4	190	2.0	8.0
95641	"	3/8	95	1.0	8.0
95642	"	3/8	95	1.0	8.0

(a) 50% styrene - 50% Plaskon 941; viscosity of mixture, 9 cps at 77°F (25°C).

(b) Specimen broken during handling, not returned to FHWA; visual examination indicated 3/4-in. penetration.

surface to melt the ice. After the slabs had reached room temperature the salt solution was rinsed off and the cycle repeated.

Periodically the slabs were examined and the condition of the surface rated. The results of these tests are shown in Table 36, where maximum durability is given a value of 0 and complete disintegration of the surface is assigned a value of 10. It can be seen that compared with the unimpregnated controls considerable improvement in durability was obtained. A correlation with penetration depth is apparent.

Table 36

Scaling Under Freezing and Thawing with Calcium Chloride Treatment of Partially Impregnated Slabs

Specimen	Nominal impregnated depth[(a)]	Rating of Surface at Indicated Cycles					
		20	35	42	70	75	80
95632	3/8 in.	0	2	3	5	5[(c)]	-
95635	"	0	0	0	-	-	-
95633	3/4 in.	0	1	1½	2+	2+	2+[(b)]
95634	"	0	1	1	1	1	1[(b)]
94422[(c)]	0	7	8	9			
94486	0	3	6	6			

(a) Actual depth of polymer about 1 in.

(b) Slabs removed from test; bottom of slab disintegrating

(c) From Ref. 5

6. FUNDAMENTAL STUDIES

A brief investigation was undertaken to see if the Riverton limestone aggregate supplied by the FHWA resulted in a concrete comparable to that prepared with use of a limestone aggregate that was available at BNL. Two series of laboratory concretes were prepared from each aggregate. In the first series, the as-received -3/8-in. aggregate was used. In the second series, only the -3/8 + 4 mesh fractions were used. A screen analysis of the as-received aggregate is given in Table 37. The concrete formulation used was based on standard CP-type concrete, as given in Ref. 1 [(1:2.5:3.4) cement:sand:aggregate; W/C=0.51.] The 1.5-in.-diam. x 3-in.-long samples were water-cured for 28 days, dried at room temperature for 7 days, then oven-dried at 212°F (100°C) for 4 days. Four samples from each group were impregnated with MMA by use of the vacuum-soak technique. Benzoyl peroxide catalyst was used to initiate polymerization which was performed at 158°F (70°C) for 16 hr. Impregnated and nonimpregnated sample ends were not ground parallel. The results from this series are listed in Table 38.

In spite of a lower polymer loading, the Riverton aggregate concrete was significantly stronger than the concrete containing BNL aggregate. The low strength of the BNL aggregate was surprising.

Table 37

Screen Analysis of FHWA and BNL Aggregates

	Amount Retained, %	
Screen Mesh	Riverton Limestone	BNL
-3/8 + 4	87.9	80.0
-4 + 8	11.9	16.6
-8 + 16	0.0	2.5
-16 + 30	0.0	0.4
-30	0.2	0.5

Table 38

Comparison of FHWA and BNL Concretes

Monomer, MMA.
Thermal-catalytic polymerization.

First series, as-received aggregate

Aggregate	Polymer loading, %	Compressive strength,[a] psi
Riverton	0	5,050
	4.8	20,700
BNL	0	5,060
	5.1-5.2	16,800

Second series, aggregate size -3/8 + 4 mesh

Aggregate	Polymer loading, %	Compressive strength,[a] psi
	2.8	7,200
Riverton	3.3	5,760
	3.3	6,400
	5.1	19,310
	0	4,720
BNL	3.3	5,600
	4.9	11,900
	4.9	12,100
	5.1	15,250
	0	3,970

[a] Average of 4 samples.

The second series differed from the first in two important ways. The -3/8 + 4 mesh fraction of both aggregates was used to prepare the concrete, and the polymer-impregnated sample ends were ground smooth and parallel prior to compression testing. In this series the polymer loadings for both concretes varied over a wide range. The reason for this has not been determined. The results of this series are also listed in Table 38.

Although only one Riverton aggregate concrete sample (the 5.1 wt % loading) is comparable to the BNL samples, its strength was considerably higher than that of the BNL samples, and was consistent with the Riverton aggregate results from the first series. Again the low results for the BNL aggregate samples were surprising.

Although there are some unexpected observations in these tests, the results in no way suggest that the Riverton limestone aggregate is inferior to the BNL aggregate. Indeed, it appears to be superior.

7. DESIGN STUDIES

The work for the FHWA covered in this section is divided into two tasks: luminaire support structures for highway applications, and PIC bridge deck assemblies and their associated components. The former must be strong enough to withstand normal service loads including winds of storm force, while on the other hand, it is also required that in a collision the vehicle velocity change (Δv) due to impact be small, preferably in the 2 to 4 mph range.[15] Durability, resistance to chemical attack, and strength considerations, especially when evaluated in terms of the high present-day replacement costs, are the main reasons for the latter task. Substantial savings in dead weight load and in maintenance costs should be realized from bridge designs incorporating the ultrahigh strength and low water permeability properties observed for these materials.[1-4] Before discussing actual designs, a few general remarks are in order regarding the rationale behind the BNL-FHWA Concrete-Polymer Materials Program. It is important to emphasize that the structural behavior of PIC is quite different from that of regular concrete. Whereas PIC exhibits a near-perfect linear stress-strain relationship, as shown in Figure 7, the regular concrete or "control" usually undergoes substantial inelastic deformation before failure. Thus, although PIC is considerably stronger than regular concrete, it is more brittle. It is possible that much of the design data and specifications for regular concrete are not applicable to PIC. It should be pointed out that the distinction between brittle and ductile can be quite arbitrary. Brittleness is not only a material property but also an interaction between the material properties, the shape of the structure, and the type of loading. The same material can be ductile under one set of conditions and brittle under another. In previous discussions reference was made to the conventional engineering concepts of brittleness. Specifically, a material is regarded as brittle if failure of the test specimens occurs with <1½% plastic deformation. This seems to be the case for the test results shown in Figure 7, which would indicate that the mechanisms of failure for PIC are different from those for regular concrete. In view of the brittleness, it is the opinion of the BNL group that a thorough stress analysis of all designs is indicated, with emphasis on localized areas of stress concentrations.

As of now, too few test data are available to yield a clear-cut PIC failure theory. Specifically, as far as practical designs are concerned, information is lacking on fatigue and on the effect of temperature in the service range upon the strength measurements.

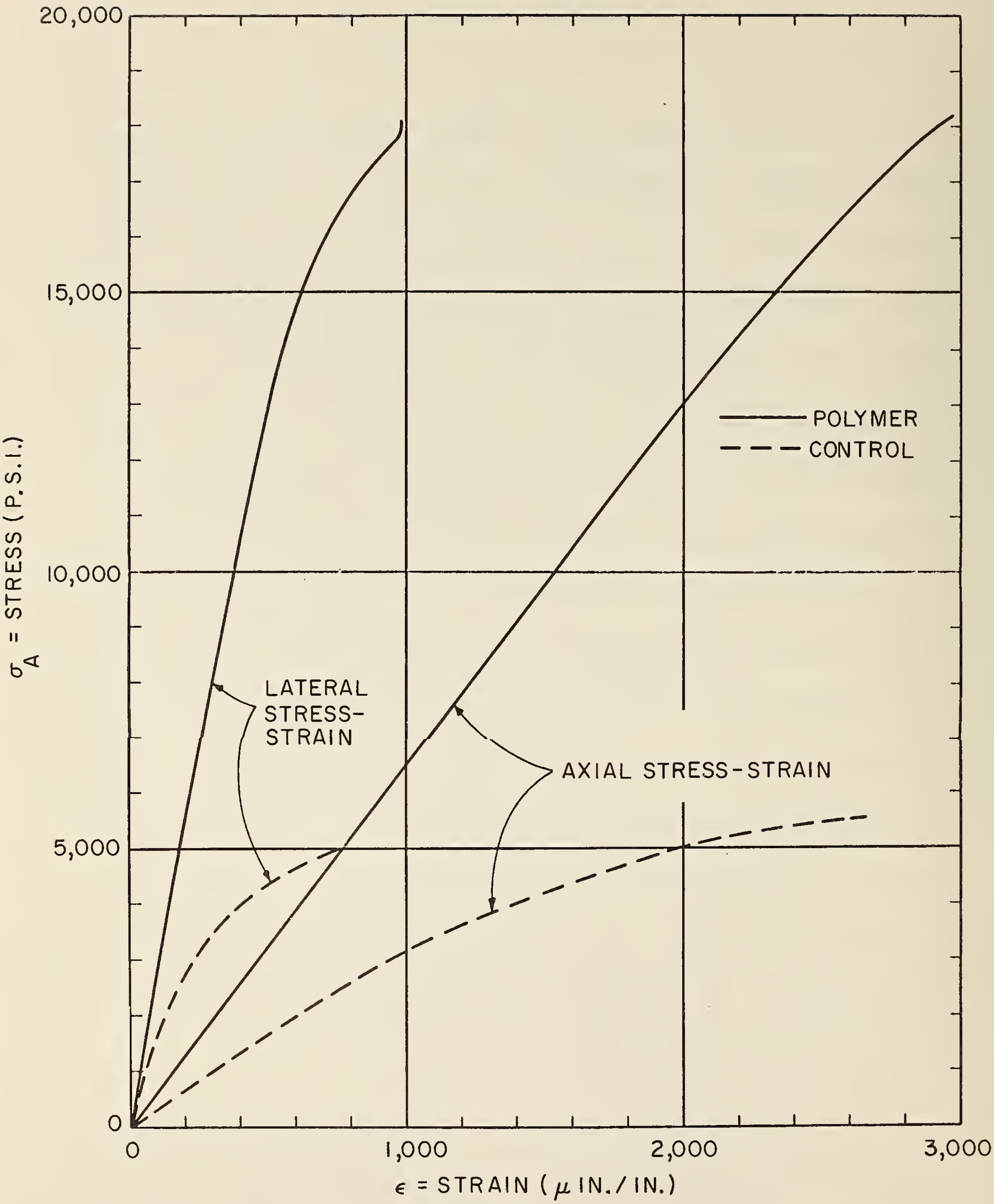


Figure 7

Compressive Stress-Strain Curves for Polymer-Impregnated Concrete and Conventional Control Concrete at 70°F

Monomer, 60% Styrene - 40% TMPTMA

As more material test results become available, a more reliable basis for PIC designs should evolve. For the designs discussed in this report, it is assumed that a stress level equal to 60% of the test ultimate stress values when applied in conjunction with the Rankine maximum normal stress theory will yield a safe design. Load conditions as specified by the AASHO-HS 20-44 standard were assumed for all bridge-deck designs. In view of the lack of test data, current designs can be classified as preliminary.

