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PARTIAL POLYMER-IMPREGNATION
OF HIGHWAY BRIDGE DECKS

by

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ABSTRACT

Polymer-impregnated concrete is being considered as a means of increasing the durability of bridge decks. For application to existing bridges whereby the bridge deck is partially impregnated with polymer, the process includes drying the bridge deck to remove the free moisture in the pores; soaking a low viscosity monomer solution into the concrete; and applying heat to polymerize the monomer. Drying, soaking and curing requirements are discussed. A limited area of a bridge deck has been successfully polymerized to a depth of approximately one inch (2.5 cm).

Evaluation studies have been conducted to determine the freeze-thaw resistance, skid and wear resistance and protection against corrosion of the reinforcement. It has been found that freeze-thaw resistance is significantly increased. Skid resistance has been found to improve significantly for the partially-impregnated slabs when the tests were performed with the surfaces dry. The skid resistance was slightly higher when the surfaces were covered with abrasive grit and kept wet. Wear measurements generally indicated little difference between treated and untreated specimens. Corrosion resistance for slabs with a low quality polymer impregnation have been found to be about 25 times greater than for unimpregnated slabs.

Introduction

The development of polymer-impregnated concrete (PIC) has given rise to many potential applications in the construction industry. The significant increases in strength, stiffness, water permeability, resistance to corrosion, and abrasion resistance (1, 2, 3) suggest many possible applications in highway construction. While the possibilities of using the material structurally, to take advantage of the strength and stiffness, are very appealing, the most logical uses at first appeared to be in the area of materials improvement for durability. As PIC is proven as a practical, durable material, the structural uses will naturally evolve.

The maintenance of deteriorating bridge decks is a major problem throughout the United States that results in the annual expenditure of many millions of dollars. The primary cause of bridge deck deterioration appears to be the presence of moisture in the concrete which causes corrosion of the reinforcing and freeze-thaw deterioration. Researchers at the Center for Highway Research at the University of Texas have pursued the idea of developing methods to partially impregnate bridge decks in situ. It was theorized that if such a polymer surface treatment were practical, the increased resistance to water penetration and the strength of the impregnated concrete should result in significant increases in durability.

There were many questions to be answered, but generally they fell into two basic categories: (1) How can the concrete be impregnated with polymer, and (2) What are the advantages of the partially-impregnated concrete for use on bridge decks? Research supported by the Texas Highway Department and the Federal Highway Administration was initiated in 1970 in an attempt to develop and to evaluate polymer surface treatments for bridge decks. (4, 5).

Field Impregnation of Bridge Decks

Prior to this research, practically all of the research had been directed toward full-impregnation in which the concrete is fully dried, evacuated, and soaked in a monomer solution until the specimen is fully saturated. The liquid monomer is then converted to a polymer by addition of heat or by irradiation. Under laboratory or plant conditions the full-impregnation process is relatively simple and reproducible.

Surface impregnation in the field is a more complicated process even though only partial impregnation is required. There are three basic interrelated steps in the process: (1) drying the concrete; (2) impregnating the surface zone of concrete with the liquid monomer solution; and (3) polymerizing the monomer. The depth of monomer impregnation is affected by the depth to which the concrete is dried. The type of monomer system affects the requirements for polymerization.

Drying. Normal weight concrete has 11 to 13 percent voids which are partially filled with moisture under usual environmental conditions. This moisture must be removed to the depth to which monomer penetration is desired.

The amount of moisture removed is primarily a function of surface temperature and drying time, although other variables such as air humidity and velocity can also be important.

Initially in this research it was planned to dry concrete at less than 200° F (95° C) to avoid any danger of cracking or of excessive thermal expansion. A number of 40-in. x 43-in. (1.0 m x 1.1 m) slabs were cast and treated under field conditions. Drying was accomplished by air drying in the sun for several months and using a curing blanket for a minimum of three days which developed maximum concrete surface temperatures of 140° to 150° F (60° to 65° C). Polymer-impregnated concrete of depths from 1/4 in. to 3/4 in. (0.6 cm to 1.9 cm) were obtained although there was considerable variation in depth and some of the polymer was faint. However, the durability properties of this material was very good as will be discussed subsequently.

Based on later research at the University of Texas, Lehigh University and the Bureau of Reclamation, there seems to be little question that higher temperatures are both preferable and safe. The temperature at the depth to which penetration is desired should be at least 212° F (100° C).

