

POLYMER CONCRETE OVERLAY TEST PROGRAM

FINAL REPORT

by

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## P R E F A C E

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## INTRODUCTION

The deterioration of bridge decks has gained national attention during the past decade as millions of dollars were spent for repairs. The cause of much of the deterioration has been blamed on the use of deicing chemicals, although inadequate design and construction practices contributed to the problem. Deterioration has been found mostly in the form of concrete section loss due to scaling and spalling. This has created not only overstressing of the deck but a driving hazard as well. Conventional repair methods such as overlaying with asphalt concrete or portland cement concrete were generally found to be unacceptable for two reasons. First, the asphalt concrete overlay provided only a wearing surface and offered little protection from future deterioration due to chemical corrosion. Second, although portland cement concrete overlays provided an improved wearing surface and increased the structural capacity of the deck, their prolonged curing time was judged unacceptable in some cases because of extended disruption of traffic flow. For these reasons a structural overlay material called polymer concrete was developed. It cures rapidly, improves the structural quality of the existing deck, and provides protection from deicing chemicals.

In 1973, the Federal Highway Administration sponsored a study of polymer concrete materials by the Oregon State Highway Division. Part of the initial task consisted of analyzing various resins in the laboratory to find the most promising for producing a polymer concrete in the field. Up to that time only limited work had been done with polymer concrete in the United States. Most of the developmental work had been concentrated on a system known as polymer impregnation (1, 2, and 3). In that system a low viscosity monomer penetrates into a fully cured and dried portland cement concrete element. This is followed by heating the monomer to 165<sup>o</sup>F (73.9<sup>o</sup>C) which causes it to polymerize. This system greatly improves the structural properties of the original concrete element. Recent reports have described the successful impregnation of entire bridge decks (4, 5).

The production of polymer concrete consists of mixing a well graded, good quality aggregate with a resin binder. The liquid resin is transformed into a solid through a chemical reaction known as polymerization. This reaction can be accomplished by three methods which are: (1) radiation, (2) initiator-heat and (3) initiator-promoter. The third system is used almost exclusively in the production of polymer concrete in the field.

By combining various monomers and resins, different properties were enhanced in the finished polymer concrete. The ability to use chemical compounds to control the allowable work time and rate of cure over a large temperature range added to the appeal of polymer concrete for structural overlays.

During the initial laboratory work several resin suppliers and manufacturers were contacted and invited to submit resin formulations suitable for polymer concrete. At the conclusion of the screening process 13 resin formulations were selected for additional study. One of the systems selected was a monomer blend containing 95% methyl methacrylate (MMA) and 5% trimethylol propane trimethacrylate (TMPTMA). This system was used to a great extent in the polymer impregnation work because of its low viscosity. Using benzoyl peroxide and dimethyl aniline for the initiator and promoter respectively, several polymer concrete mixes were made to produce test cylinders and small overlays. Compressive strengths of over 8,000 psi (55.1 MPa) were consistently recorded after a 24-hour cure when cylinder fabrication time was limited to under 10 minutes. When polymer concrete made with the MMA systems was used on small overlays however, excessive evaporation and drainage of the monomer caused the surface to be weak and subject to abrasion. Because of these problems, work with methyl methacrylate was abandoned in Oregon and full attention was devoted to polyester styrene systems. Experimental bridge deck patching has been reported by the Brookhaven National Laboratory using a methyl methacrylate polymer concrete (6).

The initial polyester styrene system examined in the laboratory consisted of blending styrene with a flexible polyester resin (GR 511) and a rigid polyester resin (GR 941). Both of these resins were products of the Marco Division of the W. R. Grace Company. Using the proportions 23% styrene, 38.5% GR 511, and 38.5% GR 941, several small polymer concrete mixes were prepared. The workability and the compressive strength of mixes containing different resin loadings were examined. In addition, the chemical additives which affect the rate of polymerization were examined in a series of workability tests. By varying the initiator, methyl ethyl ketone peroxide, and the promoter, cobalt octoate, between 0.5% and 2.5% for each, the allowable work time of mixes was regulated at room temperature. When the lower percentages of additives were used, the allowable work time was extended but the rate of cure was slowed to an unacceptable amount. Hydroquinone was then found to inhibit the rate of polymerization for a short period of time without greatly extending the total cure time.

In order to study the behavior of resins at different temperatures, a time-to-gel study was conducted within the normal working temperature range. By varying the additive proportions within different temperature ranges it was found the gel time of the binder could be predicted. This allowed mix designs to be prepared with a satisfactory work time at several different temperature levels.

A silane coupling agent was added to the resin in many of the initial mixes to gain a chemical bond to the aggregate in addition to the physical bond between the polyester styrene resin and the aggregate. The small gain realized in the structural properties did not justify the high cost of this material. Silane was eliminated for the polymer concrete mixes, but is still specified for use in the tack coat.

Polymer concrete mixes that were prepared by hand in the laboratory appeared too dry when an 8.5% resin content was used, while a resin content of 14% appeared too wet when mixed with a well graded aggregate. Because of the relatively high cost of the resin, a great deal of work was done in attempting to reduce the amount of binder required to produce a dense concrete. Emphasis was placed on developing an aggregate gradation that would minimize the voids to be filled by the resin. Results of testing showed the amount of fines in the mix was very important. Because of its low viscosity, the resin tended to drain from the aggregate if sufficient fines were not available. Excessive fines, on the other hand, caused additional resin to be required to coat the greater surface area. A design gradation of between 6% to 8% for material passing the No. 200 sieve was finally specified.

Most of the laboratory trial batches were mixed by hand using a large bowl and spoon. A Hobart dough mixer and a small electric driven concrete mixer were used on some of the larger laboratory batches. When 6 ft x 6 ft x 1.5 in. (1.8 m x 1.8 m x 38 mm) polymer concrete overlays were placed in the maintenance yard, larger gasoline powered mixers were used. The conventional rotating drum concrete mixer and the paddle type mortar mixer were both used on several projects. The wiping motion of the paddles and the overall ease in clean-up of the mortar mixer and the tendency of fines to build up on the drum of the conventional mixer are the reasons why the mortar mixers are preferred over the conventional concrete mixer.

Good bonding between the polymer concrete overlay and the substrate concrete received much attention during the development process. Through the use of a resin tack coat adequate bonding was gained in the laboratory. When field work began, only partial bonding of the polymer concrete to the existing concrete was realized. Additional study of substrate preparation and allowable moisture content produced a cleaning procedure that ensured satisfactory bonding.

Included in this report are results of tests to determine modulus of elasticity, thermal coefficient, shrinkage coefficient and the results of a freeze-thaw study. A report is also presented on three polymer concrete overlays and one polymer concrete chip seal overlay that were placed on bridge decks.

Finally, descriptions are included covering the technical assistance provided to Idaho Transportation Department during their polymer concrete overlay project and the Polymer Concrete Materials Seminar hosted by the Oregon State Highway Division.

## TEST DESCRIPTIONS AND RESULTS

### Resin Gel Time Study

The ability to control the gel time (allowable work time) of polymer concrete mixes at different temperatures was found to be of primary concern. During early testing, sets of six 2-in. (51 mm) cubes were molded to measure the workability of various polymer concrete mixes and the effect of continued manipulation on strength. An evaluation of the stiffness during mixing and the difficulty in finishing was determined as the mix was placed in the cube molds at 5 minute intervals. The test cubes were then allowed to cure for 24 hours and tested for comparative compressive strength. Testing was conducted at room temperature 72°F to 75°F (22.2°C to 23.9°C) and also at reduced temperatures of 56°F (13.3°C) and 60°F (15.6°C).

The amount of time required to mix, place and finish the polymer concrete was defined as handling time. During the early phase of the gel time study the handling time was purposely extended to exceed the allowable work time. This resulted in the polymer concrete becoming too stiff and the compressive strength of the polymer concrete to decrease (see Figure 1). Allowable work time was then extended with the introduction of hydroquinone as an inhibitor. The time available for placing the mixes was extended to 1.5 hours in the laboratory at 75°F (23.9°C) with a corresponding increase in cure time.

The rate of polymerization of polyester styrene resin was found to be dependent upon many factors. These include the amount of initiator, promoter and inhibitor, along with environmental factors such as temperature, humidity, and amount of ultraviolet light. Using a Sunshine Gelmeter, the gel time of several resins was studied in the laboratory. Gel time is the elapsed time from when the initiator and promoter are added to the resin until the resin first begins to solidify. The proportions of the chemical additives were varied, along with the temperature, to determine suitable formulas for field application within a range of normal working ambient temperatures. Much of the initial gel testing work was concentrated on a resin designated LB 183-13. After some problems occurred in the field, however, a slightly more flexible resin, GR 11044, was studied for use in polymer concrete. Both resins were produced by the Marco Division of W. R. Grace Co. The following tables (1A through 1E) show the results of the time-to-gel study using different concentrations of additives at different temperatures and the two resins.

### Workability

The ease of mixing, placing, and finishing polymer concrete was also examined during the laboratory phase of this work. Mixes containing either natural or crushed aggregate were evaluated while being prepared by hand. The resin content of the mixes was varied from 8% to 14% by weight of aggregate.

These batches were mixed in a steel mixing bowl using a steel spoon. The size of the batches was approximately 0.77 lbs (.35 kg). Generally speaking,

2" Cubes  
 24 hr. Cure  
 8 1/2% Resin Content

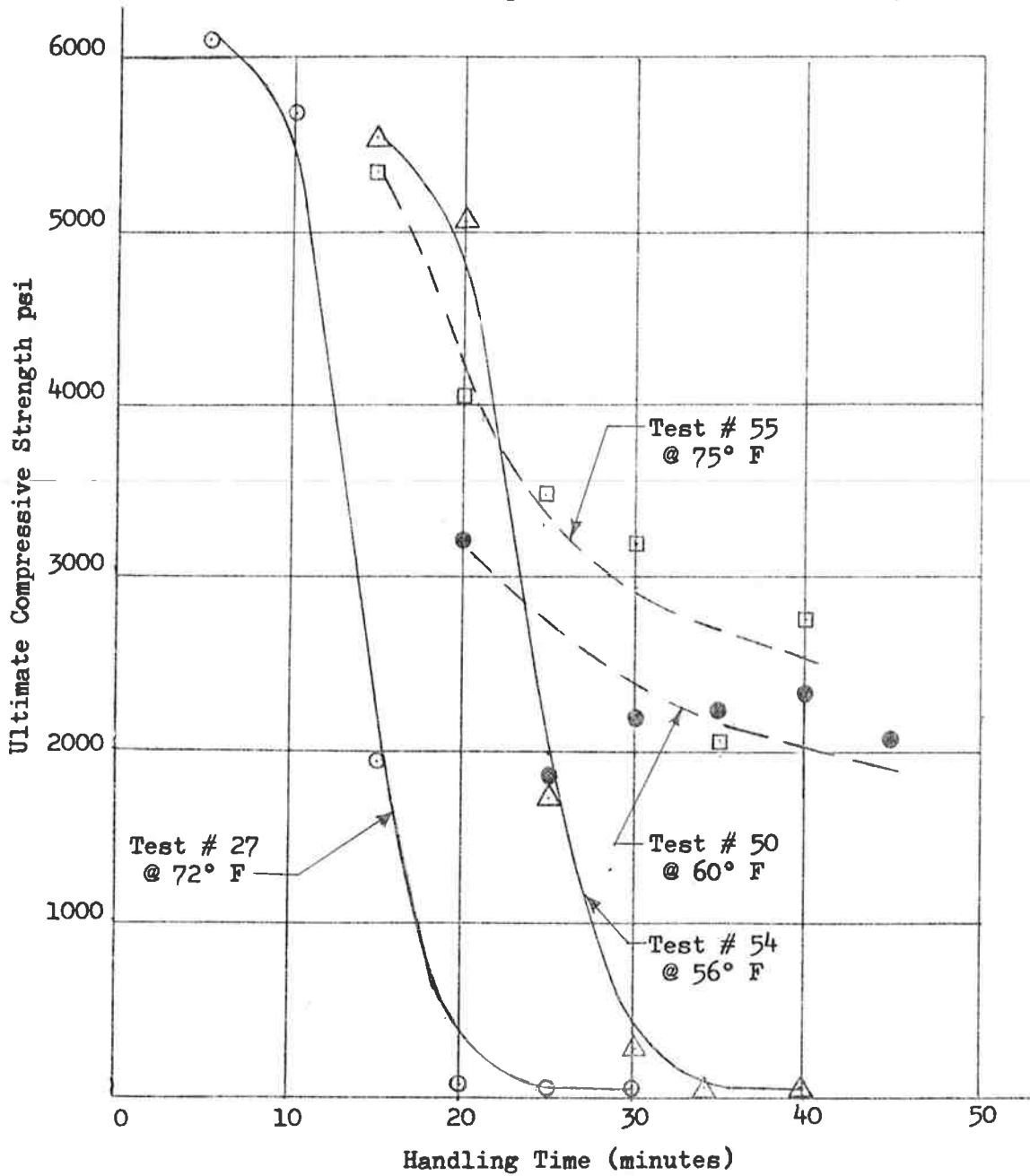
— 1.5% Initiator  
 0.75% Promoter

- - - 0.5% Initiator  
 0.25% Promoter

$^{\circ}\text{C} = (^{\circ}\text{F} - 32) / 1.8$

1000 psi = 6894.8 kPa

1" = 25.4 mm



Effect of initiator-promoter and mixing temperatures on ultimate strength vs. handling time.