The size and capacity of current and near-future impregnation facilities is another design consideration. A new and larger impregnation vessel now being installed at BNL is 10 ft long and 5 ft in diameter (internal dimensions).

In order to take maximum advantage of the high compressive strength of PIC materials, the bridge components must be either pretentioned or post-tensioned. The disadvantages of ordinary reinforced concrete would also apply to PIC components reinforced by steel bars. The 1500 to 1800-psi tensile strengths obtained for some of the PIC materials are still too low to prevent the initiation of tensile cracks. On comparing ordinary concrete with PIC for the prestressed or post-tensioned case, however, it is apparent that the PIC is superior. The fourfold increase in compressive strength can be utilized to yield structures that are lighter in weight and yet capable of carrying substantially greater loads than those carried by a thicker reinforced, prestressed, or post-tensioned structure consisting of regular concrete. Only post-tensioned designs were considered for the relatively short bridge components studied by BNL in the FHWA program.

As mentioned previously, a thorough stress and strain analysis of all designs is indicated, with special emphasis on localized areas of stress concentrations. In a previous report[6] for the FHWA, a three-dimensional finite-element computer code capable of analyzing heterogeneous elastic structures was described in detail. Mention was also made of attempts to extend this program so that inelastic cracking effects could also be investigated. This has been accomplished during the past year. If a material behaves in a brittle manner, the crack growth can be followed as it moves from element to element in the structure. From investigations of three-dimensional earth strata design problems[9] and other activities during the past few years, other numerical methods have been developed which are useful in the PIC program.

In many of the design considerations, membrane forces cannot be neglected. In addition, most designs incorporate folds that serve as stiffeners in addition to functioning as containments for prestressing tendons. In these cases, it would be costly to apply the approach mentioned in the previous report.[6] Indeed, in some extreme cases, satisfying the admissibility conditions of the displacement and stress fields for the finite element assembly could be a problem. For these designs a different approach was adopted. A triangular element is utilized in which the membrane and bending deformations are approximated by cubic polynominal functions. This element allows for the idealization of the folds and thin structures while permitting an economical solution. The method applies equally well to the thin-shell, hollow-cone luminaire support structures, where with some additional effort, dynamic effects can also be incorporated into the finite-element stress analysis. A more detailed discussion will appear as a separate BNL publication.[10]

7.1 Bridge Decks

A small two-lane overpass bridge deck test assembly, shown in Figure 8, was designed for testing prototype bridge deck panels. The panels were arranged so that the 10-ft width of the decking faces the oncoming vehicle. If the decking were placed with the 4-ft side facing the oncoming vehicle, the additional supports and assemblies needed would add substantially to the overall costs of the facility.

The method used for the evaluation of the flat bridge decking shown in Figure 8 assumes that the strength, variations of strength, temperature, fatigue data, Young's modulus, and Poisson's ratio for PIC are known. It is then possible to design this structure and ascertain its safety factor by the finite-element approach mentioned previously. Figure 9 shows the idealized mesh containing the elements and nodal points comprising the flat bridge deck. As mentioned, load conditions compatible with those specified for HS 20-44 were assumed. However, whereas the AASHO specifications call for point or line loads, in this analysis it was assumed that the areas of contact are the cross-hatched areas shown in the figure. Thus, the 32,000-lb truck load is idealized as a 165-psi pressure load* acting on the upper surface of elements 67, 68, 91, 92, 139, 140,

*Upon completion of this analysis, FHWA measurements of an AASHO HS-20-44 truck indicated a tire contact area of ≈90 in.^{2}, which would give an average tire contact pressure of ≈98 psi rather than the 165 psi used in these calculations.

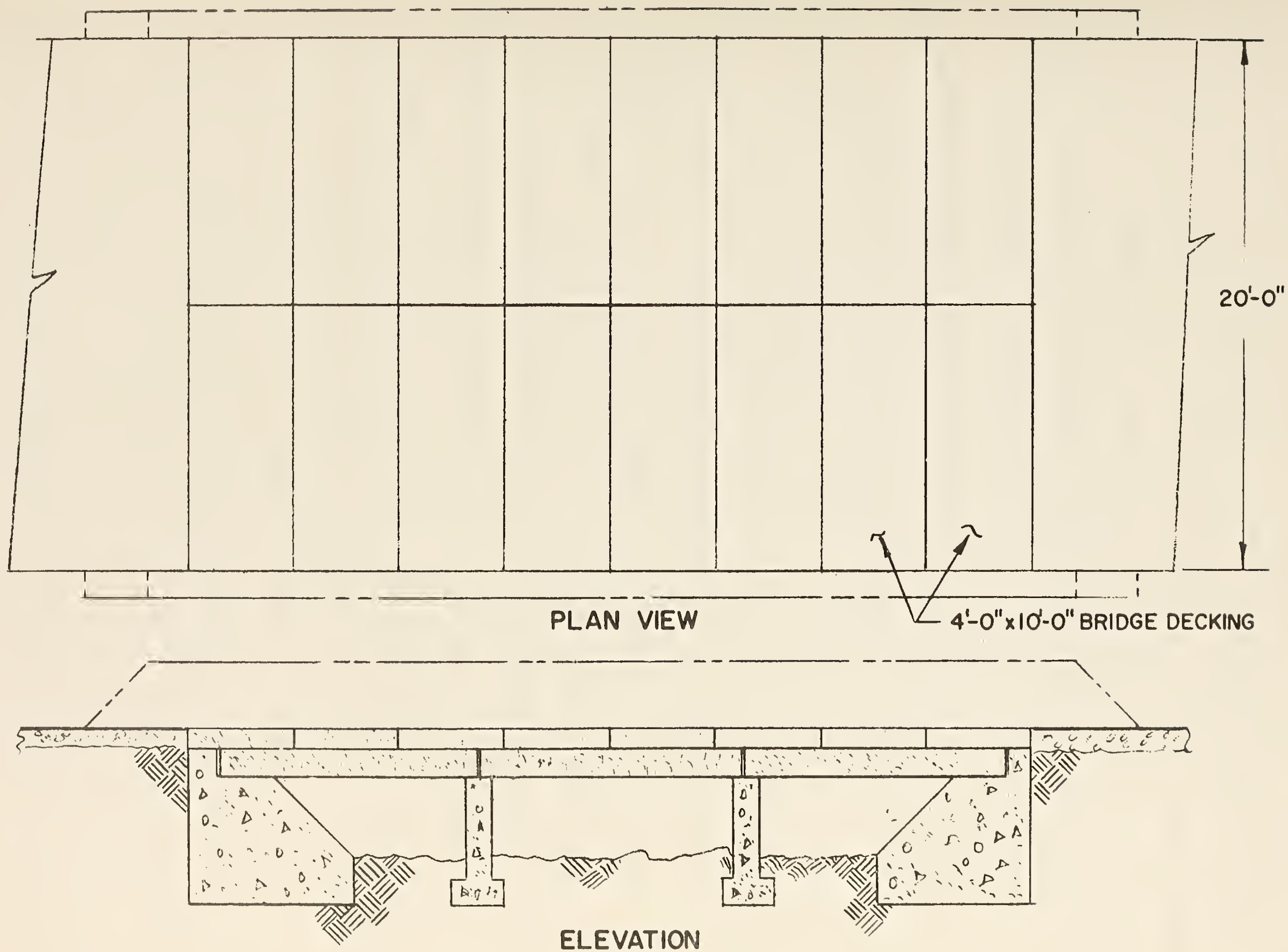


Figure 8
Small Two-Lane Overpass Assembly

163, 164, 331, 332, 355, 356, 403, 404, 427, and 428. Inspection of the ground surface - tire interface of a loaded truck trailer shows that the above condition is closer to reality than point or line contact assumptions. Furthermore, from simplified cantilevered or simply supported beam analogy, it can readily be shown that the maximum overall stress conditions will not be greatly affected if either a concentrated load or a distributed load of about 12-in. bearing length for a 20-ft-long beam is assumed. Local areas adjacent to the applied load will, however, be greatly affected. These conditions are difficult to ascertain with accuracy by analytical means. By bunching elements closely in the areas surrounding the acting loads, a good approximation of the actual local stress condition can be obtained with the finite-element method. In passing, it is worth noting that according to Seni,[11] no changes in AASHO code load specifications have been made since 1944, a date prior to the advent of most computerized numerical techniques. This does not mean that the methods of design and specification limits for bridges have not changed since 1944. Although the most modern methods of design cannot be economically justified for all bridges, they are permitted by the AASHO specifications and are used for selected structures.[16]

The mesh representation in Figure 9 is very coarse. For final analysis, a much closer or bunched mesh configuration should be assumed, especially around the clamped and supported areas of the structure and in the areas adjacent to the moving loads. It is less costly to first approximate the structure with a rough mesh and then follow up with a more detailed analysis if the approximation shows a promising stress pattern.

Other input conditions for the design shown in Figure 9 included seven post-tensioned 150,000 psi tendons which were arbitrarily selected and placed parallel to the y axis. Their respective positions are indicated by the dashed lines running along the entire length of the deck. For this problem it was also assumed that only x, y, and z-direction displacements and those rotations caused by the bending of the plate cross section take place. This last condition implies that all in-plane rotations about the surface-normal "z" are neglected. This is shown in Figure 10. This condition will not hold true for plates containing stiffeners or folds. In such cases, plane rotations about the surface normal "z" must also be included as an integral part of the analysis. Since the bridge deck for the sample problem contains no folds or stiffeners, the conditions shown in Figure 10 apply.