Fig. 1 indicates the temperature gradients in a six-in. slab for a surface temperature that increases to 320° F (160° C). Thermocouples were inserted into holes drilled from the bottom surface and were located at various depths from the heated surface. Temperatures are shown for times varying from 30 to 180 minutes after the heat source was applied. Although the temperature varied with depth, the change in temperature with time was approximately constant. After one hour, only the upper one-half inch of concrete is heated to 212° F (100° C) or higher. The concrete is heated to 212° F at a depth of 1.7 in. (4.3 cm) after two hours and nearly 2.5 in. (6.3 cm) after three hours. These temperature gradients and rates are, of course, dependent upon the rate of temperature build-up on the surface. It should also be noted that the temperature gradients can be predicted analytically with good accuracy.

The drying time required to achieve a particular depth of polymer impregnation has been found to be considerably longer than the time to achieve a temperature of 212° F (100° C) at the same depth. Fig. 2 indicates the depth of polymer impregnation achieved for a surface temperature-time relationship similar to the one shown in Fig. 1. From Fig. 1 it was observed that a temperature of 212° F was reached nearly 2.5 in. (6.3 cm) from the surface after three hours. However, the depth of polymer impregnation after four hours of drying was only about 0.6 in. (1.5 cm). Slightly over eight hours of drying produced a polymer depth of 1.25 in. (3.1 cm).

At this time, drying is the most difficult step in the process from a practical standpoint. The maximum or optimum temperature for drying is still not well defined. It is reported that other researchers have used temperatures of 500° to 700° F (260° to 370° C) and even higher without serious effects. It is the opinion of the authors that the maximum temperatures should not exceed 300° F until more experience is gained in large-scale field treatments.

Monomer Systems and Application. The monomer system that was used initially consisted of methyl methacrylate, 10% (wt) trimethylpropane trimethacrylate (TMPTMA) and 1% (wt) benzoyl peroxide (BP). More recently, other catalysts have been used because of the improved mixing characteristics and the longer storage life when in solution. This monomer system has a low viscosity which is essential to achieving good penetration without overpressure. In addition, polymerization occurs relatively fast at temperatures of 150° F (66° C) or higher. Other monomers that have been used are isobutyl methacrylate (IBMA) and isodecyl methacrylate (IDMA).

A 1/4-in. (0.6 cm) sand layer is used on the surface to hold the monomer in place during soaking and to prevent monomer evaporation from the concrete surface. The monomer solution is sprinkled or sprayed onto the sand in the usual amount of 3000 to 4000 ml/m^2 or more. The primary requirement is to initially moisten the sand thoroughly and to keep it moist during the soaking period. A plastic sheet or aluminum foil is applied during the soak period to retard evaporation. It is also necessary to keep the temperature of the slab to less than 100° F (38° C) to prevent polymerization from occurring.

Fig. 3 indicates the polymer impregnation achieved for soak times ranging from five to eight hours in six-in. slabs that had been thoroughly dried. A soaking time of four hours produced an impregnated depth of one inch. Longer soaking times of seven or eight hours resulted in about 1.5 in. of polymer depth.

Polymerization. The two most common methods for polymerizing monomer in concrete are radiation and thermal-catalytic processes. Due both to the weight of shielding and to potential safety hazards for a mobile irradiator, this research has relied on thermal-catalytic methods. Several sources of heat have been investigated: solar energy, microwave ovens, reactive monomer systems, heating blankets, steam, and ponded hot water (Ref. 7). At the present time steam and ponded hot water appear to be the most practical means of achieving polymerization.

Hot water can be ponded by erecting a simple framework on the slab and lining it with a waterproof membrane such as polyethylene film. The sand cover is usually left in place since the time required for removal would permit evaporation of monomer from the slab. Water heated to about 195° F (90° C) is ponded to a depth of approximately 3 in. (7.5 cm). This produces a maximum temperature on the slab surface of about 140° F (60° C). The slab surface was initially at room temperature. The water was removed after two hours after which the slab temperature dropped rapidly.

Fig. 4 indicates the polymer depth for different application times of the water. Both lightweight aggregate fines and regular sand were investigated., For two hours of hot water application over regular sand, a 1.25 in. (3.2 cm) polymer depth was achieved. The use of lightweight aggregate fines resulted in only about 60 percent as much impregnated depth, apparently due to the greater insulating effect.

The advantages of hot water are: (1) uniform heat; (2) creation of an airtight barrier over the concrete which eliminates monomer evaporation; and (3) polymerization can proceed without the additional application of heat or energy after the hot water is initially applied which minimizes the problems encountered in mechanical or electrical failures during polymerization. The curing time could be accelerated by use of submersible heaters or a hot water circulating system. Insulation for the sides and top would be required for large scale treatments to reduce the energy requirements. An enclosed water bag may have some merit.