Figure 1

RESIN GEL TIME STUDY

Table 1A  
Resin LB183-13  
74 F (22.4°C)

| <u>Test</u> | <u>MEKP %(1)</u> | <u>Co Oc %(2)</u> | <u>HQ ppm(3)</u> | <u>Gel Time - min.</u> |
|-------------|------------------|-------------------|------------------|------------------------|
| 1           | 1.5              | 1.0               | 100              | 11                     |
| 2           | 1.5              | 1.0               | 200              | 20                     |
| 3           | 1.5              | 1.0               | 400              | 43                     |
| 4           | 1.0              | 1.0               | 100              | 25                     |
| 5           | 1.0              | 1.0               | 200              | 45                     |
| 6           | 1.0              | 1.0               | 400              | 207                    |
| 7           | 1.5              | .75               | 100              | 12                     |
| 8           | 1.5              | .75               | 200              | 26                     |
| 9           | 1.5              | .75               | 400              | 68                     |
| 10          | 1.0              | .75               | 100              | 27                     |
| 11          | 1.0              | .75               | 400              | 215                    |
| 12          | 1.5              | .50               | 100              | 16                     |
| 13          | 1.5              | .50               | 200              | 25                     |
| 14          | 1.5              | .50               | 400              | 73                     |
| 15          | 1.0              | .50               | 100              | 25                     |
| 16          | 1.0              | .50               | 200              | 50                     |
| 17          | 1.0              | .50               | 400              | 240                    |

Table 1B  
Resin LB183-13  
90°F (32.2°C)

|    |     |     |     |     |
|----|-----|-----|-----|-----|
| 1  | 1.5 | 1.0 | 100 | 9   |
| 2  | 1.5 | 1.0 | 200 | 14  |
| 3  | 1.5 | .75 | 400 | 28  |
| 4  | 1.5 | .75 | 100 | 10  |
| 5  | 1.5 | .75 | 200 | 15  |
| 6  | 1.5 | .50 | 400 | 45  |
| 7  | 1.5 | .50 | 0   | 3   |
| 8  | 1.5 | .50 | 100 | 7   |
| 9  | 1.5 | .50 | 200 | 9   |
| 10 | 1.5 | .25 | 400 | 20  |
| 11 | 1.5 | .25 | 0   | 2   |
| 12 | 1.5 | .25 | 100 | 6   |
| 13 | 1.5 | .25 | 200 | 33  |
| 14 | 1.0 | 1.0 | 100 | 11  |
| 15 | 1.0 | 1.0 | 200 | 17  |
| 16 | 1.0 | 1.0 | 400 | 152 |

- (1) methyl ethyl ketone peroxide  
(2) cobalt octoate  
(3) tert-butyl hydroquinone

Table 1B (continued)

| <u>Test</u> | <u>MEKP %(1)</u> | <u>Co Oc %(2)</u> | <u>HQ ppm(3)</u> | <u>Gel Time - min.</u> |
|-------------|------------------|-------------------|------------------|------------------------|
| 17          | 1.0              | .75               | 0                | 5                      |
| 18          | 1.0              | .75               | 100              | 12                     |
| 19          | 1.0              | .75               | 200              | 25                     |
| 20          | 1.0              | .75               | 400              | 112                    |
| 21          | 1.0              | .50               | 0                | 4                      |
| 22          | 1.0              | .50               | 100              | 15                     |
| 23          | 1.0              | .50               | 200              | 35                     |
| 24          | 1.0              | .50               | 400              | 155                    |
| 25          | 1.0              | .25               | 0                | 5                      |
| 26          | 1.0              | .25               | 100              | 37                     |
| 27          | 1.0              | .25               | 200              | 45                     |
| 28          | 1.0              | .25               | 400              | 180+                   |

Table 1C  
Resin LB183-13  
50°F (10°C)

|    |     |    |     |      |
|----|-----|----|-----|------|
| 1  | 2.0 | .5 | 0   | 10   |
| 2  | 2.0 | .5 | 100 | 60   |
| 3  | 2.0 | .5 | 200 | 105  |
| 4  | 2.0 | .5 | 300 | 150  |
| 5  | 1.5 | .5 | 0   | 10   |
| 6  | 1.5 | .5 | 100 | 50   |
| 7  | 1.5 | .5 | 200 | 105  |
| 8  | 1.5 | .5 | 300 | 240+ |
| 9  | 1.0 | .5 | 0   | 50   |
| 10 | 1.0 | .5 | 200 | 65   |
| 11 | 2.5 | .5 | 0   | 5    |
| 12 | 2.5 | .5 | 200 | 35   |

Table 1D  
Resin LB183-13  
40°F (4.4°C)

|   |     |    |     |     |
|---|-----|----|-----|-----|
| 1 | 2.0 | .5 | 0   | 15  |
| 2 | 2.0 | .5 | 100 | 60  |
| 3 | 1.5 | .5 | 0   | 20  |
| 4 | 1.5 | .5 | 100 | 240 |
| 5 | 2.5 | .5 | 0   | 15  |
| 6 | 2.5 | .5 | 100 | 25  |
| 7 | 2.5 | .5 | 200 | 55  |

- (1) methyl ethyl ketone peroxide  
(2) cobalt octoate  
(3) tert-butyl hydroquinone

Resin Gel Time Study (continued)

Table 1E  
Resin GR11044  
77°F (25°C)

| <u>Test</u> | <u>MEKP %(1)</u> | <u>Co Oc %(2)</u> | <u>HQ ppm(3)</u> | <u>Gel Time - min.</u> |
|-------------|------------------|-------------------|------------------|------------------------|
| 1           | 2.0              | .5                | 200              | 16                     |
| 2           | 2.0              | .5                | 400              | 42                     |
| 3           | 2.0              | .25               | 100              | 20                     |
| 4           | 2.0              | .25               | 200              | 28                     |
| 5           | 2.0              | .25               | 400              | 61                     |
| 6           | 1.5              | 1.0               | 200              | 21                     |
| 7           | 1.5              | 1.0               | 400              | 59                     |
| 8           | 1.5              | .75               | 200              | 24                     |
| 9           | 1.5              | .75               | 400              | 70                     |
| 10          | 1.5              | .50               | 200              | 26                     |
| 11          | 1.5              | .50               | 400              | 95                     |
| 12          | 1.5              | .25               | 100              | 30                     |
| 13          | 1.5              | .25               | 200              | 44                     |
| 14          | 1.0              | 1.0               | 100              | 23                     |
| 15          | 1.0              | 1.0               | 200              | 53                     |
| 16          | 1.0              | .75               | 100              | 29                     |
| 17          | 1.0              | .75               | 200              | 56                     |
| 18          | 1.0              | .50               | 0                | 17                     |
| 19          | 1.0              | .50               | 100              | 37                     |
| 20          | 1.0              | .25               | 0                | 23                     |
| 21          | 1.0              | .25               | 100              | 72                     |
| 22          | .75              | .75               | 100              | 52                     |
| 23          | .75              | .75               | 200              | 120                    |
| 24          | .75              | .50               | 0                | 20                     |
| 25          | .75              | .50               | 100              | 57                     |
| 26          | .75              | .50               | 200              | 145                    |
| 27          | .75              | .25               | 0                | 24                     |
| 28          | .75              | .25               | 100              | 85                     |
| 29          | .50              | .50               | 0                | 28                     |
| 30          | .50              | .50               | 100              | 110                    |
| 31          | .50              | .25               | 0                | 48                     |
| 32          | .50              | .25               | 100              | 180+                   |
| 33          | 1.0              | .75               | 200              | 69                     |

- (1) methyl ethyl ketone peroxide
- (2) cobalt octoate
- (3) tert-butyl hydroquinone

workability improved as the amount of liquid binder increased. However, some bleeding of the surface occurred when the resin content exceeded 12%. The harshness of several crushed aggregate gradations required slightly greater resin content to produce the same workability obtained with natural gravels. Depending on the gradation, suitable workability was found using resin contents of between 10% and 12% when mixing by hand.

In addition to the laboratory study, several 6 ft x 6 ft x 1.5 in. (1.8 m x 1.8 m x 38 mm) polymer concrete overlays were placed in the field using two mixing techniques and several methods of finishing and compacting. Both a conventional rotating drum mixer and a paddle-type mortar mixer were used to blend the polymer concrete. After being in service for approximately 30 minutes some material build-up was noted on the vanes and sides of the drum mixer. There was also material build-up on the paddles of the mortar mixers after 30 minutes, but the mixer's walls were wiped clean by the blades. Because of the greater ease of cleaning, the mortar mixer is preferred over the conventional drum mixer. One disadvantage of the mortar mixer is that only relatively small quantities can be mixed at a time. Experience has shown the mortar mixers are capable of mixing polymer concrete at between one-third to one-half their rated mortar capacity.

Polymer concrete can not be finished like conventional concrete because it lacks fluidity and it tends to be sticky. The methods used to finish and compact the 6 ft x 6 ft x 1.5 in. (1.8 m x 1.8 m x 38 mm) test slabs included the following:

- Light steel beam screed - 5 in. x 6.7 lb (130 mm x 10 kg/m) channel.
- Light steel beam screed with internal concrete vibrator clamped to it - 5 in. x 6.7 lb (130 mm x 10 kg/m) channel.
- Heavy steel beam screed - 10 in. x 42 lb (250 mm x 62 kg/m) H beam.
- Heavy steel beam screed with an external form vibrator bolted to it - 10 in. x 42 lb (250 mm x 62 kg/m) H beam.
- Light screed and vibrating sled compactor - Wacker Packer.
- Light screed and static asphalt concrete roller - 600 lb (272 kg) Ray-Go.
- Light screed and vibrating asphalt concrete roller - 600 lb (272 kg) Ray-Go.

After examining the surface texture and density of the field test sections, the vibrating sled and static roller were selected as producing the more desirable overlay. The resin content used in this field work also varied from 10% to 12%. Excessive liquid was brought to the surface in some cases at the higher resin loading when the polymer concrete was overworked with the finishing equipment.

An experiment using a Bidwell dense concrete finishing machine proved to be successful. Two 4 ft x 16 ft (1.2 m x 4.9 m) test slabs were finished and

consolidated using a Bidwell OF-400. Although the resin content of these slabs was reduced to 8% and 9%, good workability was obtained. The results of this trial indicated a well consolidated polymer concrete overlay with a smooth riding surface could be produced with reduced resin content if the proper placing equipment is used.

### Aggregate Gradation Study

In order to develop the most economical polymer concrete mix, a study was conducted to obtain an aggregate gradation that would minimize the amount of resin required as a binder. In comparison with asphalt cement or portland cement binders, the polymer concrete costs are extremely sensitive to the amount of resin required.

Approximately 50 tests were made on natural gravels passing the 1/2 in. (12.7 mm) sieve to arrive at a gradation giving minimum voids in dry-rodded samples. Three fine-grained fillers, portland cement, cottrell flour, and pozzolan, were included in some of the tests. Portland cement was selected as a filler material for the polymer concrete development because of its uniform grain size and also because it was more easily obtainable. The effectiveness of cement in reducing voids in the dry-rodded aggregate is demonstrated by the values in Table 2. Although the minimum void content was found at 14% cement, 6% cement was selected for the standard mix proportion (gradation VIII-c) since additional filler contributed significantly to the surface area to be coated with only a minor increase in density. For the entire results of the gradation study see Appendix C.

Some work was also done with crushed aggregates to determine the optimum gradation for maximum density. However, because of the harshness of the crushed material in working with the small samples, only the natural gravels were used in the initial polymer concrete mixtures.

A study was also made on gap-graded aggregates in an attempt to reduce the void volume. Minimum void contents of 18% were obtained, but since this value was only slightly lower than that for the uniformly graded aggregate with 6% cement, it was not low enough to make it economically desirable to separate and reblend the material.

When aggregate moisture content was found to reduce essential polymer concrete properties, a study was initiated to determine acceptable limits. Laboratory results showed the maximum allowable aggregate moisture content to be approximately 0.5%. That meant all aggregate used in polymer concrete work would require special drying.

When the polymer concrete study had progressed to the point where large quantities of dry aggregate were required for field projects, it was found the optimum gradation determined in the laboratory was not economically available. Further laboratory study was then made to find an acceptable aggregate gradation with tolerance limits which could be produced commercially.

Table 2

MAXIMUM DENSITY TRIALS  
 UNIFORM GRADATION  
 NATURAL GRAVEL, NATURAL SAND, PORTLAND CEMENT

|                    | VII-d | VIII-a | VIII-b | VIII-c | VIII-d | VIII-e | VIII-f | VIII-g | VIII-h | VIII-i | VIII-j |
|--------------------|-------|--------|--------|--------|--------|--------|--------|--------|--------|--------|--------|
| % Retained 1/2 in. | 0.0   | 0.0    | 0.0    | 0.0    | 0.0    | 0.0    | 0.0    | 0.0    | 0.0    | 0.0    | 0.0    |
| % Retained 3/8 in. | 13.5  | 13.23  | 12.96  | 12.69  | 12.42  | 12.15  | 11.88  | 11.61  | 11.34  | 11.07  | 10.8   |
| % Retained 1/4 in. | 16.5  | 16.17  | 15.84  | 15.51  | 15.18  | 14.85  | 14.52  | 14.19  | 13.86  | 13.53  | 13.2   |
| % Retained #4      | 20.0  | 19.6   | 19.20  | 18.80  | 18.4   | 18.0   | 17.8   | 17.2   | 16.8   | 16.4   | 16.0   |
| % Pass #4 (Sand)   | 50.0  | 49.0   | 48.0   | 47.0   | 46.0   | 45.0   | 44.0   | 43.0   | 43.0   | 41.0   | 40.0   |
| % Cement           | 0.0   | 2.0    | 4.0    | 6.0    | 8.0    | 10.0   | 12.0   | 14.0   | 16.0   | 18.0   | 20.0   |
| % Voids            | 22.01 | 21.64  | 20.46  | 19.37  | 19.03  | 18.67  | 18.47  | 18.36  | 18.52  | 19.27  | 20.60  |

The following gradation band was found to be most acceptable and closely follows the 3/8 in. to 0 (9.5 mm to 0) Fuller's maximum density curve. It is suitable for both natural and crushed aggregate.

| Sieve Size         | Percent Passing |
|--------------------|-----------------|
| 1/2 in. (12.7 mm)  | 100             |
| 3/8 in. (9.5 mm)   | 100-86          |
| 1/4 in. (6.3 mm)   | 85-71           |
| No. 10 (2.0 mm)    | 47-40           |
| No. 40 (.42 mm)    | 23-18           |
| No. 200 (0.075 mm) | 8-6             |

The amount of material passing the No. 200 sieve is of particular importance since excessive amounts will require additional resin for complete surface coating, while insufficient amounts will allow the resin to drain from the larger aggregate. A deficiency of fines can be corrected by adding portland cement or pozzolan.

When crushed aggregate was specified on one polymer concrete bridge deck overlay project, it was purchased from an asphalt concrete producer who dried the aggregate in an asphalt concrete plant drier. The pug mill in the plant was first cleaned by running aggregate through it to remove any asphalt residue. This aggregate was wasted. The 0.5 in. to No. 4 (12.7 mm to 4.7 mm) aggregate component was then dried and discharged through the pug mill into a 5 cu yd (3.8 m<sup>3</sup>) dump truck. The No. 10 to 0 (2.0 mm to 0) component was also dried and discharged into another 5 cu yd (3.8 m<sup>3</sup>) dump truck. Both were stored under cover until needed. This aggregate was proportioned at the job site to produce the designed final gradation (Table 3, Column 3). A description of this work appears in the section on bridge deck overlays.

Dry mix concrete, which is available at home improvement centers and building supply stores, was examined as a potential source of dry natural aggregate for polymer concrete. A sieve analysis of the dry mix determined that an excessive amount of material passing the No. 200 sieve was present in the over-the-counter stock (Table 3, Column 5). By reducing the amount of cement in several sacks an acceptable aggregate gradation was attained. Arrangements were made with the dry mix producer to reduce the cement content in order to meet gradation requirements. The aggregate gradation shown in Table 3, Column 6 is representative of the material specially prepared in 90 lb (40.8 kg) sacks and successfully used in the production of polymer concrete for a bridge deck overlay and miscellaneous concrete patching projects.