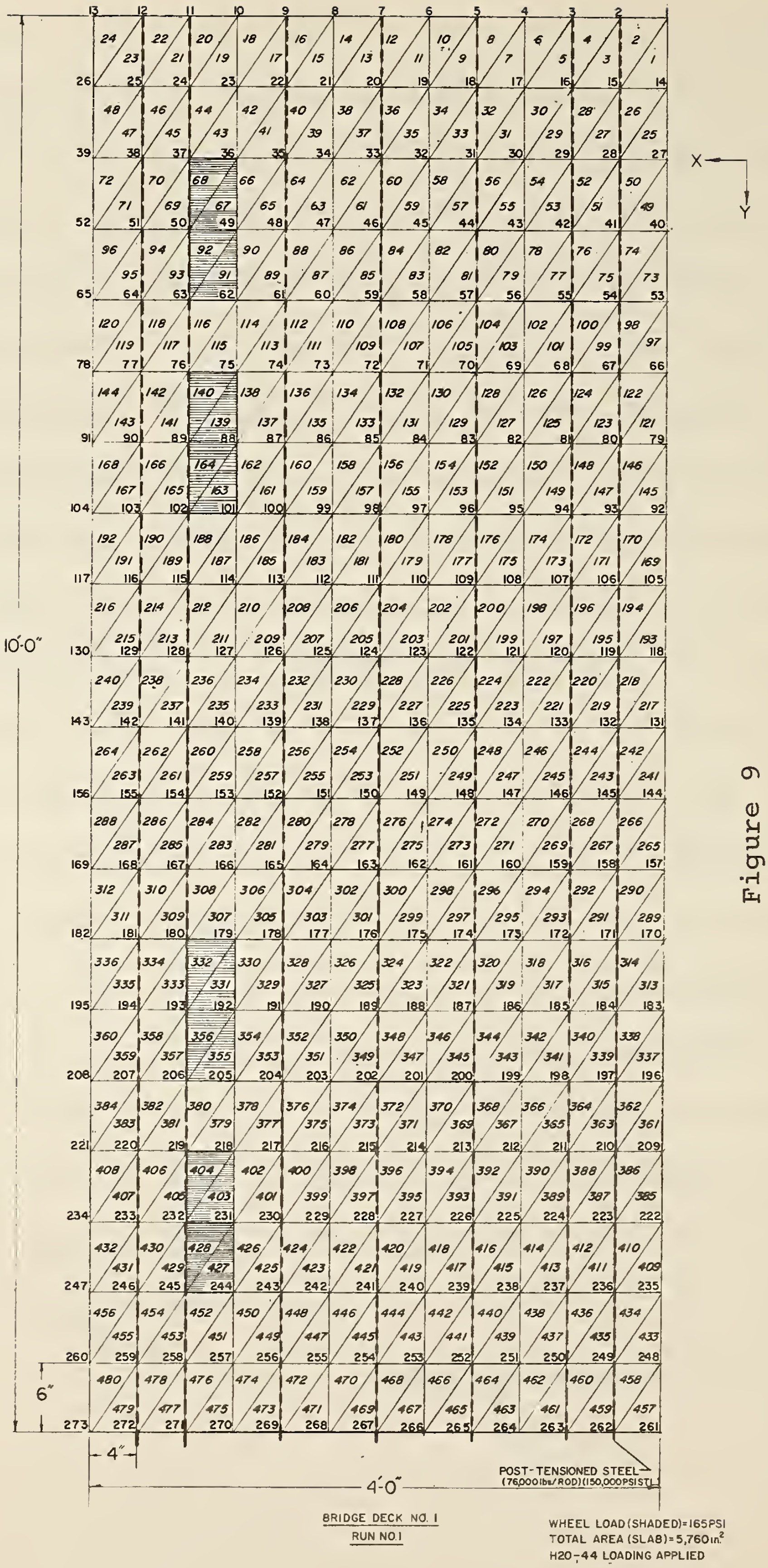


Figure 9 Flat-Plate Finite-Element Idealization

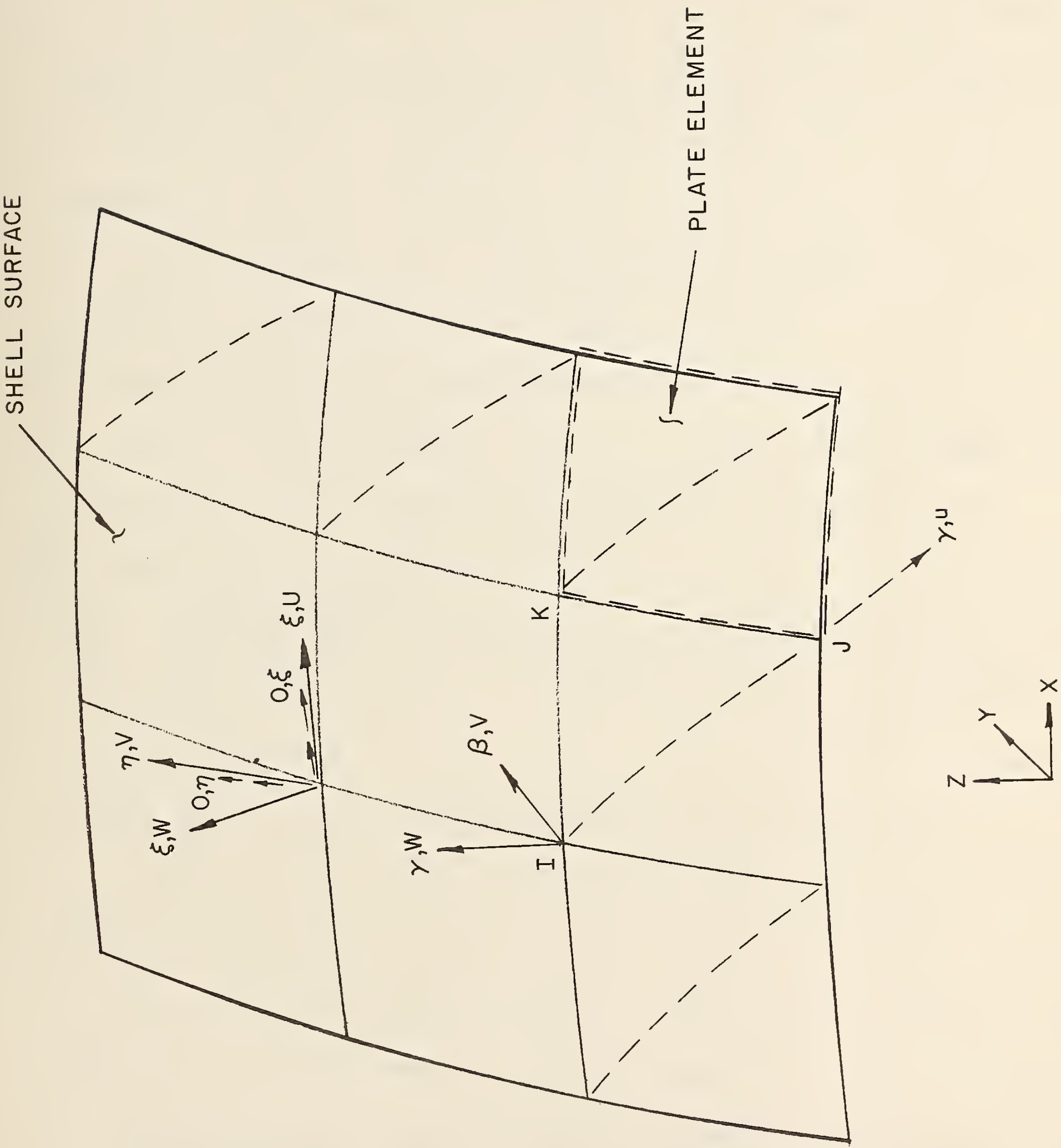


Figure 10

Local and Global Coordinate System for
Plate Elements

The edge containing nodal points 261 through 273 was considered completely restrained for all displacements, while the edge containing nodes 1 through 13 was constrained only from moving and bending in the z and y directions, respectively. Some of the nodal stresses and displacements for this problem, in which it was assumed that the thickness, Young's modulus, and Poisson's ratio were 2½ in., 7×10^6 psi, and 0.25, respectively, are shown in Figures 11 to 13. As indicated by the stress plots, this design would have failed because of excessive tensile stresses near the completely constrained edge. Had this not been the case, a more detailed analysis would have been undertaken. After a satisfactory stress plot is found, various other wheel positions and their effects on the structural behavior of the bridge deck must be included. Thus, a final design requires a substantial number of iterative procedures.

A thorough evaluation of the computer output will indicate in most instances the structural modifications necessary to ensure safe stress levels. Most of the design details of the PIC bridge are the result of careful evaluation of previous computer runs. An example of this technique will be included in Ref. 10, where a complete computer output for the bridge deck shown in Figures 8 and 9 will be evaluated in detail.

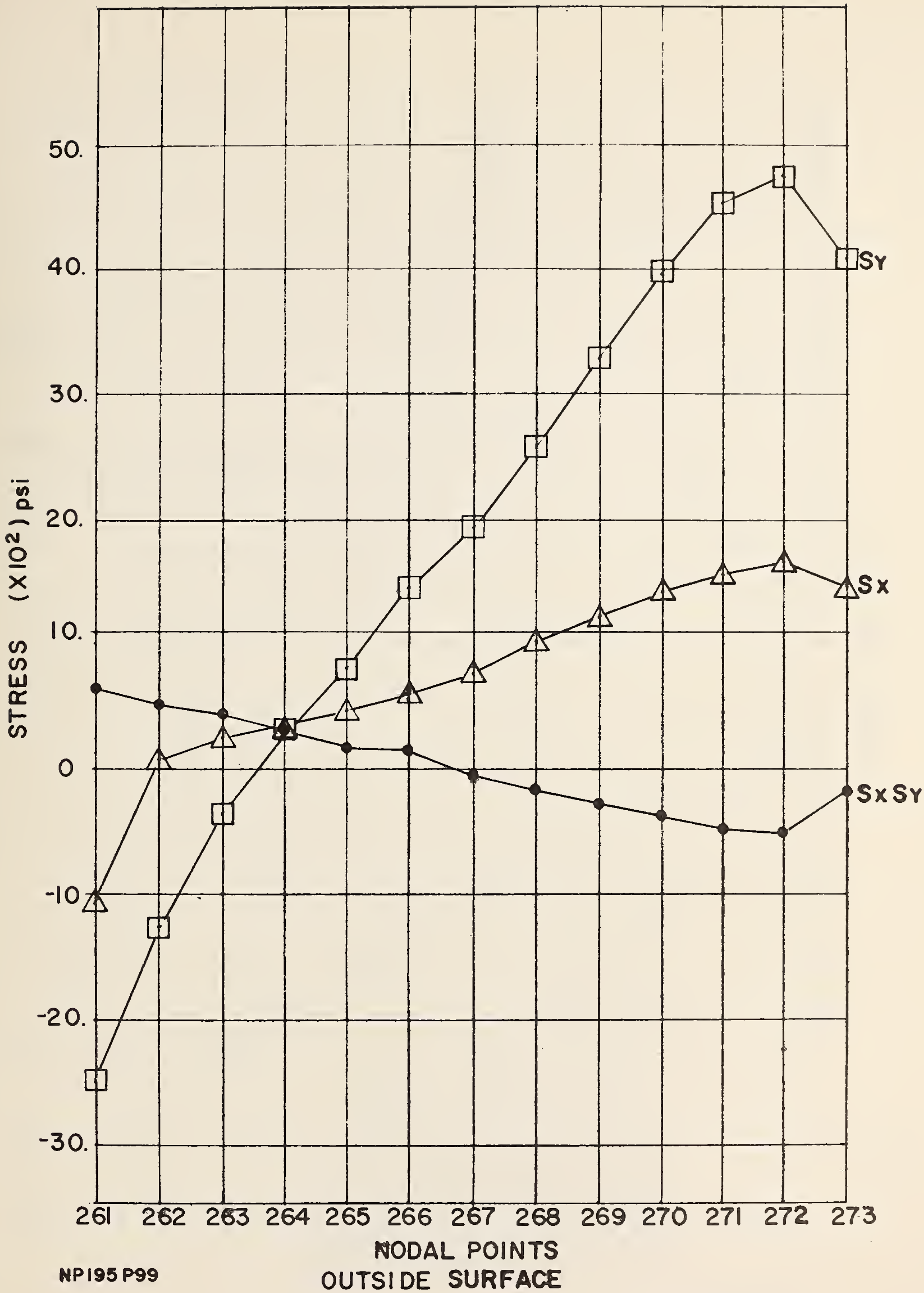


Figure 11

Nodal stresses, outside surface.