The disadvantages of ponded hot water are: (1) difficult to use on superelevated bridge decks; (2) difficult to move from one location to another; and (3) relatively large amounts of water required.

Steam has worked very well to generate the heat required for polymerization. In the first attempts to use steam, steam was sprayed directly onto the surface of the slabs which had been soaked with monomer. The slabs were polymerized to a depth of 3/4 in. (2 cm.) but the monomer had evaporated from the top 3/16 in. (0.5 cm) due to the high surface temperature. A number of evaporation barriers were tried with little success in an attempt to reduce the evaporation.

Steam injected into an enclosure over the slab serves to heat the slab more slowly and to a lower maximum temperature. However, slab temperatures can be increased to 95° C in a short time. Polymer depths of one to two inches (2.5 to 5 cm) are regularly obtained in slabs that have been adequately dried and saturated with monomer. Fig. 5 indicates the polymer depth of slabs heated to a surface temperature of 170° F (77° C) and cured for 30, 60 and 90 minutes. The 30 minute curing time was about as effective as the longer times.

The advantages of steam are: (1) higher temperatures, which reduce the curing time; (2) can be used on superelevated decks; (3) requires less water; and (4) simpler to move without the ponded water. The disadvantages are: (1) the need for steam generating equipment, and (2) the need for a continuous supply of steam for the curing period which may require a backup capability in case of a malfunction. It will be necessary to have an easily portable, well-insulated enclosure to minimize labor and energy requirements.

Small Scale Field Treatment

In addition to laboratory treatments and simulated field treatments, a limited small area on a new bridge deck in Austin was successfully treated. The bridge had already been sprayed with linseed oil but had not been opened to traffic. An area 12 ft. by 12 ft. was selected to be treated and one-half of the area was lightly sandblasted to remove the linseed oil. One-half of each sandblasted strip and each now sandblasted was dried for 72 hours with a kerosene construction heater with a blower and undried. A maximum surface temperature of 270° F was measured. The monomer system (MMA, 1 percent benzoyl peroxide and 10 percent TMPTMA) was applied to a 1/4 in. sand cover and soaked overnight for approximately 13 hours. Just prior to the monomer application a cloudburst passed over the bridge and rainwater broke the dike that had been erected around the test area, wetting most of the sand on the undried area. Only the non-wetted area was treated with monomer. The monomer was polymerized with steam heat. Cores taken from the sandblasted area indicated a polymer depth of about one inch. The non-sandblasted, dried area was not successfully impregnated which indicates the need to remove the linseed oil film. For this test, a light steel frame 24 in. high was used to support a tarpaulin enclosure for drying. Fig. 6 shows the uncovered frame while sand is being spread over the slab. The same enclosure was used to contain the steam heat during curing.

A four-inch core taken from the sandblasted, dried area has undergone 155 cycles of freeze-thaw. A steel ring was attached to the treated surface and a 1/4-in. (0.6 cm) depth of water is maintained on the specimen. No deterioration has been observed except minor surface scaling typical for all treated slabs during freeze-thaw tests.

One other field treatment has been attempted on an older bridge deck. The drying and monomer application steps apparently were quite successful but polymerization was not achieved when continued malfunctions of the steam generator occurred and prevented the necessary slab temperatures from being attained.

Evaluation of Surface-Treated Slabs

The performance of surface-impregnated concretes has been evaluated for freeze-thaw durability, resistance to water penetration, surface wear and abrasion, and skid resistance (4, 5). Long-term tests have been underway to evaluate the protection afforded reinforcement in polymer-impregnated slabs subjected to frequent applications of salt water spray. A summary of some of these evaluations is presented.

Freeze-Thaw Behavior. A large number of specimen have been subjected to freeze-thaw tests to determine their durability. These specimens were tested with a 0.6 cm depth of water ponded within a 20-cm-diameter steel ring bonded to the surface.

One series of specimens, treated under simulated field conditions, provided a good indication of the durability of surface-impregnated slabs that would be representative of less-than-ideal quality. These specimens were 30 cm x 30 cm sawn from 1.0 m x 1.1 m x 14 cm thick slabs that had been cast, dried and cured outdoors. The slabs were air dried for several months and then further dried for a minimum of three days with a heating blanket. The usual monomer system was applied to the slabs which were covered with lightweight fine aggregate. Some were cured with heating blankets and others were cured with ponded hot water. The low temperatures used for drying, which were typical for the earlier treatment processes in the study, produced polymer depths of 0.6 to 2 cm in depth. The color of the polymer was relatively light indicating a low polymer loading which was due to the low drying and the high quality of the unimpregnated concrete which developed 6400 psi.