Table 3

AGGREGATE GRADATIONS (a)

| Sample No. | 1               | 2   | 3   | 4  | 5   | 6   | 7   | 8   | 9   | 10  |
|------------|-----------------|-----|-----|----|-----|-----|-----|-----|-----|-----|
| Sieve Size | Percent Passing |     |     |    |     |     |     |     |     |     |
| 1/2        | 100             | 100 | 100 | 98 | 100 | 100 | 100 | 100 | 100 | 100 |
| 3/8        | 87              | 96  | 86  | 85 | 91  | 88  | 86  | 86  | 86  | 86  |
| 1/4        | 71              | 67  | 71  | 77 | 68  | 66  | -   | -   | -   | -   |
| #4         | 53              | 53  | 61  | 76 | 61  | 56  | 60  | 60  | 60  | 60  |
| #8         | 44              | 45  | 42  | 57 | 60  | 46  | 43  | 43  | 43  | 43  |
| #16        | 38              | 38  | 31  | 35 | 54  | 40  | 30  | 31  | 31  | 31  |
| #30        | 28              | 25  | 22  | 23 | 45  | 33  | 23  | 23  | 23  | 24  |
| #50        | 12              | 15  | 15  | 17 | 24  | 16  | 15  | 16  | 18  | 20  |
| #100       | 7.4             | 10  | 11  | 13 | 18  | 8   | 12  | 14  | 15  | 17  |
| #200       | 6.5             | 9   | 7   | 10 | 16  | 6.3 | 10  | 12  | 14  | 16  |

(a) Aggregate samples 1, 2, 5, and 6 are natural gravels.

Aggregate sample 3, 4, 7, 8, 9, and 10 are crushed gravels.

(b) The material passing #200 includes portland cement.

Aggregate Source: Walling Sand & Gravel

D & D Paving

Hilroy Pit

Ross Island Sand & Gravel

Col. 1 and 2

Col. 3, 7, 8, 9 and 10

Col. 4

Col. 5 and 6

## Compressive Strength Tests

The strength of polymer concrete was found to be dependent on many factors during early compression testing. Using both cubes and cylinders, studies were conducted to determine the effects of such variables as type of resin, binder concentration, and aggregate gradation on ultimate compressive strength. Other variables examined in subsequent testing included ambient temperature during mixing, placing and curing, chemical additive concentrations, and moisture content of the aggregate.

During the initial testing, allowable work time was limited to approximately 10 minutes at 70°F (21.1°C) without the use of an inhibitor. Later testing with an inhibitor showed the allowable work time could be extended to 1.5 hours without apparent loss of compressive strength although the total cure time was also extended. The aggregate gradation in Table 3, Column 1 was used in much of the early testing. Both the gradation and type of aggregate were changed in the later testing when it was determined that large quantities of this gradation were not readily available from commercial sources.

To compare strengths at different polymer loadings, compressive tests were conducted on samples containing 8.5% and 10% resin (by weight of aggregate). Cylinders tested after 24 hours had an average compressive strength of 10,300 psi (71.0 MPa) for the 10% mix, while an average compressive strength of 7,900 psi (54.4 MPa) was obtained for the 8.5% mix. These samples did not contain inhibitor and provided allowable work times of under 10 minutes. The results of testing other polymer concrete mixes with 8.5% and 10% resin content, but containing the inhibitor hydroquinone, indicated average compressive strengths of 7,075 psi (48.7 MPa) and 7,935 psi (54.7 MPa), respectively, when tested after a 24-hour cure. Handling time of these mixes was extended to 45 minutes.

Before the use of an inhibitor was adopted, tests were made to study the effects of extending the time of working on compressive strength of polymer concrete mixes. Ultimate compressive strengths of over 5,000 psi (34.5 MPa) for uninhibited specimens were consistently recorded with 8.5% resin content mixes when the handling time was under 10 minutes and the polymer concrete was allowed to cure for 24 hours. As handling time was extended to 25 minutes, the compressive strengths dropped to 3,000 psi (20.7 MPa). The allowable work time was then extended when mixes were prepared containing an inhibitor. One mix containing 10% resin and 450 ppm hydroquinone was mixed and placed in cylinders after delays of 30, 60, and 90 minutes following mixing. Allowing a 24-hour cure at room temperature, the cylinders yielded ultimate compressive strengths of 7,820 psi (53.9 MPa), 8,490 psi (58.5 MPa), and 7,980 psi (55.0 MPa), respectively. These breaks indicated the allowable work time had been successfully extended.

The effect of ambient temperature during mixing, placing, and curing was examined during two studies. The investigation was conducted at two temperature levels: 68°F (20°C), and at a range of 56°F to 60°F (13.3°C to 15.5°C). In the first test an 8.5% resin content was used to prepare two groups of polymer concrete cubes containing no inhibitor. One group was initiated at 0.5% and promoted at 0.25%, while the other group was initiated

at 1.5% and promoted at 0.75%. A delay in placing and finishing the polymer concrete varied from 5 to 40 minutes while the cure time remained constant at 24 hours for all specimens (see Figure 1).

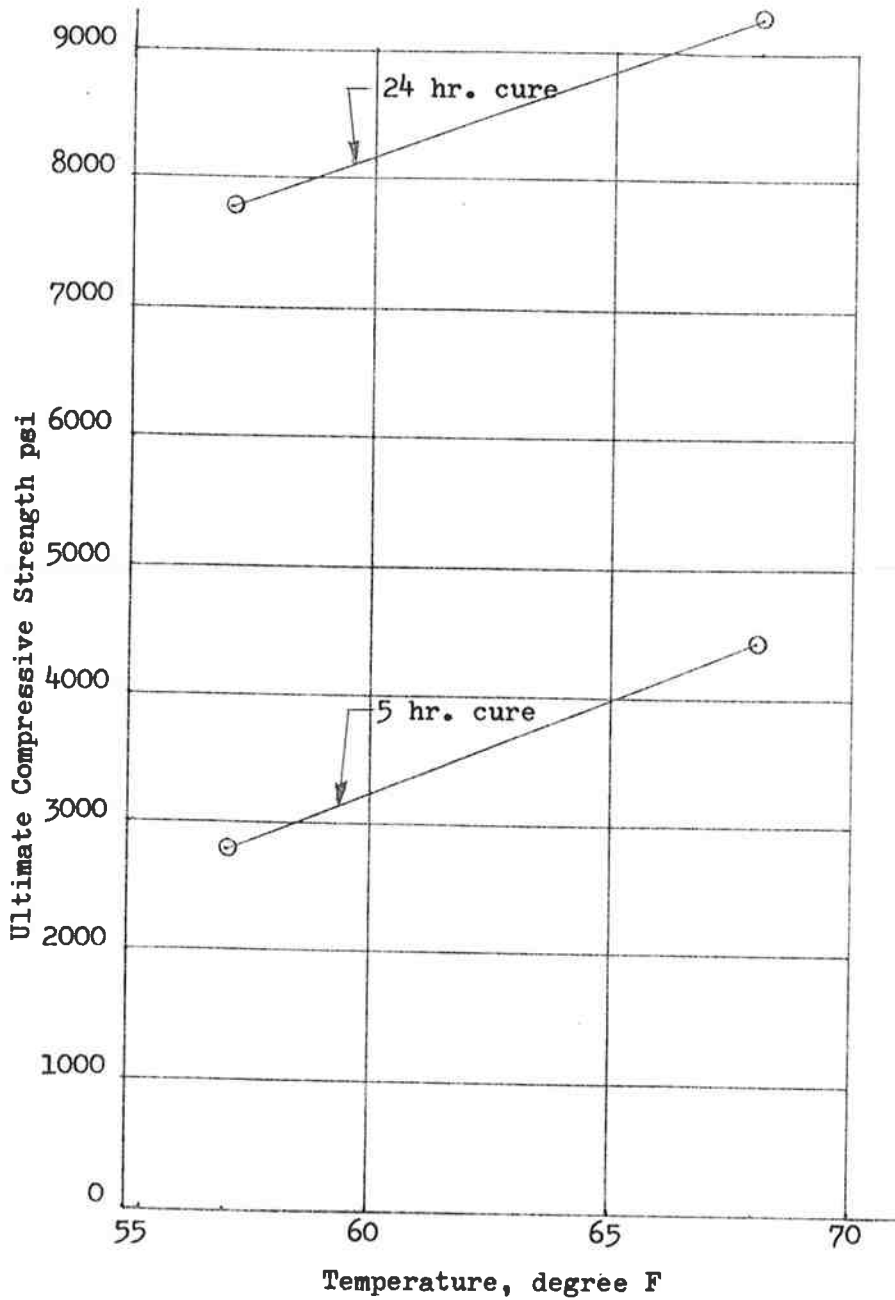
The mix containing 1.5% initiator was found to have a compressive strength of 5,700 psi (39.3 MPa) when worked for 10 minutes and only 100 psi (690 kPa) when worked for 20 minutes at approximately 72°F (22.2°C). The mix containing 0.5% initiator meanwhile was found to have a compressive strength of 5,500 psi (37.9 MPa) when worked for 15 minutes and 3,500 psi (24.1 MPa) when worked for 25 minutes at approximately 72°F (22.2°C).

When tested at the lower temperature, 56°F (13.3°C), however, the polymer concrete made with the higher initiator concentration developed a compressive strength of 5,600 psi (38.6 MPa) after a handling time of 15 minutes and only 200 psi (1,380 kPa) when the delay in placing and finishing was extended to 30 minutes. When polymer concrete containing the lower concentrations of initiator and promoter was mixed and cured at 60°F (15.5°C) it registered an ultimate compressive strength of 7,200 psi (49.6 MPa) when worked for 20 minutes. When the handling time was extended to 40 minutes with this system, the cylinders broke at 2,000 psi (13.9 MPa). The results from this test indicated that even at lower temperatures, an uninhibited mix containing 1.5% initiator and 0.75% promoter set up too rapidly to be used as a batch-mix overlay. The polymer concrete containing the lesser amount of initiator and promoter did not fully polymerize at the lower temperature within a 24-hour period.

Satisfactory results were obtained with polymer concrete mixes when an inhibitor was used to extend the allowable work time. Figure 2 shows a comparison of compressive strength of polymer concrete mixes with a handling time of 30 minutes when made and cured at 57°F and 69°F (13.9°C and 20.6°C). Cylinders were tested at 5 and 24 hours to determine early strength characteristics. When tested after a 5-hour cure, the specimen that was prepared and cured at 57°F (13.9°C) failed at 2,900 psi (19.9 MPa) while the specimen that was cured at 69°F (20.6°C) broke at 4,500 psi (31.0 MPa). After a 24-hour cure, however, the specimens failed at 7,900 psi and 9,400 psi (54.5 MPa and 64.8 MPa) respectively. Results of this testing clearly show the value of the inhibitor in extending allowable work time while maintaining an acceptable rate of polymerization.

The effect of aggregate moisture on compressive strength was investigated when polymer concrete mixes were prepared using LB 183-13 resin. The moisture content within the mix was controlled at 0, 2, 4 and 6 percent by weight of the aggregate. Mixes providing a 45 minute allowable work time were cast into 3 in. x 6 in. (76 mm x 152 mm) cylinders and cured at room temperature. Figure 3 shows a decrease in ultimate compressive strength as the moisture content is increased. The mix prepared with a zero percent moisture content failed at 8,500 psi (58.6 MPa) while the samples containing 6% moisture broke at only 2,100 psi (14.5 MPa). All specimens were tested after a 24-hour cure. Because of these results, only dry aggregate was specified in overlay work. An extension of the aggregate moisture study was used to determine the benefits of using silane as an additive to enhance the bond between the aggregate and the resin. The silane concentration was varied from zero percent to 4% by weight of the resin for comparison purposes. The results shown in Figure 4

Test # 249  
3" X 6" Cylinders  
Resin Content 12%  
30 Minute Handling Time



1000 psi = 6894.8 kPa

$^{\circ}\text{C} = (^{\circ}\text{F} - 32) / 1.8$

1" = 25.4 mm

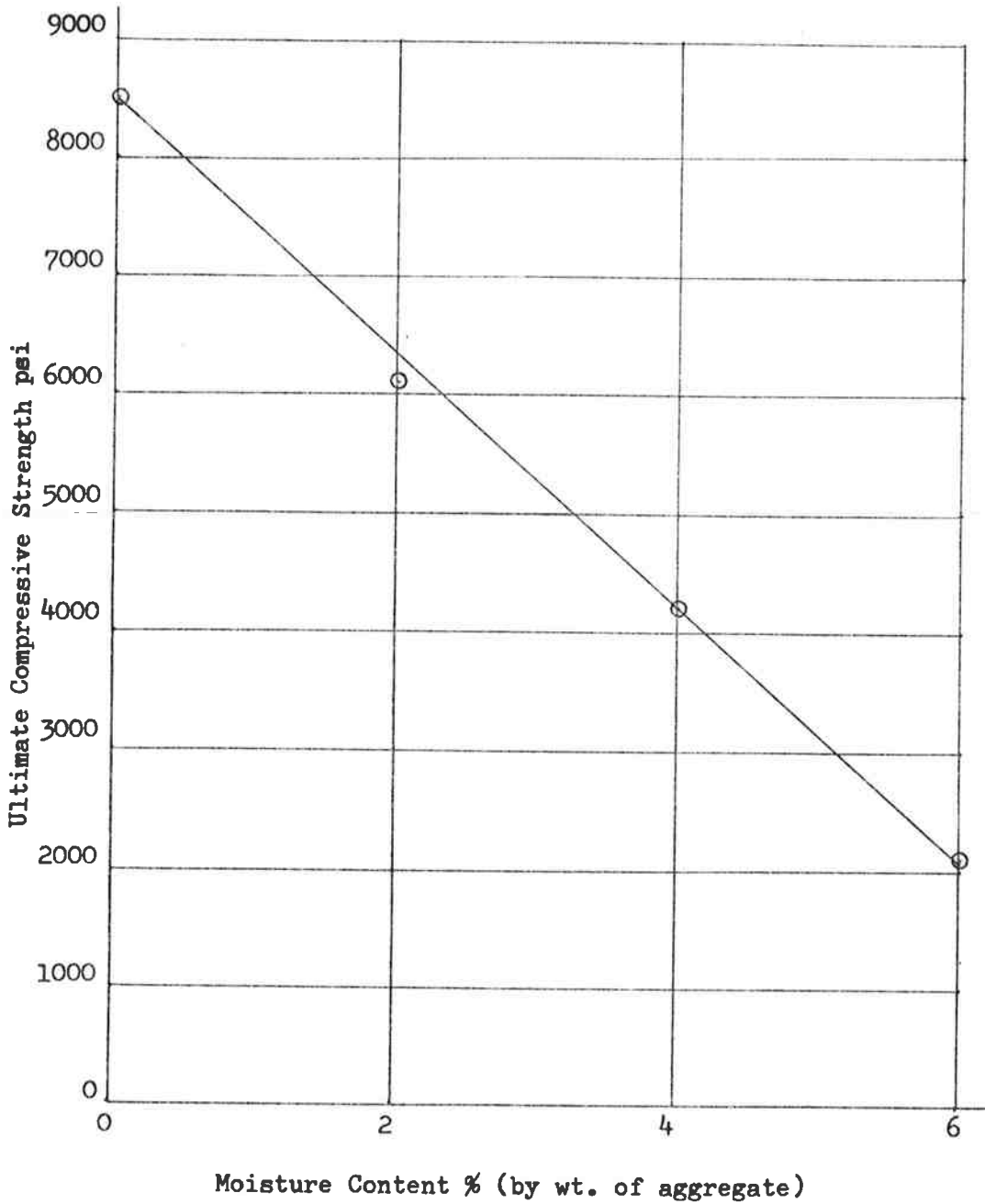
Compressive Strength vs. Curing  
Temperatures at different cure times