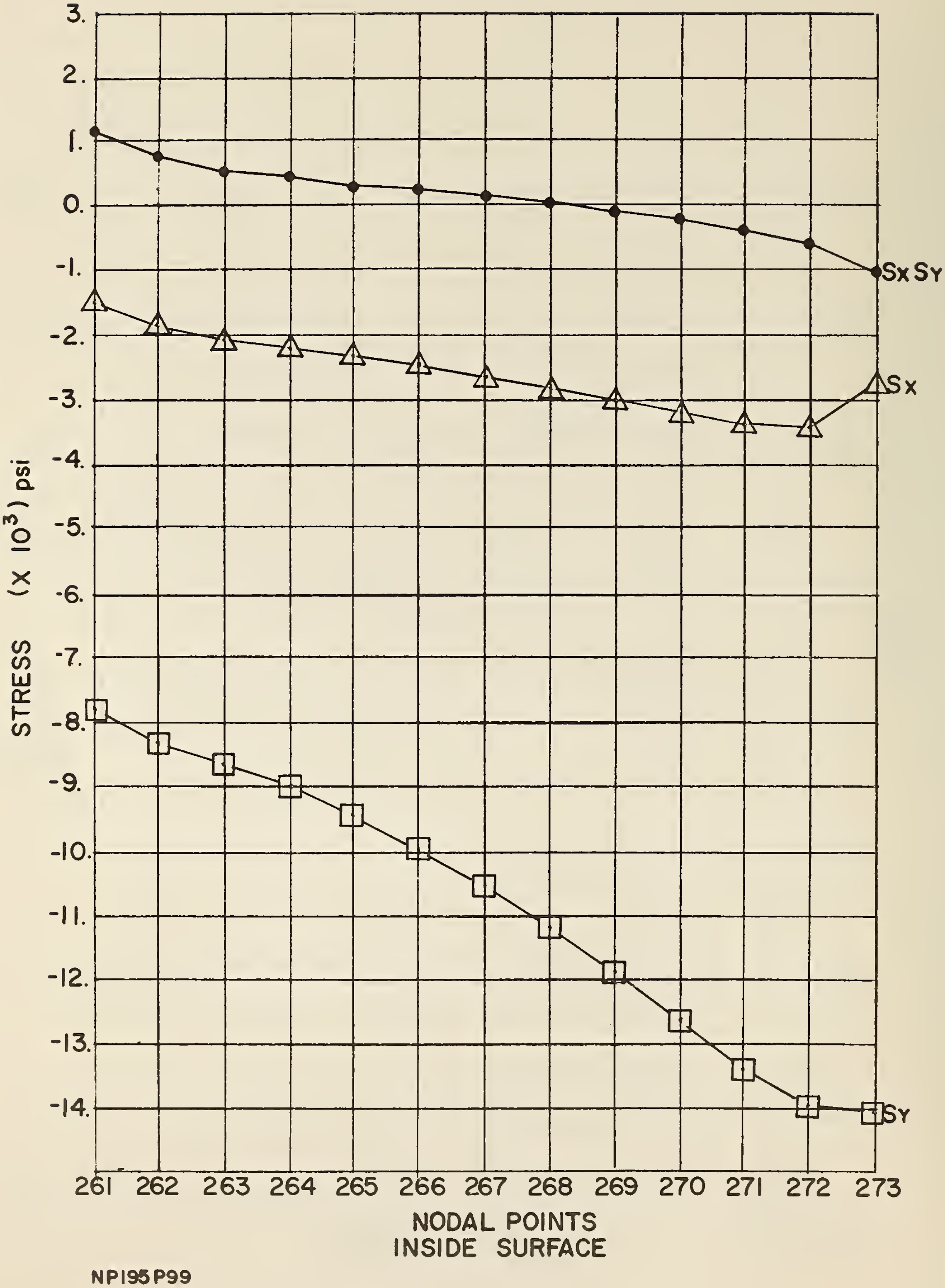
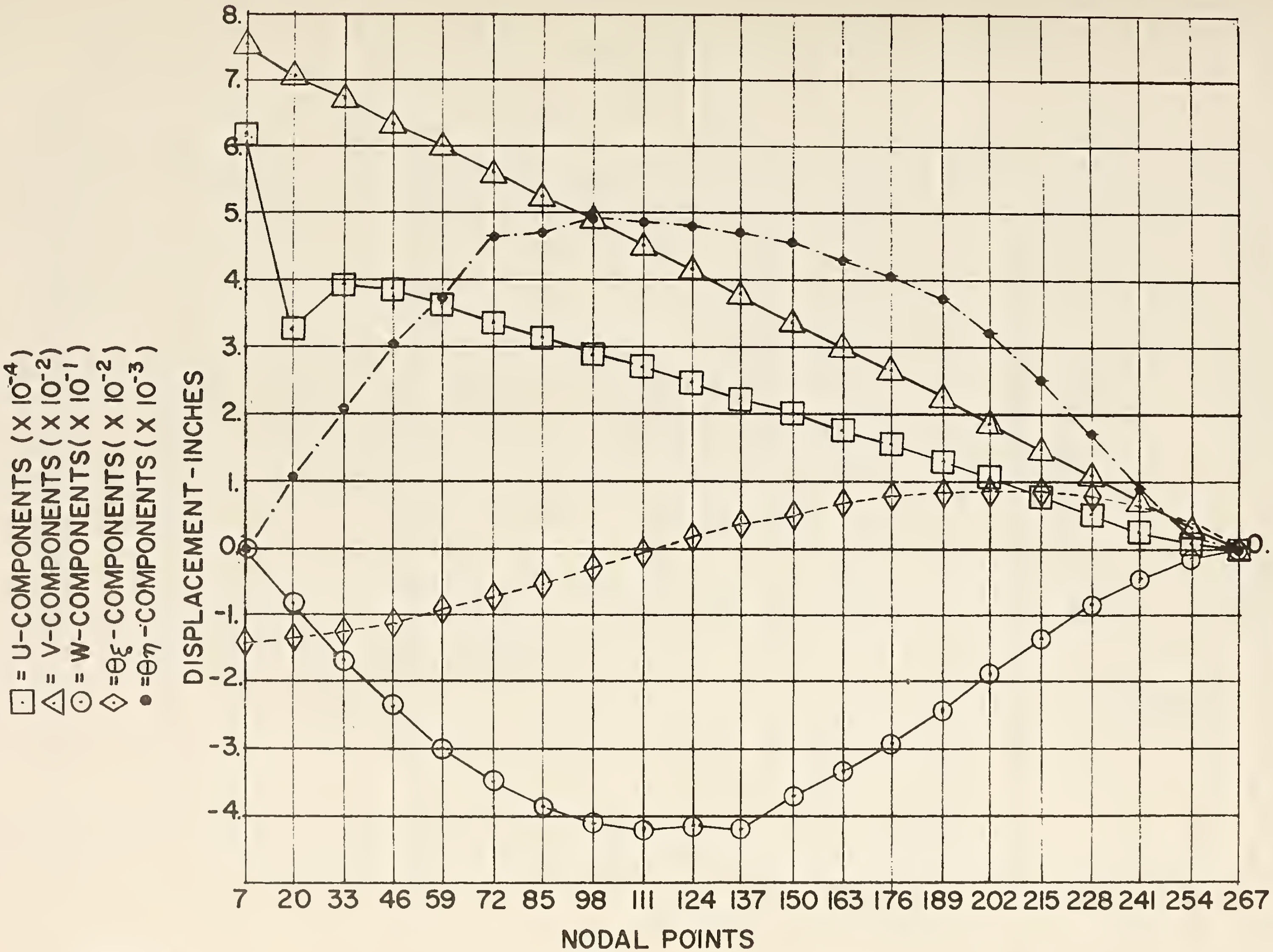


Figure 12

Nodal stresses, inside surface.



NP195P99

Figure 13
Nodal Displacements for a Line
Parallel to the "y" axis

Figure 14 depicts one of the first design modifications for the flat type of bridge deck. Here, the folds on the four-foot sides of the structure serve a twofold purpose. First they reinforce the most highly stressed areas of the bridge deck, and second they serve as part of the assembly scheme for the overall structure. Although only partially complete, the analysis for this structure also indicates stress problems. Two alternatives under consideration are shown in Figures 15 and 16. The former design is a direct outgrowth of the one shown in Figure 14, while the latter seeks to take advantage of the relative stiffness, torsional rigidity, and structural efficiency inherent in box-type structures. The design shown in Figure 15 looks promising. Not only is this structure much stiffer than the deck shown in Figure 14, but the post tensioning wire can be better utilized because of the folds located along the entire 10-ft length of the structure. Larger diameter wire can be used and a more detailed tendon profile is possible with the modifications shown in Figure 16.