The treatments are summarized in Table 1. Specimens 8 and 9 were treated with a second reactive monomer system consisting of MMA, 4% (wt) layryol peroxide, and 4% (wt) n,n-dimethyl-p-toluidine (DMPT) which polymerized in a short time and bonded the aggregate cover to the slabs. It was theorized that the lightweight aggregate topping would provide a skid resistant topping that would also provide additional protection to the impregnated concrete. Fig. 7 indicates the appearance of one of the control specimens after 40 cycles contrasted with one of the treated specimens after 120 cycles which was the arbitrary limit of freeze-thaw cycles.

Horizontal strain measurements were made on the side of each of the freeze-thaw specimens by means of four stainless steel tabs bonded 8 in. (20 cm) apart 1.25 cm above the bottom surface and 1.25 cm below the top surface. Measurements were made with an 8-in. Berri gauge with the slabs in the frozen state. The strain measurements indicated that eight of the field-treated specimens developed a 45 micro in./in. greater contraction in the top than in the bottom, while the control specimens averaged zero strain differential. The other two treated specimens (specimens 8 and 9) exhibited 120 micro in./in. greater contraction in the top. The greater contraction in the top is apparently due to the 30 percent higher coefficient of thermal expansion for polymer-impregnated concrete as compared to unimpregnated concrete (Ref. 1). For specimens 8 and 9, the even greater differential was probably caused by the high concentration of polymer in the 0.6 cm layer of intentionally bonded lightweight fine aggregate.

The strains in the top of the slab for the specimens impregnated with MMA are shown in Fig. 8 as a function of the number of freeze-thaw cycles. It can be observed that the strain measurements provide a good indication of the impending failure of a slab. The control specimens had an average strain of about 1500 micro in./in. after only 20 cycles although failure occurred at an average of 35 cycles. Although specimens 8 and 9 continued for 120 cycles, the volume instability as evidenced by the increasing strains and by cracking observed visually indicated that failure was imminent. Specimen 10 developed a strain of about 1000 micro in./in. at 55 cycles but then stabilized for the remainder of the testing, with moderate cracking and moderate water loss being noted during that period. It is interesting to note that a relatively large amount of monomer and a long soak time was used in the treatment of this specimen which indicates that durability is not a simple function of monomer quantity or soak time used. The other treated specimens indicated very good volume stability.

The strain measurements have provided a more reliable measure of strain stability and freeze-thaw durability than visual observation alone, especially since surface scaling is not the primary mode of deterioration for treated specimens. Visual cracks were usually observed whenever the top strain exceeded about 1000 micro in./in. It may be reasonable to define the durability range of the concrete as the number of cycles below which the top strain does not exceed a certain value, say 750 micro in./in.

Other freeze-thaw tests on specimens in which very good polymer impregnation was achieved also indicate good durability. Reinforced specimens, with reinforcement in the bottom and in the top and bottom, are still in progress after 150 cycles. But the tests on the marginal-quality field-treated specimens are significant from the standpoint that very good improvements were obtained over the unimpregnated controls.

Corrosion Protection. Reinforced companion slabs were treated at the same time and with the same treatments as shown in Table 1. These slabs, also 1.0 m x 1.1 m, were sprayed with salt water twice daily, five days per week, for 27 months to determine the protection against corrosion provided by the surface polymer impregnation. The No. 8 bars had a nominal one-inch cover. After the tests were terminated, the bars were removed and measured to determine the corroded area.

The treated slabs had the same quality of polymer impregnation as given in Table 1. The reinforcing near the edges of the slab which were not sealed against water intrusion indicated some corrosion. But considering only interior bars and neglecting the outer three inches of each interior bar, the bars from the treated slabs had an average of only 1.1 percent corroded surface area as compared to 27.0 percent for the corresponding bars from the unimpregnated controls. The fact that the treated slabs do not represent the quality of polymer impregnation that can now be achieved makes the results even more significant. Studies are in progress to determine the chloride content in the concrete.

Skid Resistance. The skid resistance of polymer-impregnated concrete was of considerable interest since it was not initially known if the polymer impregnation would result in a surface with a lower frictional resistance. A series of two-inch thick trapezoidal-shaped slabs, including controls, were placed in the Texas Highway Department wear track facility. The facility has a 10-ft. (3 m) diameter test track over which a non-grooved tire mounted at each end of a weighted beam was driven at 10 mph (16 kmh). Periodically the tire loading was stopped while surface friction measurements were made with the British Portable Testor (BPT) in accordance with ASTM E303-69.