Figure 2

3" X 6" Cylinders  
Resin Content 10%  
Ambient Temp. 72°F (22.2°C)  
24 hr. Cure

1000 psi = 6894.8 kPa

1" = 25.4 mm



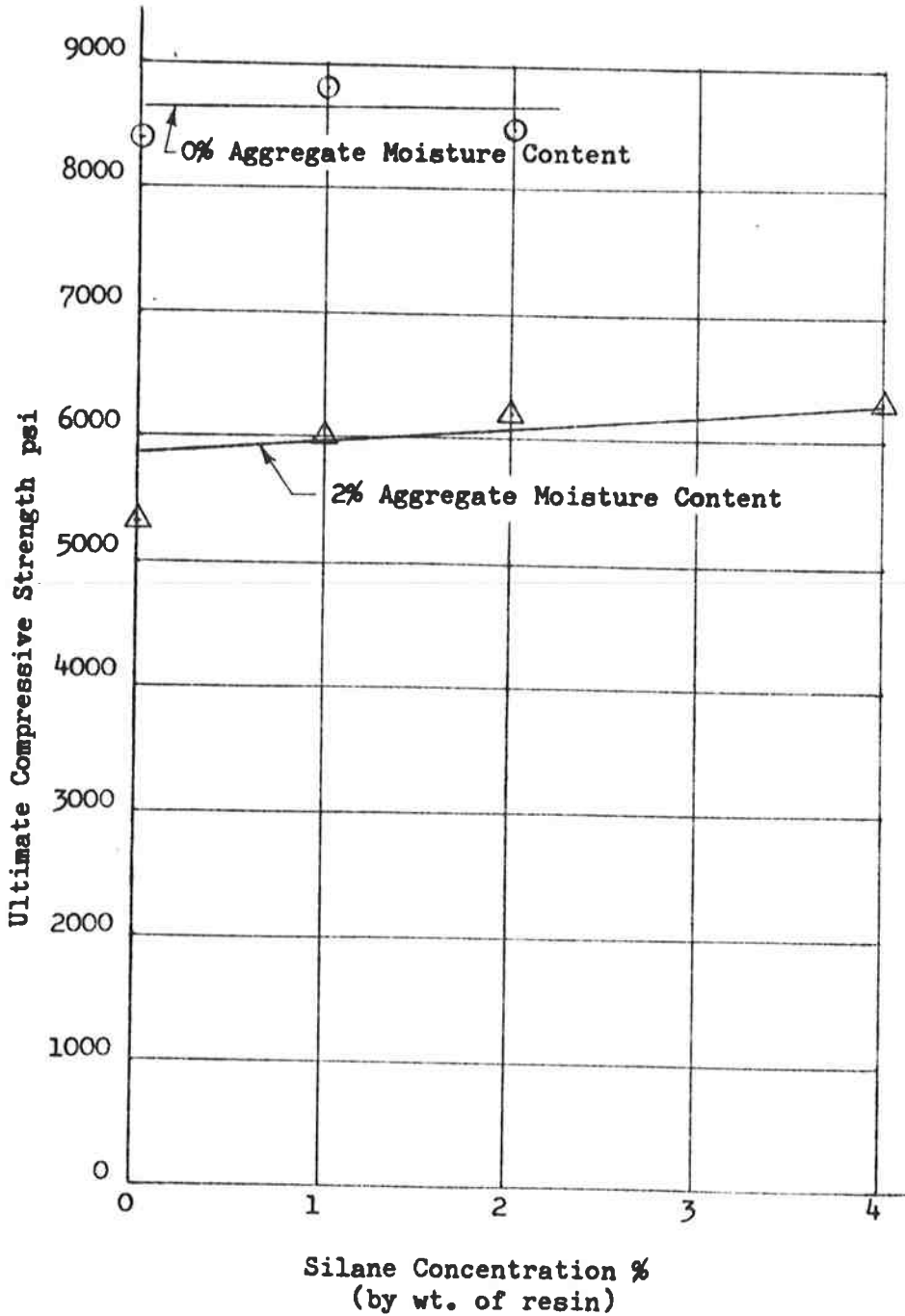
Compressive Strength vs. Aggregate Moisture Content

Figure 3

3" X 6" Cylinders  
Resin Content 10%  
24 hr. Cure

1000 psi = 6894.8 kPa

1" = 25.4 mm



Compressive Strength vs. Silane Concentration

Figure 4

indicate only a small increase in compressive strength was gained by the addition of silane. Because silane is very expensive, it is recommended for use only in the resin tack coat to improve bonding.

### Bond Tests

One of the most important elements in successfully applying a structural overlay is the ability to acquire good bonding between the overlay and substrate. The bond shear criteria established for the polymer concrete overlays was 200 psi (1,380 kPa) when tested in shear by applying a force parallel to the interface in a guillotine apparatus.

The bond testing program consisted of testing several different resin binders in making both polymer concrete mixes and tack coats. Included were methyl methacrylate, three polyester styrene blends, and a proprietary mix called Radgrout. The polymer concrete mixes were normally placed on 6 in. x 6 in. x 21 in. (152 mm x 152 mm x 533 mm) portland cement concrete beams that had been previously cast and cured. Additional polymer concrete overlays were cast on larger concrete slabs measuring 6 in. x 12 in. x 6 ft (152 mm x 305 mm x 1.8 m) long for conducting surface preparation studies. The cure time for the polymer concrete mixes varied from 24 hours to 7 days depending on the particular variable being studied. Immediately before testing, 4 in. (102 mm) diameter cores were taken through the overlay and base material. Figure 5 shows the apparatus used during the bond shear test. Complete results of the bond test program are shown in Table 4.

During initial testing, the resin content in the polymer concrete mixes was varied within the range of 8% to 14%. The overlays were placed on surfaces that had been prepared by wire brushing only. No resin tack coat was used for bonding because it was expected an adequate amount of resin would drain from the overlay to satisfy the need at the interface. This procedure did not provide consistently high bond strengths between the substrate concrete and the overlay although some high bond strengths were recorded.

A revised procedure was adopted whereby the substrate surface was sandblasted to produce a more desirable bonding surface. In addition, a variety of resin tack coats, both promoted and unpromoted, were examined. The unpromoted tack coats were used to provide a longer allowable work time. This procedure was followed before the use of inhibitors was investigated. Results of these early tests showed the use of a promoted tack coat on a sandblasted surface produced consistently high bond values. The failures of the test specimens when using this procedure were typically in the base concrete and not at the interface. The average bond values exceeded 400 psi (2,760 kPa) consistently.

The effect of tack coat quantity on bonding strength was examined as the thickness of the tack coats was varied from 15, 20, 35, to 50 mils (.38 mm, .51 mm, .88 mm to 1.27 mm). Test results indicated the thickness did not appreciably affect the bond strength as all performed equally well. A two-tack-coat system was also examined for performance. The first tack coat was applied to the substrate concrete and allowed to cure slowly in an attempt to gain good penetration. The second tack coat was applied immediately before



Figure 5. Bond-shear testing apparatus.

Table 4

## BOND TEST RESULTS

| Test No. | Polymer Mix Resin* % | Surface Preparation | Tack Coat | Cure Time | Bond Strength, psi |      |      |      |
|----------|----------------------|---------------------|-----------|-----------|--------------------|------|------|------|
|          |                      |                     |           |           | 1                  | 2    | 3    | 4    |
| 78       | C 12                 | Wire Brush          | None      | 24 hr     | 16                 | SO   | SO   | SO   |
| 14       | B 12                 | Wire Brush          | None      | 48 hr     | 357                | 143  | 76   | SO   |
| 15       | B 10                 | Wire Brush          | None      | 24 hr     | 505                | 444  | 517  | 388  |
| 16       | B 10                 | Wire Brush          | None      | 96 hr     | 215                | 181  | SO   | SO   |
| 17       | B 10                 | Wire Brush          | None      | 7 hr      | 142                | SO   | SO   | SO   |
| 18       | B 9                  | Wire Brush          | 15 mils** | 24 hr     | 72                 | SO   | SO   | SO   |
| 19       | B 8                  | Wire Brush          | 50 mils** | 24 hr     | 454                | 267  | ---  | ---  |
| 20       | B 8½                 | Wire Brush          | 50 mils** | 24 hr     | 321                | 326  | ---  | ---  |
| 21       | B 8½                 | Wire Brush          | 20 mils   | 24 hr     | SO                 | SO   | ---  | ---  |
| 25       | B 8½                 | Wire Brush          | 35 mils   | 24 hr     | 551+               | 409+ | 456+ | 461+ |
| 28       | B 8½                 | Sandblasted         | 15 mils   | 24 hr     | 519+               | 452+ | 347+ | 556+ |
| 29       | B 8½                 | Sandblasted         | 35 mils   | 24 hr     | 503+               | 534+ | ---  | ---  |
| 30       | B 8½                 | Sandblasted         | 50 mils   | 24 hr     | 258+               | 239+ | 454+ | 375+ |
| 31       | B 8½                 | Sandblasted         | 15 mils** | 24 hr     | 402                | 659  | 557  | 724  |
| 32       | B 8½                 | Sandblasted         | 35 mils** | 24 hr     | 258                | 162  | ---  | ---  |
| 33       | B 8½                 | Sandblasted         | 50 mils** | 24 hr     | 185                | 446  | 463  | 237  |
| 41       | B 8½                 | Sandblasted         | 35 mils   | 24 hr     | 364+               | 455+ | 450+ | 352+ |
|          |                      | Wet Surface         |           |           |                    |      |      | DT   |
| 42       | B 8½                 | Sandblasted         | 15 mils   | 24 hr     | 643                | 297  | 312+ | ---  |
|          |                      | Sandblasted         |           |           | Oil                | Oil  | DT   |      |
| 45       | B 8½                 | Sandblasted         | 15 mils   | 24 hr     | SO                 | SO   | 402+ | 404+ |
|          |                      | Acid Solution       |           |           | Oil                | Oil  |      |      |
| 46       | B 8½                 | Sandblasted         | 15 mils   | 24 hr     | SO                 | SO   | 582+ | 507+ |
|          |                      | TSP Solution        |           |           | Oil                | Oil  |      |      |

\* See Appendix A for resin blends.

+ Failure in core and not at interface.

\*\* Unpromoted.

DT Direct tension test.

SO Spun off during coring.

Sandblasted = Beam initially cleaned by sandblasting

Acid Solution = Beam cleaned by acid solution after oil contamination.

1000 psi = 6.89 MPa

1 mil = 0.025 mm

Table 4  
(continued)

| Test No. | Polymer Mix Resin* % | Surface Preparation             | Tack Coat | Cure Time | Bond Strength, psi |      |        |      |
|----------|----------------------|---------------------------------|-----------|-----------|--------------------|------|--------|------|
|          |                      |                                 |           |           | 1                  | 2    | 3      | 4    |
| 51       | B                    | Sandblasted<br>Sandblasted      | 15 mils   | 24 hr     | 497+               | 533+ | 540+   | 434+ |
| 81       | E                    | Wire Brush                      | None      | 96 hr     | 70                 | 155  | SO     | SO   |
| 82       | E                    | Wire Brush                      | None      | 96 hr     | SO                 | SO   | SO     | SO   |
| 83       | E                    | Wire Brush                      | None      | 96 hr     | SO                 | SO   | SO     | SO   |
| 84       | E                    | Sandblasted                     | 15 mils   | 24 hr     | 667                | 538  | 235 DT | 572  |
| 85       | E                    | Sandblasted                     | 35 mils   | 24 hr     | 570                | 652  | 325+   | 670  |
|          |                      |                                 |           |           |                    |      | DT     |      |
| 96       | A                    | Sandblasted                     | 15 mil    | 24 hr     | 684                | 927  | 765    | 814  |
| 170      | A                    | Sandblasted<br>Wet Surface      | 15 mil    | 12 days   | 80                 | 557  | 383    | 477  |
| 200      | A                    | Sandblasted<br>Wet Surface      | 2-15 mil  | 14 days   | 617+               | 617+ | 708+   | 619+ |
| 204      | A                    | Sandblasted                     | 15 mil    | 14 days   | 240                | 418+ | 425+   | 269+ |
| 206      | A                    | Sandblasted                     | 2-15 mil  | 14 days   | 643+               | 601+ | 543+   | ---  |
| 212      | A                    | Sandblasted                     | 20 mil    | 19 hr     | 428+               | 443+ | 535+   | 640+ |
| 213      | A                    | Sandblasted                     | 30 mil    | 19 hr     | 390+               | 437+ | 481+   | 493+ |
| 215      | A                    | Sandblasted                     | 30 mil    | 72 hr     | 460+               | 511+ | 465+   | 523+ |
| 216      | A                    | Sandblasted                     | 30 mil    | 72 hr     | ---                | ---  | ---    | ---  |
| 217      | A                    | Sandblasted                     | 2-15 mil  | 72 hr     | ---                | ---  | ---    | ---  |
| 218      | A                    | Sandblasted<br>Flame Dry $\phi$ | 30 mil    | 72 hr     | 429+               | 320+ | 240+   | 214+ |
| 219      | A                    | Sandblasted                     | 30 mil    | 72 hr     | 440                | 420  | 248    | 601  |
| 220      | A                    | Sandblasted<br>Flame Dry $\phi$ | 30 mil    | 72 hr     | ---                | ---  | ---    | ---  |

\* See Appendix A for resin blends. + Failure in core and not at interface.  
SO Spun off during coring.  $\phi$  Water soaked surface.  
DT Direct tension test.

1000 psi = 6.89 MPa  
1 mil = 0.025 mm

Table 4  
(continued)

| Test No. | Polymer Mix Resin* % | Surface Preparation             | Tack Coat | Cure Time | Bond Strength, psi |      |      |      |
|----------|----------------------|---------------------------------|-----------|-----------|--------------------|------|------|------|
|          |                      |                                 |           |           | 1                  | 2    | 3    | 4    |
| 221      | A 12                 | Sandblasted<br>Oven Dry $\phi$  | 30 mil    | 48 hr     | ---                | ---  | ---  | ---  |
| 222      | A 12                 | Sandblasted<br>Oven Dry $\phi$  | 30 mil    | 48 hr     | ---                | ---  | ---  | ---  |
| 223      | A 12                 | Sandblasted<br>Oven Dry $\phi$  | 30 mil    | 48 hr     | 292+               | 280+ | 284+ | 368+ |
| 224      | A 12                 | Sandblasted<br>Flame Dry $\phi$ | 30 mil    | 72 hr     | ---                | ---  | ---  | ---  |
| 225      | A 12                 | Sandblasted<br>Flame Dry $\phi$ | 30 mil    | 72 hr     | ---                | ---  | ---  | ---  |
| 249      | L 12                 | Scarified                       | 20 mil    | 48 hr     | 812+               | 611+ | 544+ | ---  |
| 256      | L 12                 | Scarified                       | 15 mil    | 7 days    | 351+               | 159+ | 316+ | ---  |
| 257      | L 12                 | Scarified &<br>Sandblasted      | 18 mil    | 8 days    | 688+               | ---  | ---  | ---  |
| 258      | L 12                 | Scarified                       | 20 mil    | 11 days   | 430+               | 417+ | ---  | ---  |
| 269      | L 11                 | Scarified &<br>Sandblasted      | 15 mil    | 34 days   | 177+               | 341+ | ---  | ---  |
| 270      | L 12                 | Scarified &<br>Sandblasted      | 15 mil    | 34 days   | 344+               | ---  | ---  | ---  |
| 271      | L 10                 | Scarified &<br>Sandblasted      | 15 mil    | 34 days   | 290+               | ---  | ---  | ---  |

\* See Appendix A for resin blends.  
+ Failure in core and not at interface.  
 $\phi$  Water soaked surface.