Figure 17 depicts some of the fastening details for attaching the bridge decks to the various girders and other structural members of the bridge assembly. Concrete girder-bridge deck

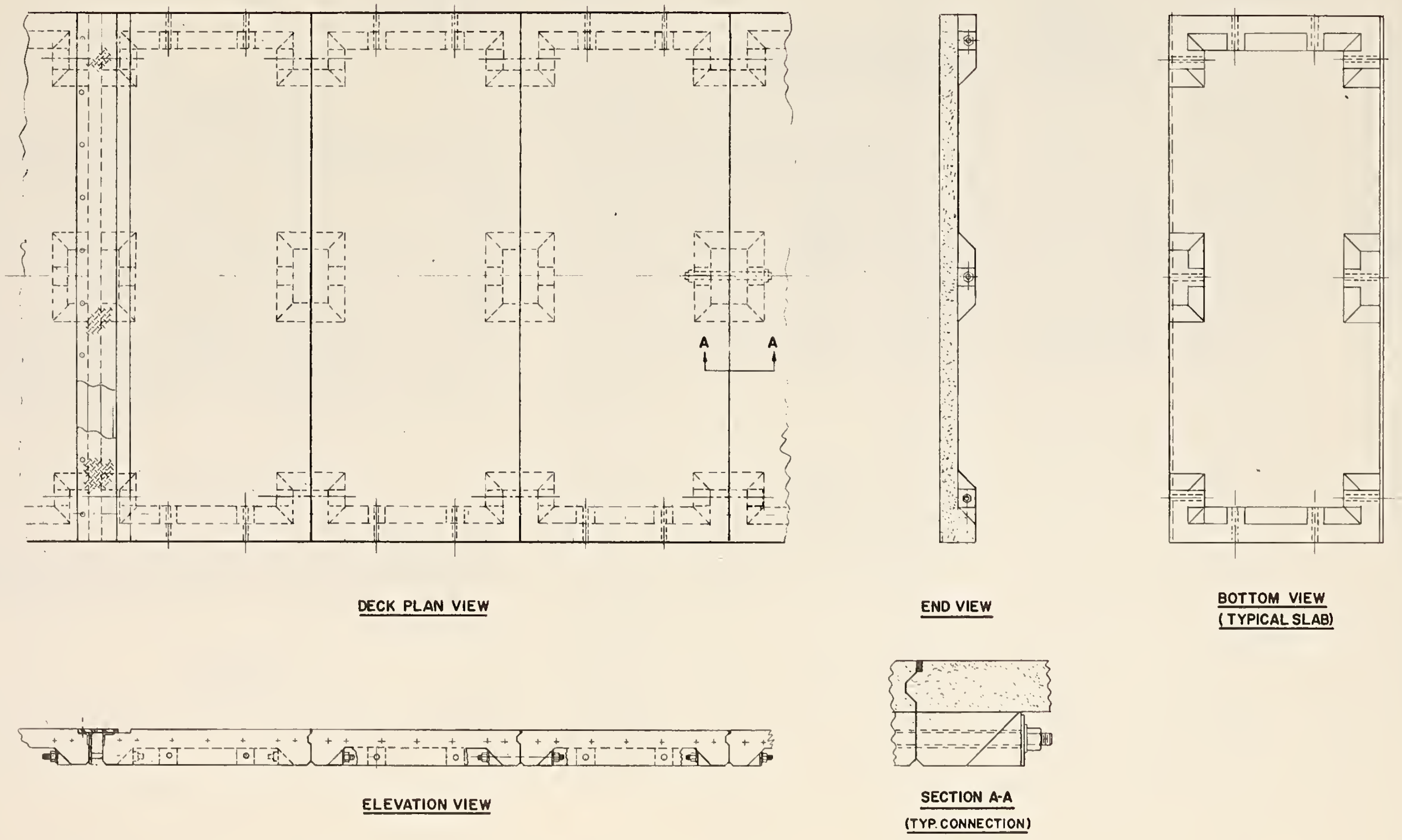


Figure 14

Modified Flat Bridge-Deck Assembly
Detail

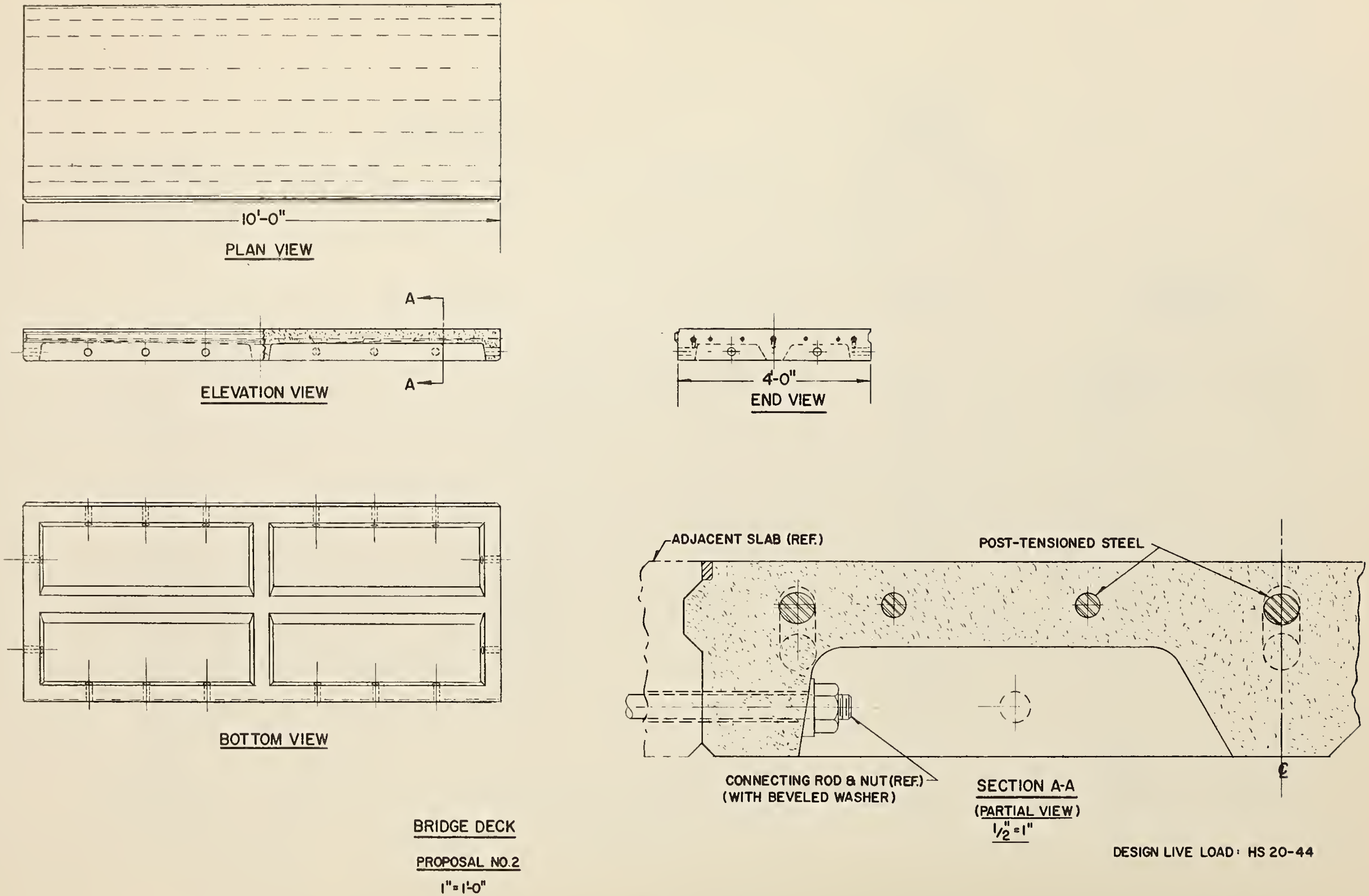


Figure 15

Fold-Stiffened Bridge Deck Design

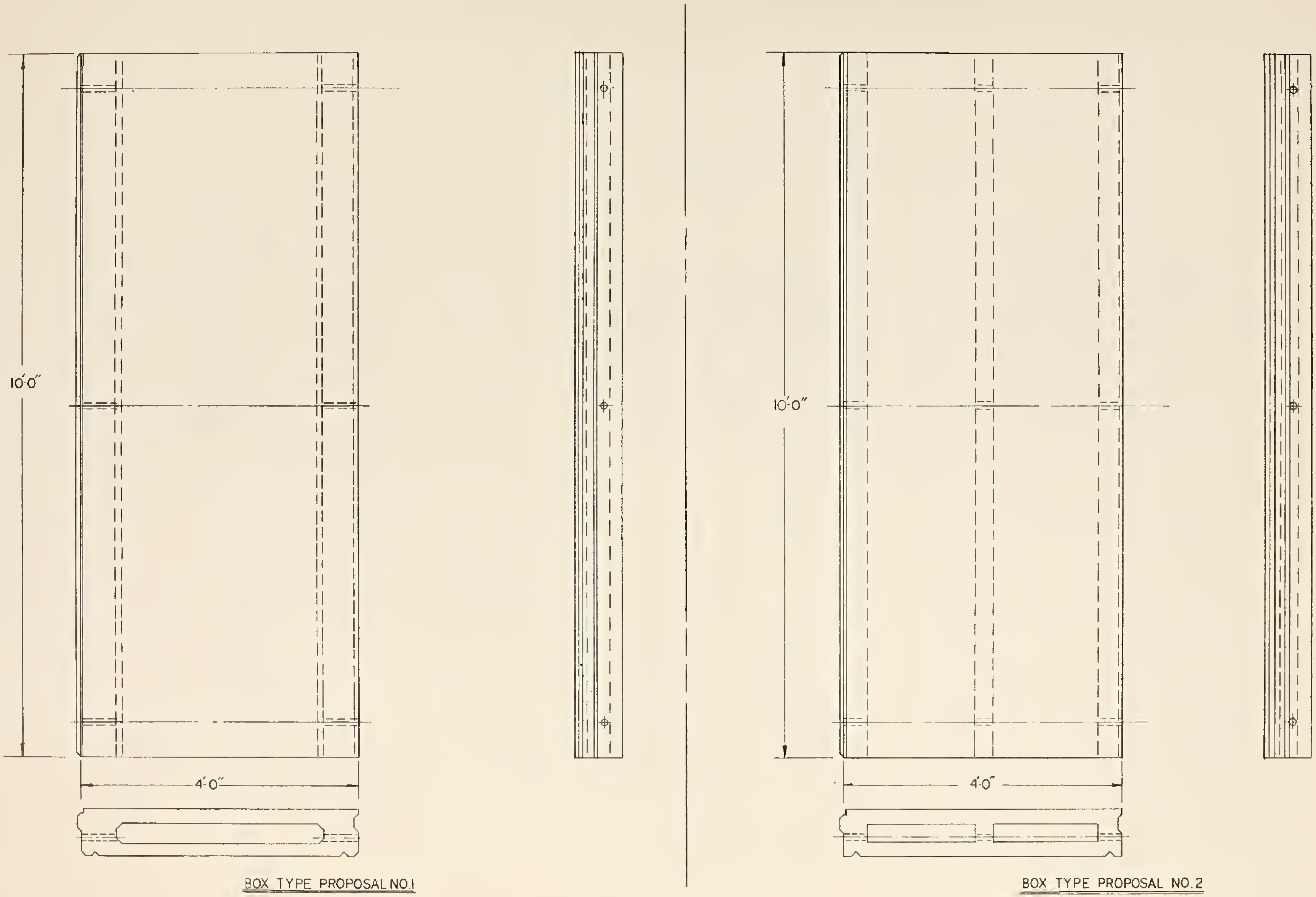


Figure 16

Box-Type Bridge Deck Design

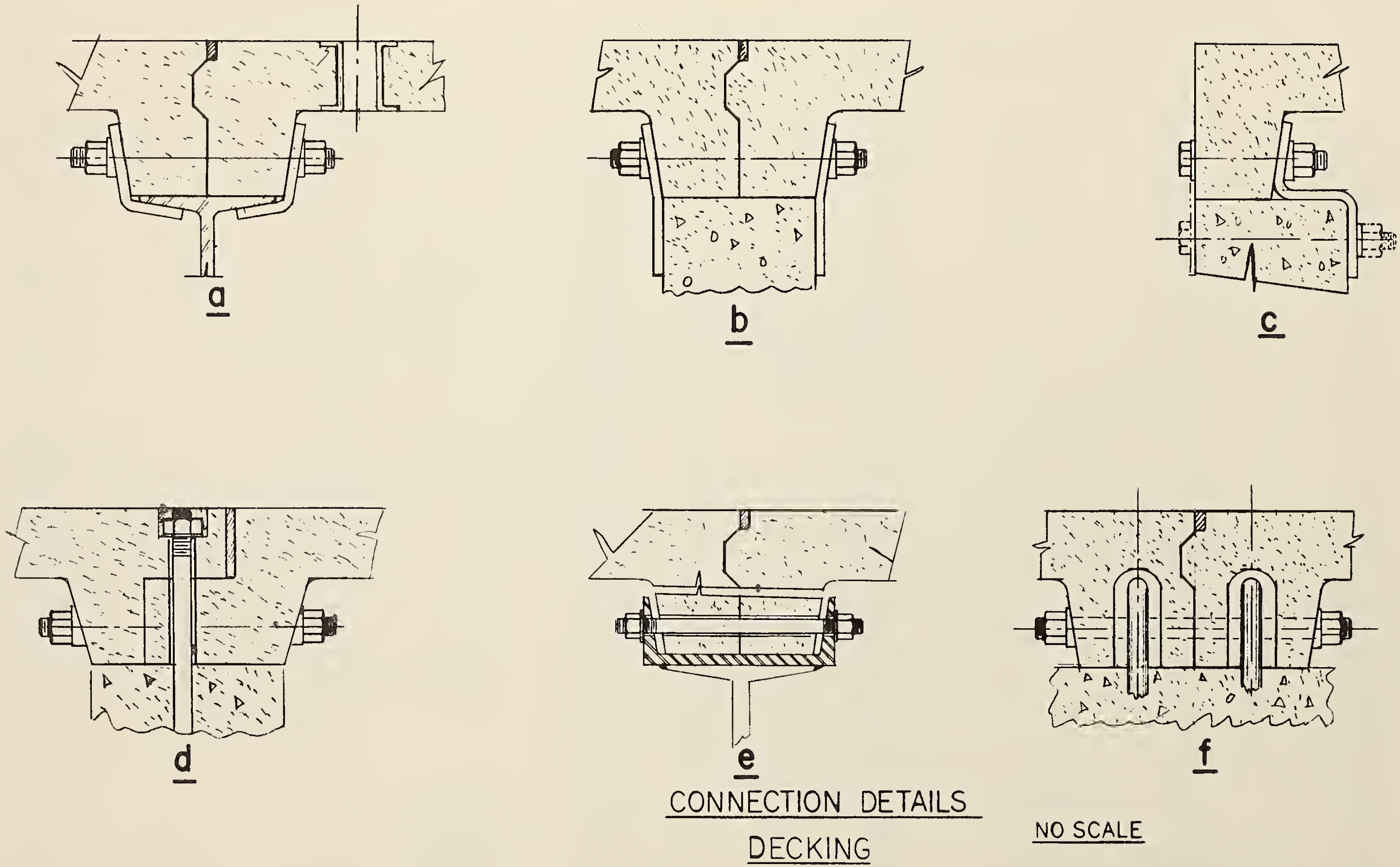


Figure 17

Deck-Bridge Girder-Fastening Details

attachment details are identified in Figure 17 as b and d, while thos for steel I-beams are identified as a and e. The pinned dowel details identified in the Figure as f are similar to those recommended for HS 20-44 designs and are covered in AASHO specification sheets No. 302 and 401. Item c in Figure 17 shows a possible end-piece fastening method, and Figure 18 depicts a typical railing detail. Finally, a conceptual assembly drawing for a bridge using the completely folded bridge deck is shown in Figure 19. The sidewalk areas and other assembly details not mentioned in the previous discussion can be made from regular concrete. However, in view of the loads experienced by the curbing because of automobile-sidewalk interactions, it is felt that these components should be constructed of PIC materials. Although the partial plan view in Figure 19 includes a girder at the midpoint of the bridge deck, it is possible that this component will not be needed. Spacings of 10 ft between supports cannot be ruled out at present.

The analyses of most designs are still in the early stages. This is especially true for the components shown in Figures 15 through 19. They do, however, indicate the direction of possible future BNL bridge-design efforts.