Typical skid numbers as a function of wear track loading revolutions are presented in Fig. 8. Skid resistance increases with the skid number. For the first 70,000 revolutions (140,000 wheel passes) the slabs were kept dry. An additional 140,000 revolutions were made under wet conditions with No. 46 silicone carbide grit as a wearing agent. Immediately after the grit was applied, the surface was abraded resulting in a higher short-term skid resistance for all slabs.

It can be observed that throughout the testing all of the treated slabs developed skid numbers as high or higher than the controls which indicates no loss in skid resistance due to polymer impregnation. In fact, before the grit was applied the skid numbers were significantly higher for the treated slabs. It can be seen that the treatment which developed the highest skid resistance was the one with the lightweight aggregate topping (LWAT) intentionally bonded to the surface as previously described for specimens 8 and 9 in the freeze-thaw tests.

During the wear track tests, depth-of-wear measurements were made across the wheel path on each test slab. These measurements provided a measure of the cross-section worn away during the tire loading. It was found that there was no appreciable difference in wear between the controls and treated slabs with the exception of the specimens with the lightweight aggregate topping. After the grit was applied, the wear in these slabs was more than twice as great as in the other specimens.

Conclusions

It has been found that partial polymer-impregnation of concrete can be accomplished by proper drying, impregnating with an appropriate low-viscosity monomer solution, and curing with external heat. A limited test treatment on a bridge deck has confirmed the validity of the process.

Extensive evaluations of partially-impregnated slabs has shown that:

(1) the freeze-thaw resistance is significantly increased;

(2) corrosion of reinforcing in PIC slabs is about 5 percent of that found in unimpregnated slabs;

(3) skid resistance is no less and in some cases higher than for control slabs; and

(4) wear is generally about the same for both control and impregnated concrete.

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The contents of this paper reflect the views of the authors, who are responsible for the facts and the accuracy of the data presented herein. The contents do not necessarily reflect the official views or policies of the Federal Highway Administration. This paper does not constitute a standard, specification, or regulation.

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Table Titles

Table I Summary of Freeze-Thaw Tests

TABLE 1. SUMMARY OF FREEZE-THAW TESTS

Slab No.	Monomer System	Quantity of Monomer, ml/m^2	Soak Time, hrs. & Temperature Range, °C	Cure Method	Average Polymer Depth, in[e]	Maximum Freeze-Thaw Cycles
1	Control	---	---	---	---	30
2	MMA[a]	4280	10 @ 23°-34°	HW[c]	0.25-0.75 faint, uniform	120
3	IBMA[a]	3600	10 @ 25°-34°	HW	0.75 faint, uniform	91
4	IBMA[a]	4500	24 @ 24°-32°	HW	0.5-1.5 faint, uniform	117
5	IDMA[a]	2700	10 @ 25°-34°	HW	0.25-0.5 very faint, uniform	120
6	Control	---	---	---	---	40
7	IDMA[a]	3600	24 @ 24°-32°	HW	0.25-0.5, dark to faint	117
8	MMA[a] and MMA[b]	6750 900	24 @ 24°-34° 0.25	HW	0.5-0.75, faint, uniform	120
9	MMA[a] and MMA[b]	4500 1350	18 @ 21°-27°	HB[d]	0.25-0.5 faint, non-uniform	120
10	MMA	6750	24 @ 24°-32°	HW	0.5-0.75 faint, uniform	120
11	MMA	9900	18 @ 21°-27°	HB	0.25-0.50 faint, uniform	120
12	MMA	9900	24 @ 20°-28°	HB	0.5 very faint, uniform	120

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[a] Monomer system included monomer, 1% BP, 10% TMPTMA

[b] Second monomer application included monomer, 4% lauroyl peroxide, 4% DMPT

[c] HW = hot water

[d] HB = heating blanket

[e] 1 in. = 2.54 cm.

Figure Titles

1. Temperature Gradients in 6-in. Concrete Slab Heated from Upper Surface
2. Effect of Drying on Polymer Depth
3. Effect of Soaking Time on Polymer Depth - 5, 6, 7, and 8 Hour Soaks
4. Polymer Depth as a Function of Curing Time with Hot Water
5. Effect of Steam Curing Time on Polymer Depth
6. Application of Sand Cover to Bridge Deck
7. Surface of Freeze-Thaw Specimens
    a. Control after 30 Cycles
    b. PIC after 120 Cycles
8. Top Strains of Freeze-Thaw Specimens in Frozen State for MMA-Treated Specimens
9. Skid Numbers from Wear Track Tests