1000 psi = 6.89 MPa  
1 mil = 0.025 mm

the polymer concrete overlay was placed. Good bonding was recorded with this system when the substrate was prepared in a satisfactory manner.

Only one bond test was performed with polymer concrete that was made with methyl methacrylate because it was decided that evaporation and viscosity problems had to be solved for this system before it would make a suitable overlay material.

A study of various surface preparation and cleaning methods was made on oil contaminated beams fabricated to simulate field conditions. The methods examined were: (1) sandblasting, (2) washing with a dilute acid solution, (3) washing with a tri-sodium phosphate solution, and (4) removal of the surface mortar by scarification. The two commercial machines used to scarify the surface were a Tennant paint stripe remover and a McDonald scabblor. The most satisfactory results were obtained by surface scarification, although sandblasting of sound concrete also produced good results. Bond strength values after scarification can be found in Table 4.

Tests were also conducted to examine the effect of moisture in the substrate on the ability to bond a polymer concrete overlay. Early results indicated adequate bonding was obtained on a beam containing surface moisture. In Test No. 41 water was ponded on a concrete slab until 30 minutes before a 35 mil (0.88 mm) resin tack coat and a 1.5 in. (38 mm) polymer concrete overlay were applied. Several days later cores were removed from the slab and a bond shear test was performed on the overlay. The results indicated a bond strength of over 400 psi (2,760 kPa) was attained. An initial conclusion that surface moisture had little effect on bond proved to be erroneous when poor bonding occurred on the first bridge deck overlay project. A combination of cold weather and moisture was suspected as causing the bonding problem. Laboratory testing on beams subjected to moisture and low temperature and various surface drying methods was then performed. Results from this work indicated the need for a dry and relatively warm surface [(50°F) (10°C)] to allow good resin penetration and complete polymerization of the tack coat. Attempts to lower the viscosity of the resin, LB 183-13, by adding styrene did not improve bonding strength but rather lowered it in most cases. A literature search of epoxy concrete studies found water vapor leaving the concrete surface to be a potential problem in acquiring good bond (7). This was equally true with a polyester styrene resin tack coat.

The results from the bonding studies show adequate bonding can be obtained if the substrate material is properly prepared. The base material must be sound, clean, dry, and at the proper temperature at the time the tack coat is applied.

### Splitting Tensile Test

The tensile strength of several polymer concrete mixes was examined by testing 3 in. x 6 in. (76 mm x 152 mm) cylinders in splitting tensile loading in accordance with ASTM C496. This testing was normally performed on specimens that were allowed to cure 24 hours, although some testing was done at longer cure times. The resin formulation, resin content and silane concentration

were varied to study their effects on tensile strength. The relationship between splitting tensile strength and ultimate compressive strength was also noted. The results of the splitting tensile studies are found in Table 5.

In the first test, three cylinders that had previously been subjected to five cycles of a freeze-thaw test in air were tested for splitting tensile strength. These cylinders were tested 42 days after fabrication. The results of this test indicated a splitting tensile strength of this polymer concrete to be above 1,500 psi (10.3 MPa), which is over two times that of conventional portland cement concrete.

In the next series of tests, polymer concrete cylinders were fabricated using LB 183-13 resin at 8.5% and 10% resin contents. Allowing a one-day cure, the cylinders were tested with an average 5% increase in tensile value noted due to the increase in resin content. The average splitting tensile strength for the 8.5% mix was calculated at over 1,300 psi (8.9 MPa).

A further study compared the tensile strength of polymer concrete mixes containing a 10% resin content but with different resin binders. The polymer concrete made with a combination of LB 183-13 and GR 941 resins provided the highest average splitting tensile strength of 1,489 psi (10.3 MPa) after a one-day cure, while the lowest average splitting tensile strength was 805 psi (5.6 MPa) for the polymer concrete containing GR 511 resin. Polymer concretes made with LB 183-13 resin and GR 11044 resin had approximately the same average tensile strength of 1,315 psi (9.1 MPa).

The effects of using silane, a coupling agent, on splitting tensile strength was also investigated. Polymer concrete mixes were prepared using silane concentration of zero to two percent by weight of the resin. Overall results indicated the addition of silane did not improve the splitting tensile strength.

Finally, the ratio of splitting tensile strength to ultimate compressive strength was found to average 0.157 when a comparison was made using the results from 10 tests without regard to the binder used.

#### Modulus of Rupture

Several polymer concrete mixes were tested in flexure in accordance with ASTM C78. All testing was performed on 6 in. x 6 in. x 21 in. (152 mm x 152 mm x 533 mm) beams which were fabricated in three lifts and consolidated with a 1 in. (25 mm) diameter concrete vibrator as shown in Figure 6. During the initial testing, two sets of three beams were cast using LB 183-13 resin. The resin content of one set was designed at 8.5% and the other designed at 10% by weight of the aggregate. The method of curing was varied as one beam from each set was placed in an oven for one hour at 140°F (60°C) to ensure complete polymerization. These beams were then allowed to continue curing at room temperature before being tested. After a total curing period of 24 hours, all beams were subjected to a third-point-loading test until failure. Both the load and deflection at failure were recorded. Figure 7 illustrates testing in progress. The results of this test show the beams that had been placed

Table 5

## RESULTS OF SPLITTING TENSILE TESTS

| Test No. | Resin* | Resin Content %*** | Aggregate Gradation** | Allowable Work Time (min.) | Age (days) | Splitting Tensile Strength (psi) | Compressive Strength (psi) | ft/fc |
|----------|--------|--------------------|-----------------------|----------------------------|------------|----------------------------------|----------------------------|-------|
| 27       | A      | 8.5                | 1                     | 10                         | 42         | 1,575                            | -                          | -     |
| 164      | A      | 10                 | 2                     | 20                         | 1          | 1,376                            | 8,512                      | 0.162 |
| 165      | A      | 8.5                | 2                     | 20                         | 1          | 1,368                            | 8,207                      | 0.166 |
| 166      | A      | 10                 | 2                     | 20                         | 1          | 1,281                            | 8,812                      | 0.145 |
| 167      | A      | 8.5                | 2                     | 20                         | 1          | 1,238                            | 7,534                      | 0.164 |
| 172      | A      | 10                 | 2                     | 20                         | 1          | 1,355                            | 8,413                      | 0.161 |
| 173      | N      | 10                 | 2                     | 20                         | 1          | 1,422                            | 10,042                     | 0.141 |
| 174      | N      | 10                 | 2                     | 20                         | 1          | 1,556                            | 10,594                     | 0.147 |
| 180      | D      | 10                 | 2                     | 20                         | 1          | 1,295                            | 8,966                      | 0.144 |
| 181      | D      | 10                 | 2                     | 20                         | 1          | 1,284                            | 8,612                      | 0.149 |
| 194      | H      | 10                 | 3                     | -                          | 3          | 1,220                            | -                          | -     |
| 195      | J      | 10                 | 3                     | -                          | 3          | 805                              | -                          | -     |
| 207      | L      | 10                 | 2                     | -                          | 8          | 1,312                            | -                          | -     |
| 250      | L      | 12                 | 4                     | 20                         | 1          | 1,093                            | 5,835                      | 0.187 |

\* See Appendix A for resin blends.

\*\* See Table 3 for gradation.

\*\*\* Percent by weight of aggregate.

1000 psi = 6.89 mpa

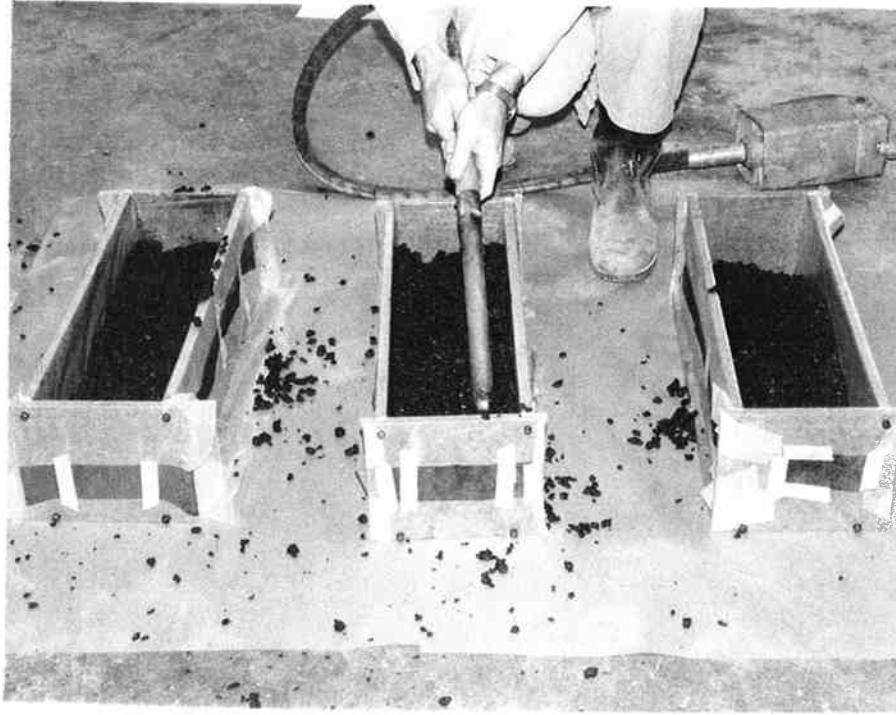


Figure 6. Consolidation of polymer concrete beams.

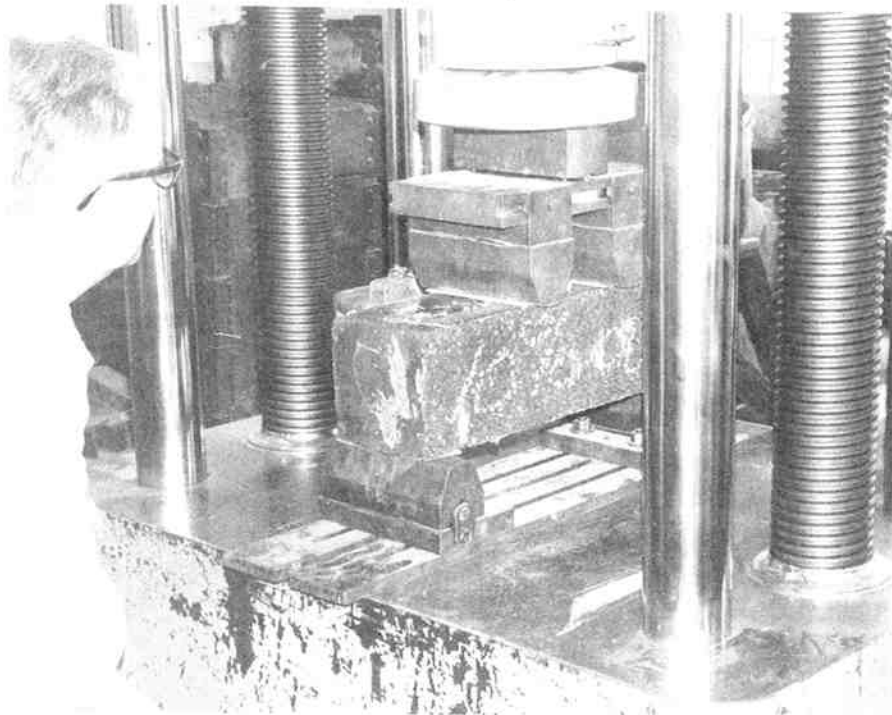


Figure 7. Third point loading for modulus of rupture test.

Table 6

## MODULUS OF RUPTURE

| Test No. | Resin* | Resin Content (%) *** | Aggregate Gradation** | Unit Weight lbs/cf | Ultimate Load (lbs) | Modulus of Rupture (psi) | Maximum Deflection (in.) |
|----------|--------|-----------------------|-----------------------|--------------------|---------------------|--------------------------|--------------------------|
| 183-1    | A      | 10                    | 2                     | 144.9              | 24,900              | 2,075                    | .0475                    |
| 183-2    | A      | 10                    | 2                     | 143.0              | 21,750              | 1,813                    | .0365                    |
| 183-3    | A      | 10                    | 2                     | 143.8              | 22,600              | 1,883                    | .0490                    |
| 184-1    | A      | 8.5                   | 2                     | 132.8              | 16,750              | 1,395                    | .0360                    |
| 184-2    | A      | 8.5                   | 2                     | 134.4              | 15,800              | 1,316                    | .0355                    |
| 184-3    | A      | 8.5                   | 2                     | 131.8              | 15,800              | 1,316                    | .0400                    |
| 194      | H      | 10                    | 3                     | 141.5              | 22,000              | 1,833                    | .0700                    |
| 195-1    | J      | 10                    | 3                     | -                  | 10,030              | 836                      | .0860                    |
| 195-2    | J      | 10                    | 3                     | -                  | 11,720              | 977                      | .0970                    |
| 205      | L      | 10                    | 3                     | -                  | 25,900              | 2,159                    | .0650                    |

\* See Appendix A for resin blends.

\*\* See Table 3 for gradation.

\*\*\* Percent by weight of aggregate.

1 lb/cf = 16.02kg/m<sup>3</sup>

1 lb = .453 kg

1000 psi = 6.89 MPa

1" = 25.4 mm

in the oven had a slightly higher modulus of rupture than those cured entirely in air. This indicated complete polymerization may not have occurred in all specimens. The beams having the 10% resin content exhibited an average modulus of rupture of 1,925 psi (13.3 MPa), which was 43% higher than the beams with the 8.5% resin content. Results of the flexure tests are presented in Table 6.

The modulus of rupture of a polymer concrete beam made with a flexible resin, GR 511, averaged 906 psi (4.2 MPa). The average deflection at failure was 0.091 in. (2.3 mm) which was approximately twice that of the beams containing LB 183-13 resin.

In the final test, a polymer concrete beam constructed with GR 11044 as the binder failed at a stress of 2,160 psi (14.9 MPa). This beam was tested after a three-day cure. A comparison of the modulus of rupture of the beams made with the LB 183-13 resin and the GR 11044 resin show relatively close values.

### Modulus of Elasticity

The modulus of elasticity of several different polymer concrete mixes was examined during this study. Individual test data are shown in Table 7. The polymer concrete samples were cast in 6 in. x 12 in. (152 mm x 305 mm), cylinders and tested at various intervals during curing. The apparatus used to measure the deformation is shown in Figure 8.