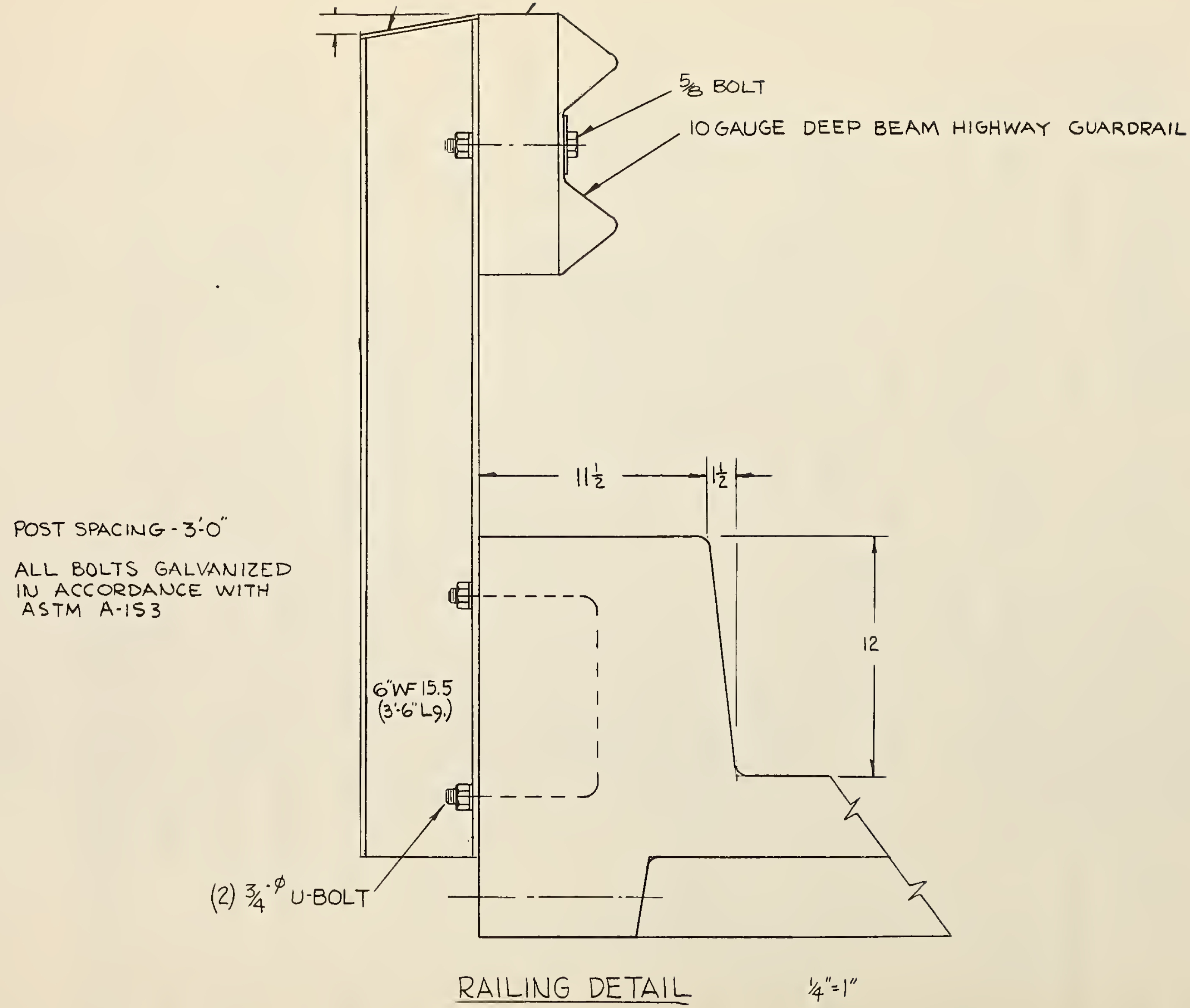


Figure 18

Bridge Railing Detail

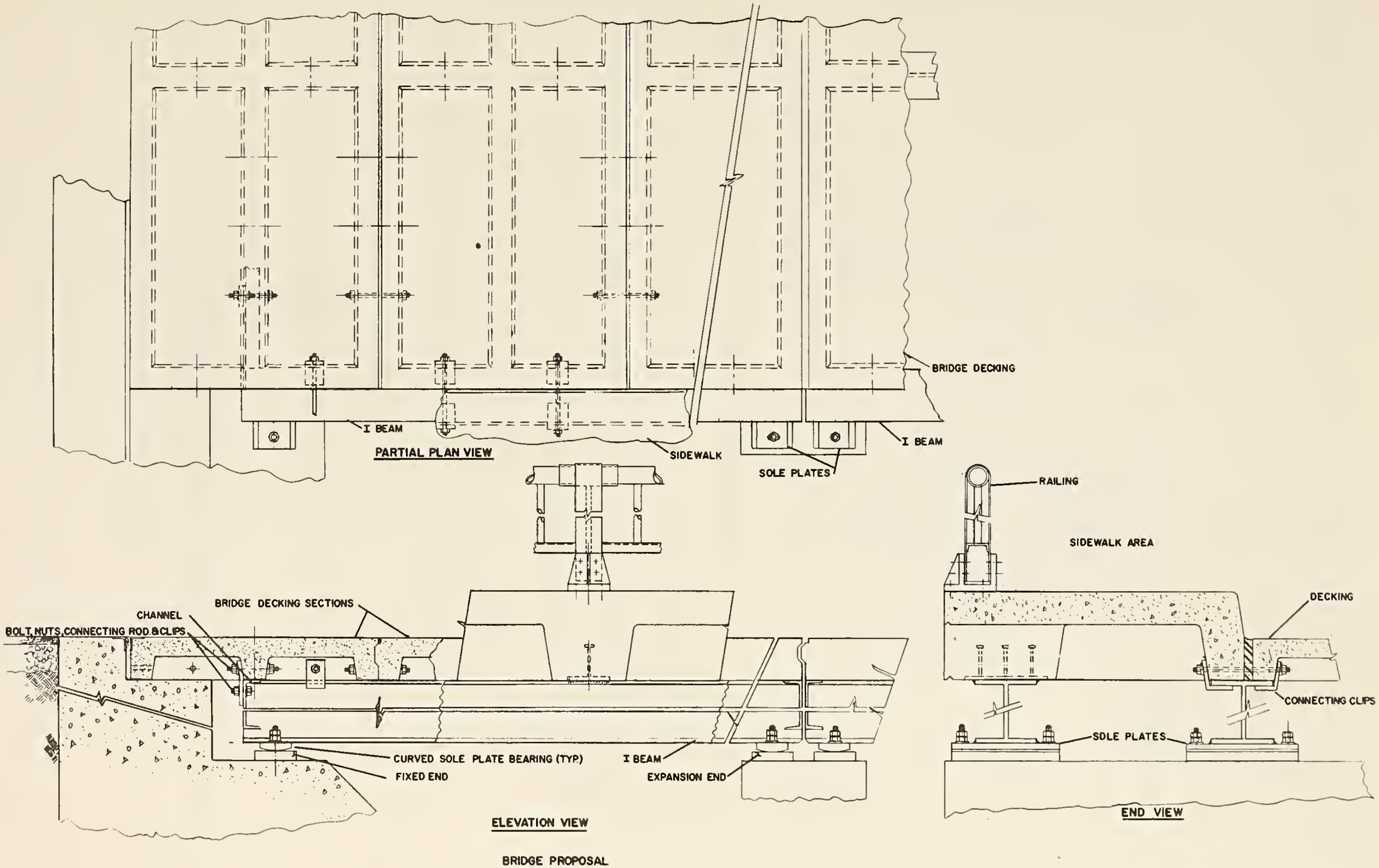


Figure 19

Bridge Assembly Using Fold-Stiffened
Bridge-Deck Design

7.2 Luminaire Supports

As mentioned in last year's report,[6] a fully impregnated luminaire support constructed from concrete of 150-lb/ft^3 density would weigh ≈750 lb. To obtain a safer design, a substantial reduction in component weight was considered necessary. It was decided to concentrate the design efforts on prototype luminaire supports constructed of polymer-impregnated lightweight concrete. Two materials were considered, both made with MMA monomer and having a final density of about 60 lb/ft^3. The low-density materials have a reduced tensile strength compared with that of the 150-lb/ft^3 PIC so that increased section thicknesses are required. Thus, the 40-ft luminaire support discussed previously would weigh about 450 lb. The material selection was based on a limited number of strength tests. Nothing is known with regard to the fatigue strength or other materials properties