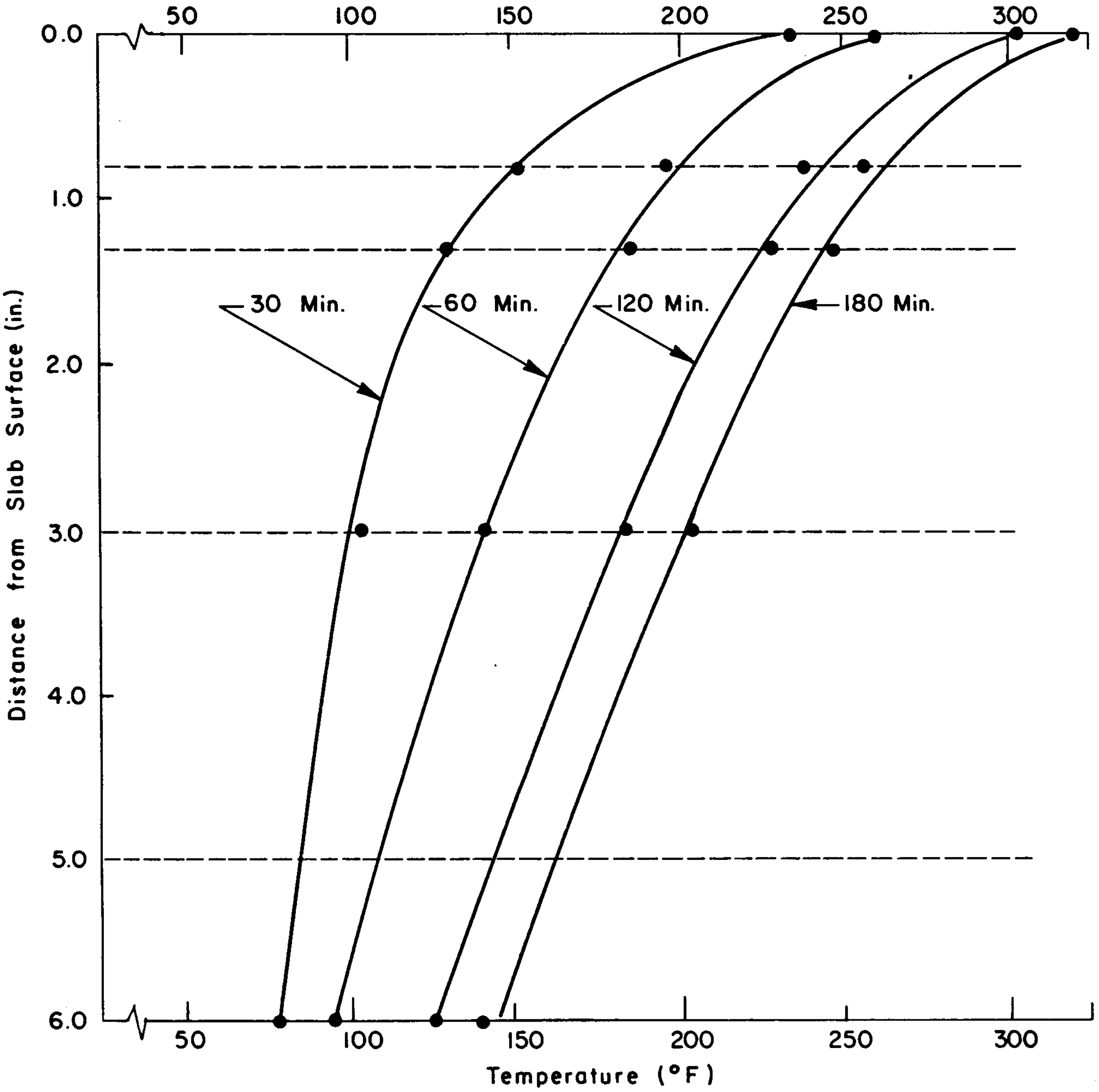

Figure I. Temperature Gradients in 6 in. Concrete Slab Heated from Upper Surface.