During the first test, two samples were made using a 8.5% resin content (Test No. 44). The handling time was varied to study its effect on the modulus of elasticity for the particular resin formulation used. The first mix was placed and finished in 12 minutes and tested at 1, 3, and 7 days. The modulus of elasticity increased from  $1.8 \times 10^6$  psi (12.4 GPa) at 1 day to  $2.6 \times 10^6$  psi (17.9 GPa) in 7 days when loaded to a maximum stress level of 3,000 psi (20.7 MPa) (Figure 9). The increase in the elastic modulus indicated complete polymerization of the polymer concrete had not occurred at the end of 1 day. The handling time of the second sample was extended for 30 minutes by delaying the placing and finishing after mixing. This sample was tested at 1 and 3 days. The testing at day 1 had to be curtailed at a stress level of 1,400 psi (9.7 MPa) because of excessive strain. The cylinder failed during the third day test at 1,730 psi (11.9 MPa) with a corresponding "E" value of  $0.4 \times 10^6$  psi (2.76 GPa). The difficulty in placing the material in the mold and the results of this test indicated that a partial polymerization had occurred before the polymer concrete was compacted and finished. This overhandling caused the binding capability of the resin to be substantially reduced. The early failure of the second cylinder showed the need of an inhibitor to extend the allowable handling time. It was at this time that hydroquinone was found to slow the polymerization to an acceptable rate. All further work utilized hydroquinone to produce handling times in excess of 30 minutes at moderate temperatures.

The LB 183 resin was used to study the effects of resin content on the modulus of elasticity in Tests No. 144 and No. 145. Figure 10 shows the "E" values at 3 and 77 days. The modulus of elasticity was not recorded at 1 day because

Table 7

## MODULUS OF ELASTICITY

| Test No.                   | 44   | 99   | 144  | 145 | 146  | 194  | 195  | 249  |
|----------------------------|------|------|------|-----|------|------|------|------|
| Resin <sup>1</sup>         | B    | A    | A    | A   | D    | H    | J    | L    |
| Resin Content <sup>2</sup> | 8.5  | 10.0 | 10.0 | 8.5 | 10.0 | 10.0 | 10.0 | 12.0 |
| MEKP <sup>3</sup>          | 2.0  | 2.0  | 2.0  | 2.0 | 2.0  | 1.5  | 1.5  | 2.0  |
| Co Oc <sup>3</sup>         | 0.25 | 0.5  | 0.5  | 0.5 | 0.5  | 0.25 | 0.25 | 0.5  |
| A174 <sup>3</sup>          | 2.0  | 2.0  | 2.0  | 2.0 | 2.0  | 1.0  | 1.0  | 0.0  |
| HQ <sup>4</sup>            | 0.0  | 425  | 400  | 400 | 400  | 200  | 200  | 200  |

| Age in days | "E" Values <sup>5</sup> |      |      |      |      |      |      |      |
|-------------|-------------------------|------|------|------|------|------|------|------|
| 1           | 1.85                    | ---  | NG   | NG   | NG   | .84  | 0.46 | 2.56 |
| 3           | 2.38                    | ---  | 2.43 | 1.67 | 1.97 | 1.62 | 0.57 | ---  |
| 7           | 2.60                    | ---  | 2.86 | 2.07 | 2.45 | 1.81 | 0.48 | 2.90 |
| 11          | 2.67                    | 3.16 | ---  | ---  | ---  | ---  | ---  | ---  |
| 14          | ---                     | 3.27 | ---  | ---  | ---  | ---  | ---  | 2.90 |
| 28          | ---                     | ---  | ---  | ---  | ---  | ---  | ---  | 2.91 |
| 44          | ---                     | ---  | 3.43 | 2.48 | 2.62 | ---  | ---  | ---  |
| 77          | ---                     | ---  | 3.43 | 2.63 | 2.70 | ---  | ---  | ---  |
| 117         | ---                     | 3.38 | ---  | ---  | ---  | ---  | ---  | ---  |

<sup>1</sup> See Appendix A for resin blends.

<sup>2</sup> Percent by weight of aggregate.

<sup>3</sup> Percent by weight of resin.

<sup>4</sup> Parts per million by weight of aggregate.

<sup>5</sup>  $1 \times 10^6$  lbs/sq. in.

1000psi = 6.89 MPa

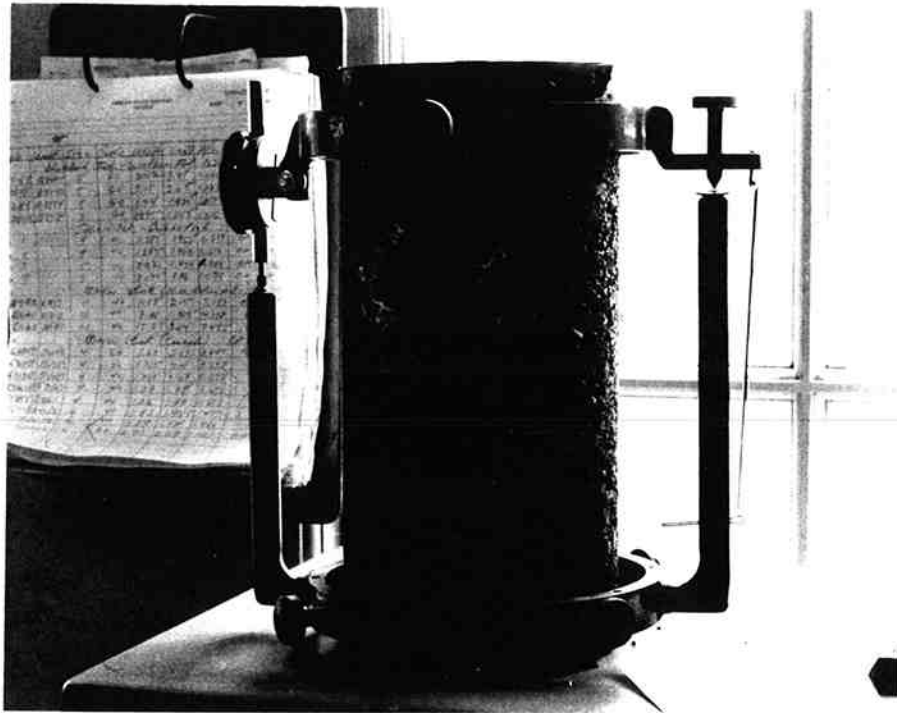
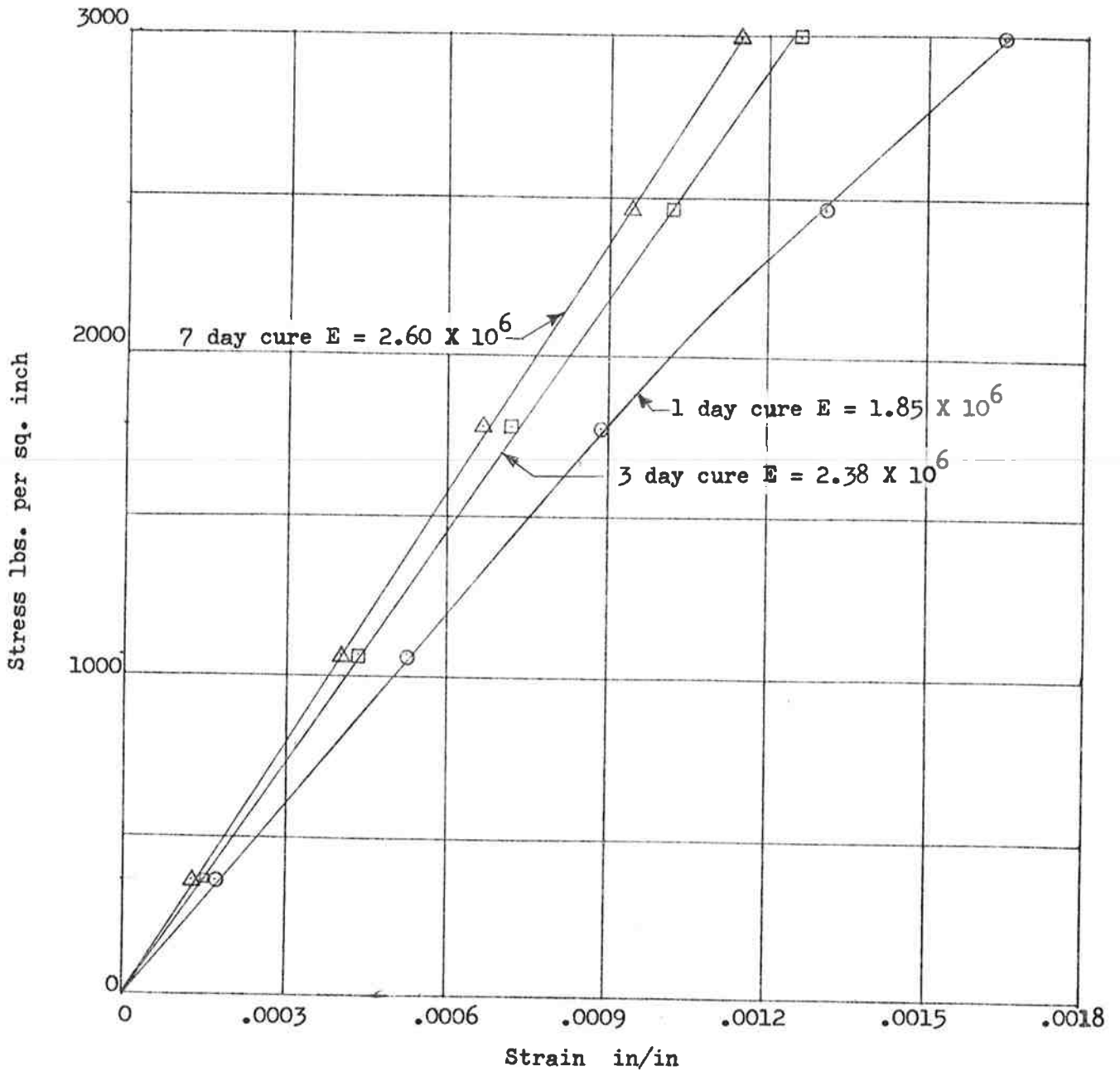


Figure 8. Apparatus for strain measurements.

Test # 44  
6" X 12" Cylinder  
8 1/2% Resin Content  
12 Minute Handling Time

1000 psi = 6894.8 kPa

1" = 25.4 mm



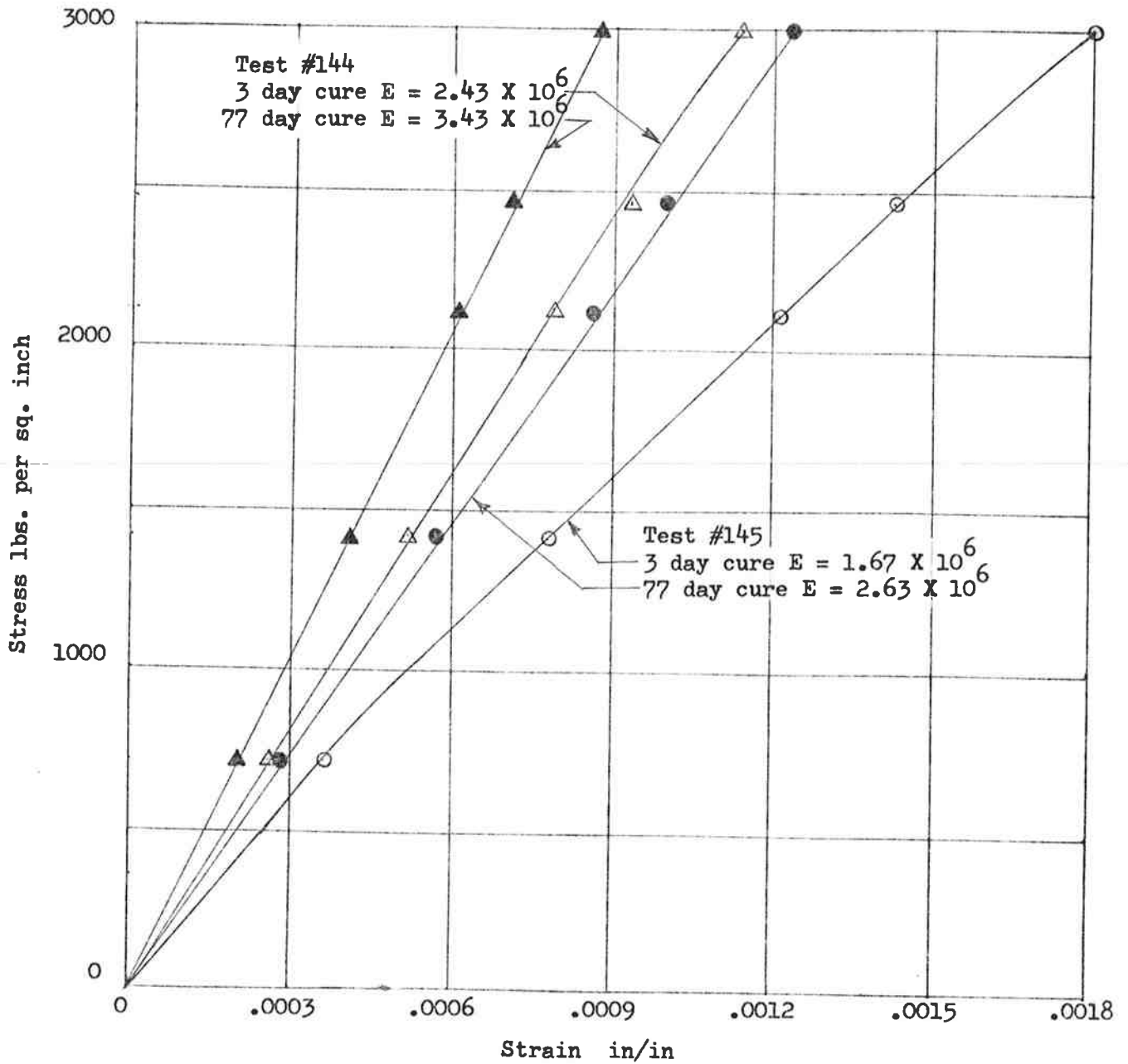
Stress-Strain curves at  
different cure times.

Figure 9

6" X 12" Cylinders  
1000 psi = 6894.8 kPa  
1" = 25.4 mm

Test # 144  
10% Resin Content

Test # 145  
8 1/2% Resin Content



Stress-Strain curves for polymer  
concretes with different resin content.

Figure 10

the polymer concrete was not sufficiently cured. This was due to a combination of low temperature during initial curing and the high concentration of inhibitor (400 ppm). The sample containing 10% resin had an "E" value of  $3.43 \times 10^6$  psi (23.6 GPa) at 77 days while the sample containing 8.5% resin had an "E" value of  $2.63 \times 10^6$  psi (18.1 GPa) at 77 days. There was a substantial gain in the modulus of elasticity between the 7 and 44 day tests also.