discussed in the previous report. With the limited data available, the simplified engineering analysis described in Ref. 6 was applied. The costlier finite element methods cannot be justified until additional data are available.

Figures 20 and 21 show the prototype design obtained from the simplified analysis. Two details should be noted: first,

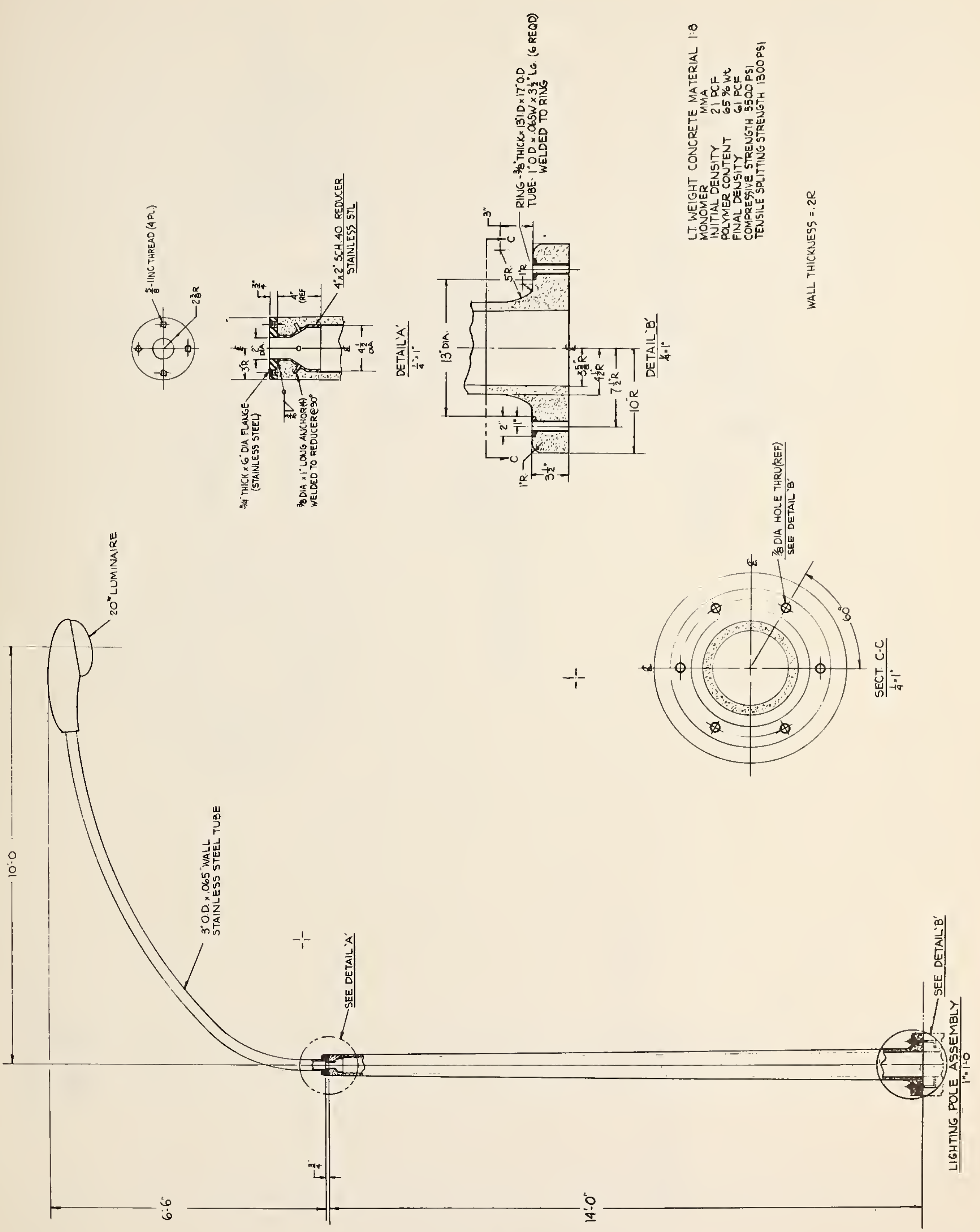


Figure 20

Lightweight Concrete Lamppost. Prototype Design for Material With a Tensile Splitting Strength of 1300 psi

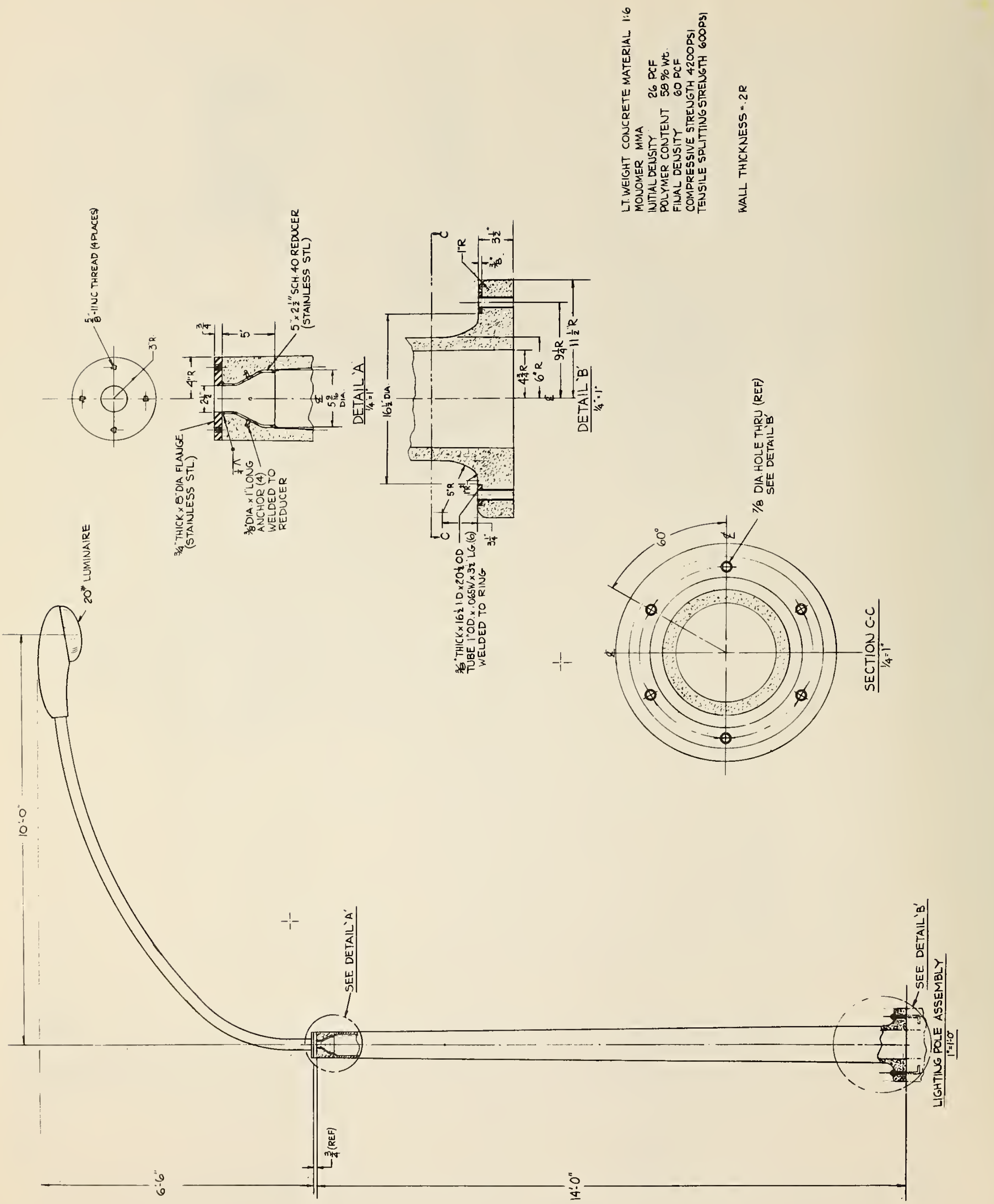


Figure 21

Lightweight Concrete Lamppost. Prototype Design for Material With a Tensile Splitting Strength of 600 psi the 14-ft length shown for the prototype luminaire support structure is a constraint imposed by the dimensions of the existing impregnation vessels. Second, the wall thickness is 0.2 R, as compared with 0.1 R for the 150-lb/ft^3 PIC. The latter change implies changing Eq. (8) in Ref. 6 so that $z = 0.463\ R^3$. All other relationships are unchanged from those previously assumed for the heavier structure.