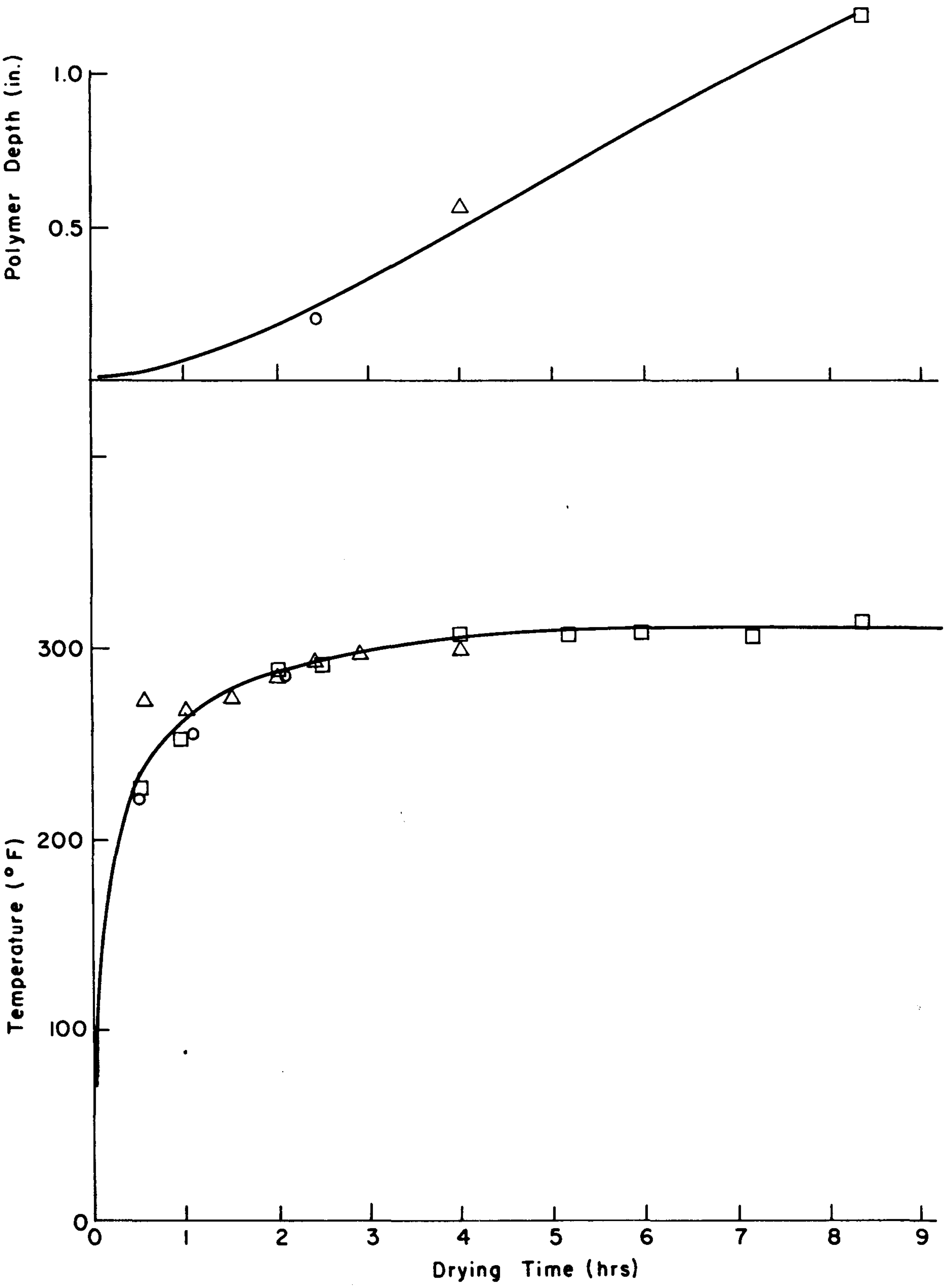

Figure 2. Effect of Drying on Polymer Depth

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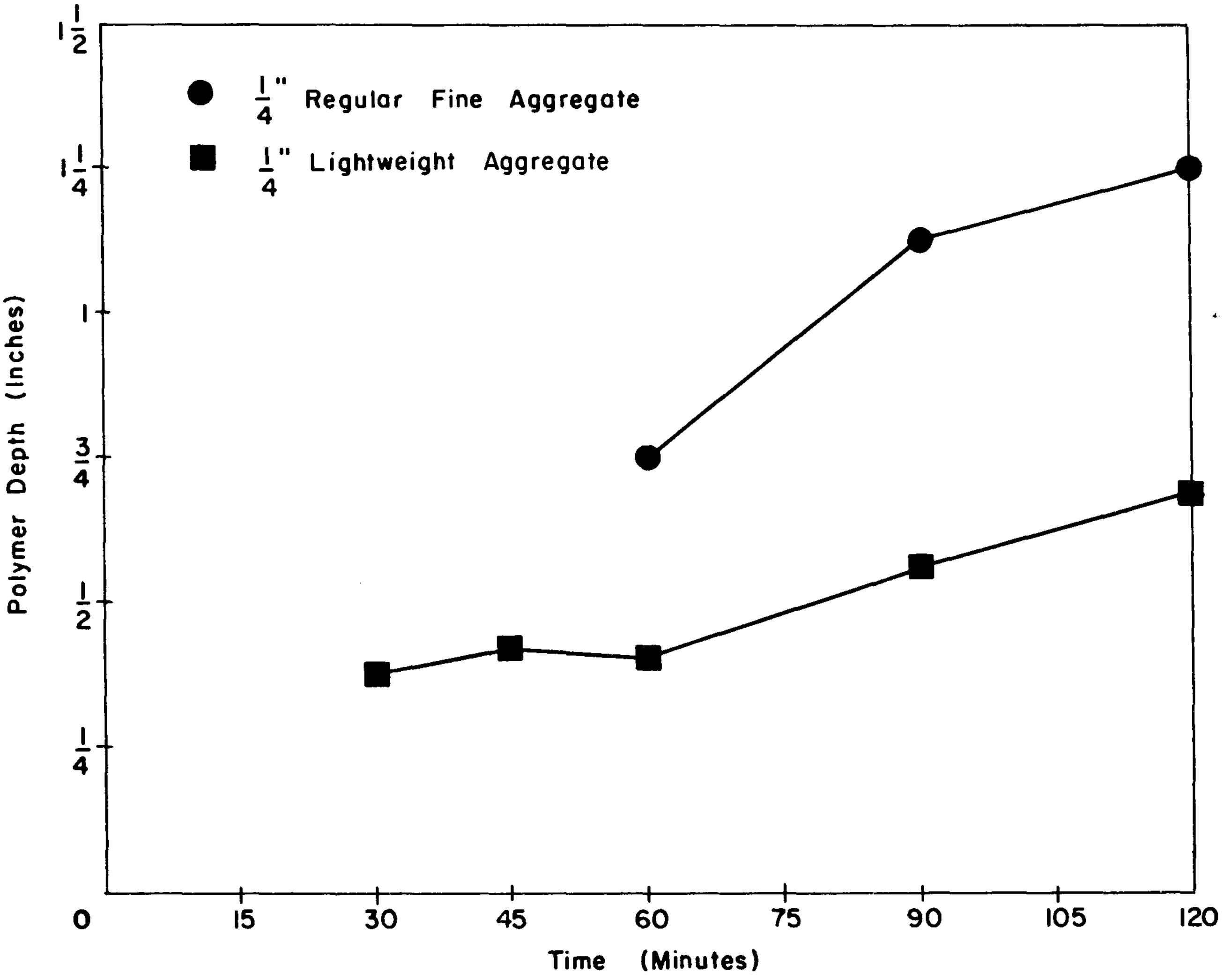
Figure 3

Figure 4



1 1/2
1 1/4
1
3/4
1/2
1/4
Polymer Depth (Inches)
● 1/4" Regular Fine Aggregate