The modulus of elasticity of a polymer concrete mixture made with GR 511, a more flexible resin, was examined in Test No. 195. Using an inhibitor concentration of 200 ppm and 10% resin content, the polymer concrete cured sufficiently to test at 1, 3, and 7 days. The modulus of elasticity for this mix was calculated to be approximately  $0.5 \times 10^6$  psi (3.4 GPa).

Another modulus of elasticity test was performed on a polymer concrete prepared with GR 11044 resin. The results of this test are plotted in Figure 11 at curing times of 1, 7, and 28 days. The "E" values measured at these times were  $2.56 \times 10^6$  psi,  $2.90 \times 10^6$  psi, and  $2.91 \times 10^6$  psi (17.6 GPa, 20.0 GPa, and 20.0 GPa) respectively. These values indicated that nearly complete polymerization had occurred at 7 days with the inhibitor concentration at 200 ppm.

#### Thermal Coefficient Test

The first thermal coefficient study was conducted on 3 in. x 6 in. (76 mm x 152 mm) polymer concrete cylinders with an 8.5% resin content. The specimens were cast and cured for several days at room temperature. Measurements of length were made at room temperature,  $140^{\circ}\text{F}$  ( $60^{\circ}\text{C}$ ), and  $-10^{\circ}\text{F}$  ( $-23.3^{\circ}\text{C}$ ) with a dial indicator as shown in Figure 12. The specimens were heated in an oven for 24 hours and cooled in a freezer for 24 hours during the testing cycles. Initial results indicated the polymer concrete made with polyester styrene to have a nonlinear coefficient of thermal expansion. The average value for the three specimens tested was  $7.8 \times 10^{-6}$  in/in/ $^{\circ}\text{F}$  for room temperature to  $-10^{\circ}\text{F}$  ( $23.3^{\circ}\text{C}$ ), while from room temperature to  $140^{\circ}\text{F}$  ( $60^{\circ}\text{C}$ ) the average coefficient was  $9.8 \times 10^{-6}$  in/in/ $^{\circ}\text{F}$  (Test No. 27).

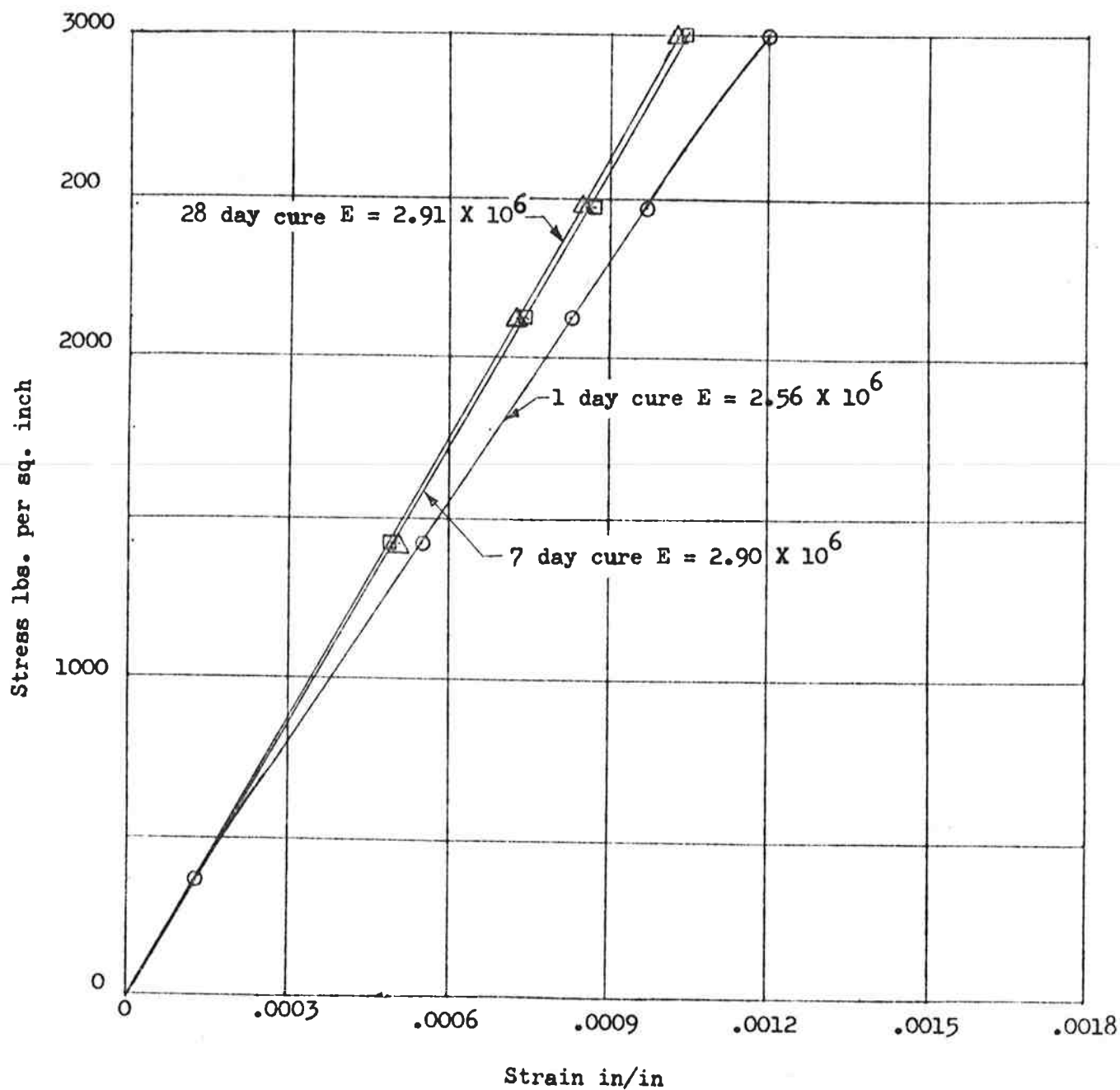
During Tests No. 56 and No. 70, the thermal coefficient was measured at intermediate temperatures to more clearly define the temperature vs. length curve. Using an 8.5% resin content, measurements were made at  $-10^{\circ}\text{F}$  ( $-23.3^{\circ}\text{C}$ ),  $35^{\circ}\text{F}$  ( $1.7^{\circ}\text{C}$ ),  $68^{\circ}\text{F}$  ( $20^{\circ}\text{C}$ ),  $100^{\circ}\text{F}$  ( $37.8^{\circ}\text{C}$ ), and  $140^{\circ}\text{F}$  ( $60^{\circ}\text{C}$ ). The results of this test were in close agreement with the earlier findings. Increasing the resin content to 10% as shown in Test No. 70, Table 8, did not alter the results significantly, but the coefficient of thermal expansion appeared to be greater at the higher temperatures.

The thermal coefficients of the polymer concrete mixes tested were somewhat higher than that of portland cement concrete, which is around  $6.5 \times 10^{-6}$  in/in/ $^{\circ}\text{F}$ . The resulting potential differential movement between the polymer concrete and the substrate concrete was not expected to cause any problems, provided the overlays were kept thin and adequate bond was obtained. By lowering the modulus of elasticity of the polymer concrete, reductions in the required bond strength could be achieved.

Test # 249  
6" X 12" Cylinder  
12% Resin Content  
30 Minute Handling Time

1000 psi = 6894.8 kPa

1" = 25.4 mm



Stress-strain curve at different cure times

Figure 11

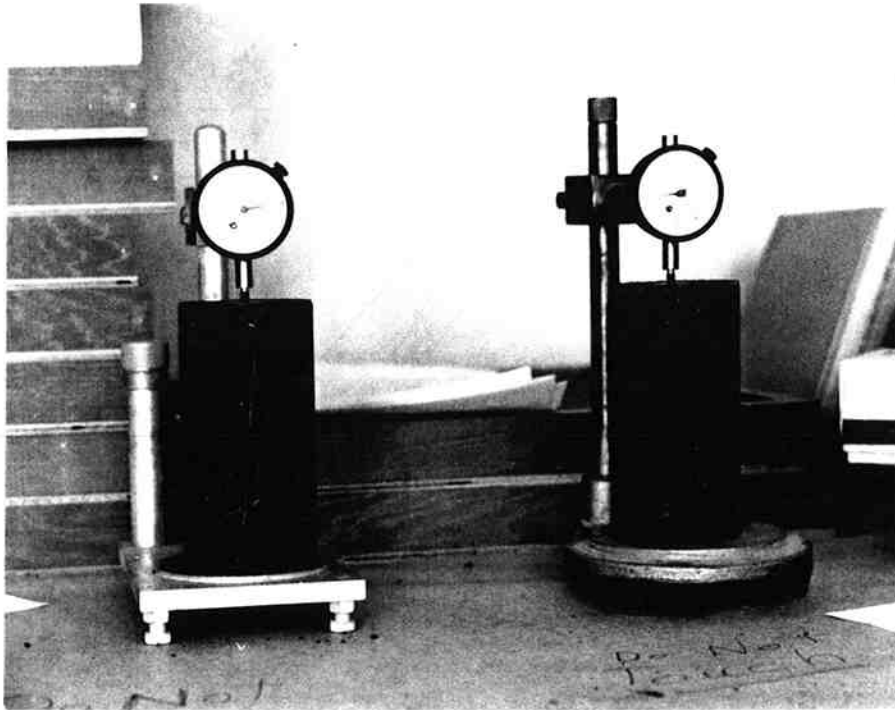


Figure 12. Dial indicator used in thermal coefficient tests.

Table 8  
THERMAL COEFFICIENT TEST RESULTS

|                            | TEST NUMBER |      |      |
|----------------------------|-------------|------|------|
| Composition                | 27          | 56   | 70   |
| Resin <sup>1</sup>         | B           | B    | B    |
| Resin Content <sup>2</sup> | 8.5         | 8.5  | 10   |
| MEKP <sup>3</sup>          | 1.5         | 0.5  | 0.5  |
| Co Oc <sup>3</sup>         | 0.75        | 0.25 | 0.25 |
| A174 <sup>3</sup>          | 2.0         | 2.0  | 2.0  |

| Temp. Range °F | Coefficient of expansion, 10 <sup>-6</sup> in/in/°F |     |      |
|----------------|---|-----|------|
| -10 to 35      | --  | 7.3 | 6.9  |
| -10 to 70      | 7.8   | --  | --   |
| 35 to 70       | --  | 7.9 | 7.9  |
| 70 to 100      | --  | 9.9 | 9.6  |
| 100 to 140     | --  | 9.5 | 10.6 |
| 70 to 140      | 9.8   | --  | --   |

<sup>1</sup> See Appendix A for resin blends.

<sup>2</sup> Percent by weight of aggregate.

<sup>3</sup> Percent by weight of resin.

1" = 25.4 mm

C° = 5/9(F°-32)

## Shrinkage Coefficient Tests

An investigation of curing shrinkage was made to determine the suitability of polymer concrete as an overlay material. The examination of polymer concrete shrinkage was conducted on a variety of mixes to compare the effects of different resins, resin contents, rates of cure, and aggregate gradations. The results of this work are found in Table 9.

In the first test series, 3 in. x 6 in. (76 mm x 152 mm) cylinder samples were cast with 8.5% and 10% resin contents. Shrinkage measurements were made after 3 hours and continued for 14 days while the samples remained in their molds. Of the four cylinders cast for each mix, one was placed permanently in a measuring apparatus (Figure 12) while the others were measured and removed after each reading. The same apparatus was used to measure the thermal coefficient. At the end of 14 days, the samples were removed from their casting molds and measured for an additional 14 days. While in the molds, the shrinkage was quite low and had apparently stabilized after 5 or 6 days. During the first 24 hours after removal from the molds, however, a dramatic additional shrinkage occurred for both mixes. This was followed by a shrinkage at a diminishing rate for several more days. Results indicated the amount of shrinkage was affected by the amount of binder used. The total shrinkage strain after 28 days was 0.0012 in/in for the 10% mix and .0009 in/in for the 8.5% mix. Each of the specimens contained LB 183-13 resin, 1.5% initiator and 0.75% promoter (Tests No. 23 and No. 24).

In the next test series, two additional cylinder samples were cast in 3 in. x 6 in. (76 mm x 152 mm) molds. This time each contained 8.5% resin, but with different amounts of initiator and promoter. These samples were removed from their molds in 3 hours and at that time shrinkage measurements began. Average measurements indicated a strain of 0.00038 in/in in 1 day and 0.00051 in/in in both 5 and 28 days for the sample containing 1.5% initiator (Test No. 56). The average strain for the sample containing 0.5 % initiator was 0.0009 in/in in 1 day, 0.0010 in/in in 5 days, and 0.0011 in/in in 28 days (Test No. 57). Measuring difficulties prevented shrinkage values being taken during the first 3 hours while the specimens were in the molds. However, it appeared 70% of the shrinkage occurred within the first 24 hours (see Figure 13).

Because of these high shrinkage values, a study was made to determine the effect of increasing the percentage of aggregate material passing the No. 200 sieve on polymer concrete shrinkage. Four aggregate gradations were selected which basically follow the maximum density curve except for the fine material. The material passing the No. 200 sieve was varied between 10% and 16%. A 12% resin content was used due to previous testing which determined it to be sufficient to produce a workable and compactible mix for each gradation. The various aggregate gradations are found in Table 2, columns 7, 8, 9 and 10.

After mixing and placing, shrinkage measurements were made at approximately 2-hour intervals during the first day and then periodically for two weeks. Test results indicate no noticeable reduction in shrinkage was accomplished by increasing the fine material. All measurable shrinkage occurred during the first 24 hours in all specimens. The calculated value of the coefficient of shrinkage of each specimen is found in Table 9 for Tests No. 244 through No. 247.



Table 9

(continued)

TEST NUMBER

| Composition     | 245 | 246 | 247 | 251 | 252 | 253 | 254 | 265 |
|-----------------|-----|-----|-----|-----|-----|-----|-----|-----|
| Resin*          | L   | L   | L   | L   | L   | L   | L   | L   |
| Resin Content % | 12  | 12  | 12  | 10  | 10  | 14  | 14  | 12  |
| Aggregate**     | 8   | 9   | 10  | 7   | 8   | 9   | 10  | 6   |
| Temp. °F        | 68  | 68  | 68  | 76  | 76  | 76  | 76  | 68  |

Cure Time (hrs)

Shrinkage Strain in/in

|   |       |       |       |       |       |       |       |       |
|---|-------|-------|-------|-------|-------|-------|-------|-------|
| 2 | ---   | ---   | .0003 | .0014 | .0019 | .0016 | .0014 | ---   |
| 3 | .0014 | .0014 | ---   | ---   | ---   | ---   | ---   | ---   |
| 4 | .0028 | .0017 | .0020 | ---   | ---   | ---   | ---   | ---   |
| 5 | .0031 | ---   | .0023 | ---   | ---   | ---   | ---   | ---   |
| 6 | ---   | ---   | ---   | .0016 | .0022 | .0019 | ---   | ---   |
| 7 | ---   | .0025 | ---   | ---   | ---   | ---   | .0017 | .0022 |
| 8 | ---   | ---   | .0023 | ---   | ---   | ---   | ---   | ---   |

Cure Time (days)

|    |       |       |       |       |       |       |       |       |
|----|-------|-------|-------|-------|-------|-------|-------|-------|
| 1  | .0031 | .0025 | .0029 | .0019 | .0025 | .0019 | .0025 | .0022 |
| 2  | .0031 | .0025 | .0029 | .0019 | .0025 | .0019 | .0025 | .0022 |
| 3  | ---   | ---   | ---   | ---   | ---   | ---   | ---   | ---   |
| 4  | ---   | ---   | ---   | ---   | ---   | ---   | ---   | ---   |
| 5  | .0031 | .0025 | .0029 | ---   | ---   | ---   | ---   | ---   |
| 6  | ---   | ---   | ---   | ---   | ---   | ---   | ---   | ---   |
| 7  | ---   | ---   | ---   | ---   | ---   | ---   | ---   | ---   |
| 8  | ---   | ---   | ---   | .0022 | .0025 | .0022 | .0025 | .0022 |
| 12 | .0031 | .0025 | .0029 | ---   | ---   | ---   | ---   | ---   |
| 14 | ---   | ---   | ---   | ---   | ---   | ---   | ---   | ---   |
| 15 | ---   | ---   | ---   | ---   | ---   | ---   | ---   | ---   |
| 28 | ---   | ---   | ---   | ---   | ---   | ---   | ---   | ---   |

\* See Appendix A for resin blends.