8. DISCUSSION OF RESULTS

The work to date has indicated that large improvements in the structural and durability properties of FHWA-type concrete can be obtained by monomer impregnation and polymerization in the hardened concrete.

In the previous FHWA report,[5] test results for MMA-impregnated concretes containing Riverton limestone aggregate indicated improvements in compressive and tensile splitting strengths up to a factor of 2.6. Although the degree of improvement was significant, it was lower than the factor of 4 obtained in earlier work.[1] The reason for the smaller increases was not fully understood. Two possible explanations are: excessive monomer drainage prior to polymerization, and reduced bonding between the low porosity limestone and the cement phase.

Experimental evidence to support both the above possibilities has since been obtained (see Sections 4.1 and 5.2). On this basis, high-quality concretes containing Riverton limestone, Kansas limestone, White Marsh gravel, diorite, slag, expanded slate, and sintered fly ash aggregates were impregnated. Two impregnation methods; encapsulation in forms during saturation and polymerization, and polymerization under water, were used with each material. The test data given in Sections 5.2 and 5.3 are summarized in Table 39.

All the materials produced high-strength, durable composites and the results indicate that concretes prepared from locally available materials can be used in the production of PIC. Similar results have been obtained with thermal-catalytically polymerized materials. Structural lightweight concrete containing 3/8-in. maximum size aggregate and impregnated with MMA in forms produced PIC with the highest compressive (24,520 psi) and tensile splitting (2230 psi) strengths and strength-to-weight ratio (186). Compared with the controls, the strength values correspond to improvement factors of 6.1 and 4.8, respectively. Similar results were obtained with 3/4-in. maximum size slag aggregate, and the small differences obtained may not be statistically significant.

Several trends are apparent from the test results. The degree of improvement in properties is greatest for the materials exhibiting the lowest initial strengths. Low-strength Riverton limestone specimens (compressive strength, 2230 psi) had an average strength of 15,500 psi after impregnation. This corresponds to an improvement factor of 7. The high-strength Riverton limestone mix (compressive strength, 5690 psi) produced PIC with a strength of 18,000 psi. This represents an improvement factor of 3.2. Previous data[5] from low and high strength

Riverton limestone specimens impregnated by the standard vacuum-soak method indicated compressive strengths of 10,000 and 16,630 psi, respectively. The strength improvements obtained during this report period are probably due to improved impregnation techniques.

The underwater polymerization method appears at least comparable to the use of forms when high-density (>140 lb/ft^3) concretes are impregnated. Forms are more effective for the low-density concretes containing expanded slate and slag aggregates. This is probably because the latter materials are more susceptible to drainage losses, and these can be reduced to negligible values by using forms. Since these trends are based on the averages of only three samples for each material, additional data are required to determine whether the results are statistically significant. In any case, the differences in strength are not large and therefore the additional cost associated with the use of forms would probably not be warranted except for specialized applications.

Freeze-thaw durability data are also summarized in Table 39. Conventional concrete is generally considered satisfactory at a durability factor of 70 at 300 cycles, when tested according to ASTM C290-67 "Rapid Freezing and Thawing In Water." The

Table 39

Summary of Strengths and Durability of Various Concretes

Type of aggregate	Dry density, lb/ft^3	Encapsulation method (a)	Average polymer content		Average strength, psi			Average durability factor at 1057 cycles	S/W (b)
			wt %	vol %	Compressive	Tensile splitting	Flexural		
Diorite	146	control	0	0	5,550	660	720	0	38
		U	5.5	11.5	20,100	1790	2615	89.1	131
		F	4.9	10.2	20,000	1320	2095	61.7	131
White Marsh gravel	141	control	0	0	5,620	675	610	0	40
		U	5.4	10.9	18,980	1677	1840	74.9	127
		F	4.5	9.0	16,500	1480	1830	99.5	112
Riverton limestone (high strength)	144	control	0	0	5,690	700	--	0	40
		U	5.6	11.6	18,280	1890	--	67.7	120
		F	4.8	9.9	16,700	1555	--	81.0	111
Riverton limestone (low strength)	136	control	0	0	2,230	395	--	0	16
		U	7.1	14.2	15,530	1515	--	-	106
		F	6.5	12.9	15,300	1325	--	-	105
Kansas limestone	133	control	0	0	5,190	570	--	0	39
		U	7.0	13.6	18,124	1470	--	84.0 (c)	130
		F	7.9	15.5	23,030	1690	--	-	161
Slag (3/4 in.)	127	control	0	0	5,220	535	705	0	41
		U	9.4	17.8	22,060	1870	2425	<66.0	159
		F	8.6	16.1	23,690	1860	1870	91.5	172
Slag (3/8 in.)	119	control	0	0	4,000	465	650	0	34
		U	11.2	20.5	21,850	1920	2690	73.0	166
		F	10.5	19.0	24,520	2230	1960	94.5	186
Expanded slate	104	control	0	0	3,670	450	590	0	35
		U	16.1	27.4	15,480	1890	2180	60.8	128
		F	16.3	27.8	17,810	1745	1510	<89.5	147

(a) U = under water; F = excess monomer, in forms.

(b) Strength-to-weight ratio = av compressive strength/av final density.

(c) Measured for one sample only, after 708 cycles.

durability factors for the various PIC concretes ranged from 60 to 99 at the greatly increased exposure of 1057 cycles. Specimens processed in forms appear to have better durability than those polymerized under water. This is probably attributable to more effective sealing of the surface. Flexural strength measurements made on impregnated normal weight specimens after freeze-thaw testing indicated reductions in strengths ranging up to 75%. Greater reductions were obtained with structural lightweight concretes.

Freeze-thaw scaling tests performed on partially impregnated slabs in accordance with ASTM C672-71 T, "Scaling Resistance of Concrete Surfaces Exposed to Deicing Chemicals," also indicated considerable improvement in durability as compared with normal concrete. Improvements in the test procedure are desirable before further measurements can be made.

The result of salt intrusion tests performed at the FHWA[12] indicated the potential of PIC for use in preventing chloride attack on reinforced concrete bridge decks. Compared with specimens of unimpregnated cement paste, samples impregnated with MMA exhibited a decrease in the quantity of chloride ion in the surface layer (top 1/8 in.) to 1/5, and to only 1/50 at levels below 1/8 in. Impregnated reinforced concrete slabs currently in test have shown no chloride penetration after exposure to brine for 5 weeks.

Lightweight concrete-polymer composites with high strength and durability have been produced by impregnating insulating-type perlite concrete with MMA and polyester-styrene. Structural properties equivalent to or greater than those of high-quality conventional concretes have been attained. In addition to the high strength of the composite, its weight is ≈1/2 that of normal weight concrete. Correlation of the data clearly shows that the strength of perlite concrete-polymer is directly related to the completeness of impregnation and to the final density of the material. In addition, higher strengths are attainable with MMA impregnated samples than with polyester-styrene. The average compressive, tensile splitting, and flexural strengths of a test series of non-air-entrained 1:8 perlite concrete - MMA samples were 7700 psi, 1328 psi, and 1700 psi, respectively (see Table 29). Similarly, the average compressive, tensile splitting, and flexural strengths of a perlite 1:5 series were 7400 psi, 1150 psi, and 2620 psi, respectively.

Samples of similar composition that were impregnated with polyester-styrene had consistently lower strengths than those with MMA (see Table 30). The monomer used for these impregnations is known to produce a fairly brittle polymer. Other more ductile polyester resins are being evaluated. These resins contain greater amounts of plasticizers, which should improve the properties of perlite concrete - polyester-styrene materials.

Prototype sections of a perlite lamppost and pipe have been made, and the fabrication of larger sections appears technically feasible.

Freeze-thaw testing of perlite concrete samples is in progress at the FHWA but data are not yet available. Testing at BNL of a section of perlite pipe impregnated with polyester-styrene has indicated no attack after exposure to 5% H_2SO_4 for 120 days.

Based upon the improved formulation of the base light-weight concrete material and impregnation techniques, it appears that a high-quality, insulating-type concrete-polymer material can be produced which will find uses as a structural material.

9. CONCLUSIONS AND RECOMMENDATIONS

Great improvements have been obtained in the structural and durability properties of concrete by monomer impregnation of hardened concrete and in situ polymerization. Test data for PIC prepared from normal and structural lightweight concretes containing several different aggregates indicate that all produce high-strength (>15,000 psi) composites. This indicates that concretes prepared from locally available materials can be used in the production of PIC. Care must be taken during impregnation and subsequent polymerization to minimize drainage and evaporation losses. Otherwise, a non-uniform polymer distribution is obtained which results in specimens with low strength and highly variable properties. Underwater polymerization appears to be an effective and practical method of encapsulation for use with large precast concrete sections such as bridge decks, beams and columns.

Based upon the limited test data, design studies for precast bridge decks have been performed. The results indicate that lightweight, durable decks can be produced. However, material properties under static and dynamic conditions for the temperature range -40° to $120^{\circ}F$ (-40° to $49^{\circ}C$) should be determined before a detailed evaluation can be made.

Techniques for producing high-strength and durable PIC from lightweight insulating-type concretes have been developed and preliminary designs for breakaway luminaire supports have been completed. On the basis of the techniques developed during the fabrication of a prototype lamppost and pipe, this material seems suitable for structural applications.

The feasibility of repairing deteriorated bridge decks by partial impregnation and in situ polymerization was demonstrated in a field experiment performed in conjunction with the FHWA and the Kansas State Highway Department. However, much work is required before the practicability of the system can be determined.

The following recommendations are made for the future program.

1. Preliminary bridge deck design studies have indicated the areas in which test data are required before a complete structural design can be made. As a prerequisite, the structural and durability properties of PIC under static and dynamic conditions should be determined for the temperature range -40° to 120°F.

2. Contingent upon the above results, prototype bridge elements should be designed and prepared for destructive testing and field evaluation.

3. Studies to select monomers for use in the partial impregnation of deteriorated and structurally sound bridge decks should be continued. Emphasis should be placed on monomer systems that can be polymerized by catalyst-promoter techniques.

4. Methods and apparatus for the repair of deteriorated concrete bridge decks by monomer impregnation techniques and application of polymer concrete (PC) materials should be developed and field-tested.

5. Improved field-type impregnation techniques and equipment should be developed for the partial impregnation of structurally sound bridge decks and field tests should be performed.

6. Preliminary product designs for other highway applications such as pilings and curbing should be made, based on the data already accumulated on PIC. The purpose of these studies should be to define the test data required for the structural design, to identify the critical components necessary for producing the structure, and to estimate the costs involved.

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