\*\* See Table 3 for aggregate gradation.

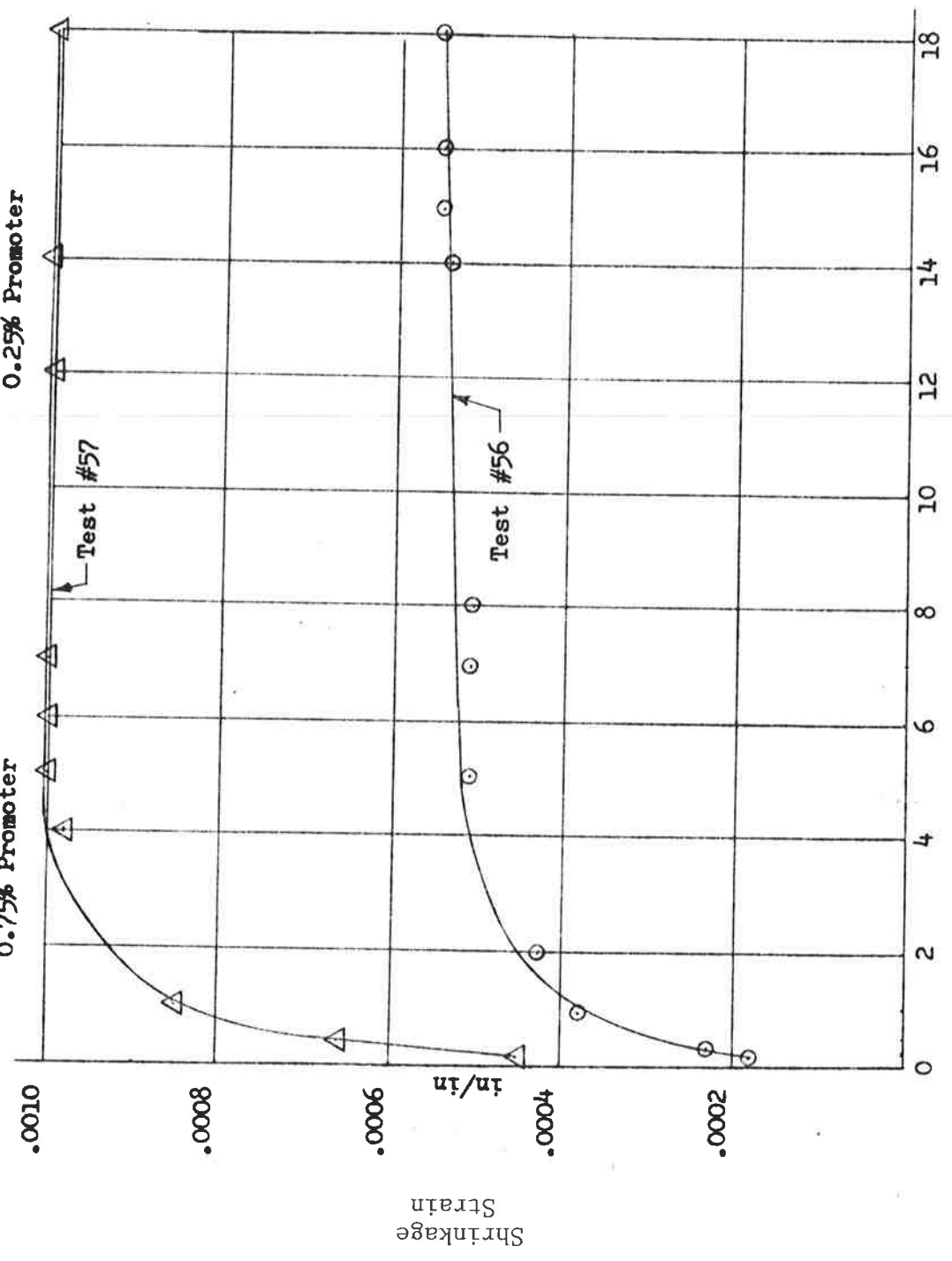
C° = 5/9(F°-32)

1" = 25.4 in/in

Test #56  
1.5% Initiator  
0.75% Promoter

Test #57  
0.5% Initiator  
0.25% Promoter

3" X 6" Cylinders  
Temp. 70°-76°  
10 Minute Handling Time  
8.5% Resin Content  
°C = (°F - 32)/1.8  
1" = 25.4 mm



Time in days  
Shrinkage Strain vs. Time  
Figure 13

Although the total shrinkage coefficient of some polymer concrete mixes were in excess of 0.002 in/in it was assumed most of the shrinkage would occur while the resin was in a semisolid state and cracking of thin overlays would not occur. The larger shrinkage coefficients occurred in mixes having the greater resin contents. By keeping the resin content at a minimum and the overlay thin, curing shrinkage stress can be greatly reduced. All of the earlier polymer concrete overlays were placed 1.5 in. thick and some minor shrinkage cracks were noted within two days after placement.

If the 0.002 in/in shrinkage were to be concentrated in, say, three cracks on a 200 ft overlay, each of these cracks would be possibly 2 x 25 ft x 12 in/ft x 0.002 in/in = 1.2 in. wide. This, of course, would be intolerable. It would also be highly unlikely, since for this to occur the overlay would have to be essentially unbonded. Since significant bond is probable, the cracks would be more equally distributed and smaller. The ideal situation would be to have all shrinkage strain to go into tensile stress below the ultimate strength with no cracks.

#### Freeze-Thaw Resistance Test

An investigation of freeze-thaw resistance of polymer concrete began with six 2-in. (51 mm) cubes being cast using LB 183 resin. Using an 8.5% resin content mix, the cubes were cast and allowed to cure for 24 hours before being subjected to alternate freeze-thaw cycles. The freeze-thaw test consisted of freezing the polymer concrete cubes in air at  $-10^{\circ}\text{F}$  ( $-23.3^{\circ}\text{C}$ ) followed by thawing in water at  $68^{\circ}\text{F}$  ( $20^{\circ}\text{C}$ ). Two complete cycles were accomplished each day with the freeze portion of one cycle extending overnight. At the end of 150 cycles, an average loss in weight of 2.43% was recorded. The cubes appeared to be losing fine sand particles when rubbed with the hand. A combination of segregation and a lack of good compaction during casting is believed to have contributed to some of the freeze-thaw loss. Also, the many edges on a cube may have increased the weight loss in these specimens.

The next freeze-thaw resistance study was performed on six 3 in. x 6 in. (76mm x 152 mm) cylinders. Two of these cylinders were made of 4,000 psi (27.6 MPa) portland cement concrete while the remaining four were made of polymer concrete. The resin content of two of the polymer concrete cylinders was 8.5% and two contained 10% (by weight of the aggregate); these mixes correspond to Tests RM 63 and RM 62 respectively. After casting, the polymer concrete samples were allowed a 24-hour cure before testing began. The portland cement concrete specimens were allowed a 28-day cure. As in the first test, the specimens were frozen in air at  $-10^{\circ}\text{F}$  ( $-23.3^{\circ}\text{C}$ ) and thawed in water at  $68^{\circ}\text{F}$  ( $20^{\circ}\text{C}$ ) with two cycles occurring each day. Figure 14 shows one cylinder of each set after 100 cycles.

Results after 150 cycles show the polymer concrete made with 10% resin content had an average weight loss of 0.90% while the 8.5% mix recorded an average weight loss of 1.11%. These values appear to be satisfactory when compared to the average weight loss of 43.3% exhibited by the portland cement concrete samples. Further test data are found in Table 10.

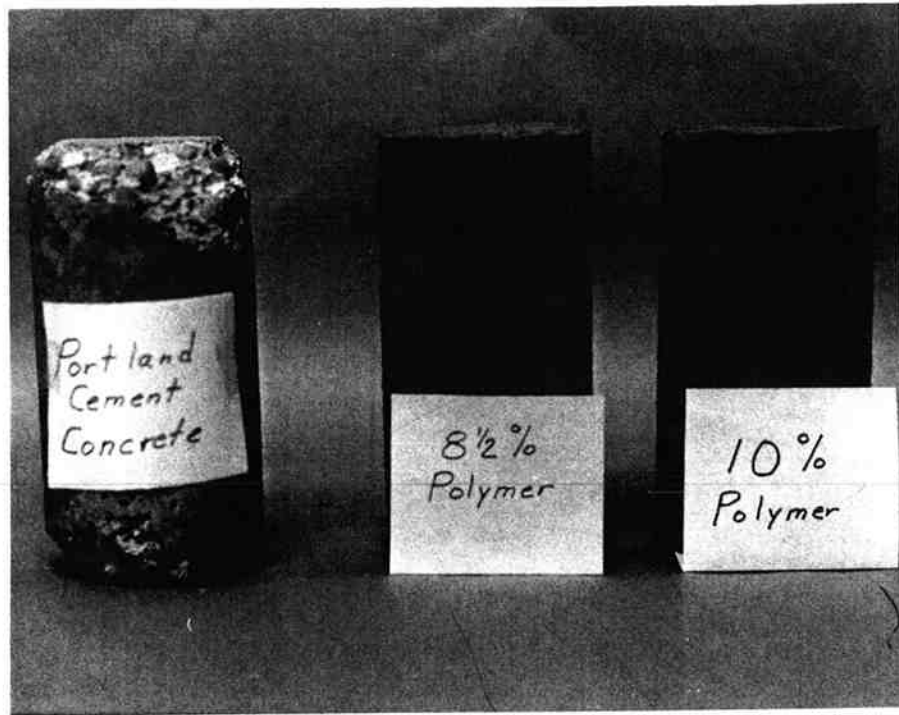


Figure 14. Freeze-thaw resistance test cylinders after 100 cycles.

Table 10

## FREEZE-THAW TEST RESULTS

| Composition                | TEST NUMBER                    |         | Reference<br>Concrete          |
|----------------------------|--------------------------------|---------|--------------------------------|
|                            | RM 62                          | RM 63   |                                |
| Resin <sup>1</sup>         | A                              | A       | 4,000 psi                      |
| Resin Content <sup>2</sup> | 10                             | 8.5     | Portland<br>Cement<br>Concrete |
| MEKP <sup>3</sup>          | 2.0                            | 2.0     | 28 day cure                    |
| Co Oc <sup>3</sup>         | 0.5                            | 0.5     |                                |
| HQ <sup>4</sup>            | 2000                           | 200     |                                |
| Aggregate                  | Wall #1                        | Wall #1 |                                |
| Cycles                     | Average Weight Loss in Percent |         |                                |
| 25                         | .40                            | .58     | .92                            |
| 50                         | .51                            | .75     | .95                            |
| 100                        | .76                            | .97     | 5.20                           |
| 150                        | .90                            | 1.11    | 43.30                          |

<sup>1</sup> See Appendix A for resin blends.

<sup>2</sup> Percent by weight of aggregate.

<sup>3</sup> Percent by weight of resin.

<sup>4</sup> Parts per million by weight of aggregate.

1000 psi = 6.89 MPa

## Permeability Test

The electrical resistance procedure was used to test the permeability of polymer concrete overlays. In this test, the electrical resistance of one square foot of overlay is measured with respect to reinforcing steel embedded in the portland cement concrete substrate. This method has found wide acceptance in measuring the quality of bridge deck waterproofing membranes. Resistance readings greater than 500,000 ohms signify an acceptable membrane (11).

To determine the permeability of polymer concrete overlays in the laboratory, portland cement concrete test slabs were cast measuring 1.5 ft (0.45 m) square and 3.5 in. (89 mm) thick. The slabs contained two No. 4 bars with 1.5 in. (38.1 mm) of cover. A 1.5-in. (38.1 mm) polymer concrete overlay was then placed on the slab after the application of a 15-mil (0.38 mm) resin tack coat. The overlay was consolidated and screeded with a 2 by 4 ft board. The first polymer concrete overlay contained 8.5% resin and natural aggregate. The overlay was allowed a 48-hour cure before testing began. Within minutes after applying water to the surface, the resistance dropped from infinity to 40,000 ohms, thus showing a failing membrane. A second slab was also overlaid with a 1.5-in. (38.1 mm) polymer concrete overlay, but this time a 50-mil (1.3 mm) tack coat was applied. Once again the overlay was consolidated with a 2 by 4 ft screed. As before, the resistivity dropped from infinity to 40,000 ohms upon wetting, indicating moisture was penetrating the overlay system.

Next, a two-15-mil (0.38 mm) tack coat system was applied followed with a 1.5-in. (38.1 mm) polymer concrete overlay. The first tack coat was applied and allowed to cure before the second tack coat and overlay were placed. The same method of consolidation was used as described. A 48-hour cure period was permitted before the permeability testing resumed. Readings after a 3-hour soaking time remained above 10,000,000 ohms, indicating an excellent membrane had been obtained. Moisture appeared to penetrate the overlay, but was prevented from reaching the concrete slab because of the two-tack-coat system.

In an additional laboratory test, a 1.5-in. (38.1 mm) overlay containing 10% resin was placed with a single 15-mil (0.38 mm) tack coat on a slab. Greater emphasis was placed on consolidation to reduce the void content within the overlay as a concrete vibrator was inserted into the polymer concrete before it was screeded. As before, a 48-hour cure time was allowed before the permeability test began. The overlay was then soaked continuously for 2 hours with resistance readings of over 10,000,000 ohms being recorded. This test demonstrated an impermeable polymer concrete system is possible with good consolidation.

A polymer concrete overlay that was placed on the Santiam River Bridge was tested for permeability one day after installation. Twenty-two readings were made at about 5 ft (1.5 m) intervals along the deck. Twelve readings were above 500,000 ohms, while only two were below 100,000 ohms. Minor shrinkage cracking and a lack of full compaction were blamed for the less than satisfactory results. Details of this overlay are presented in the next section of this report.