■ 1/4" Lightweight Aggregate
0
15
30
45
60
75
90
105
120
Time (Minutes)

Figure 5

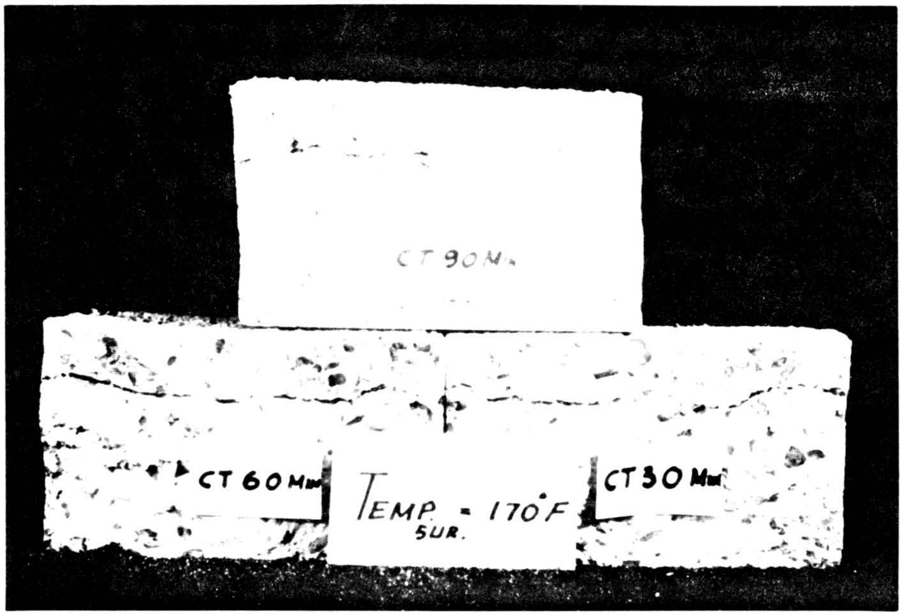


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Figure 6

Figure 7a

Figure 7b

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Figure 8

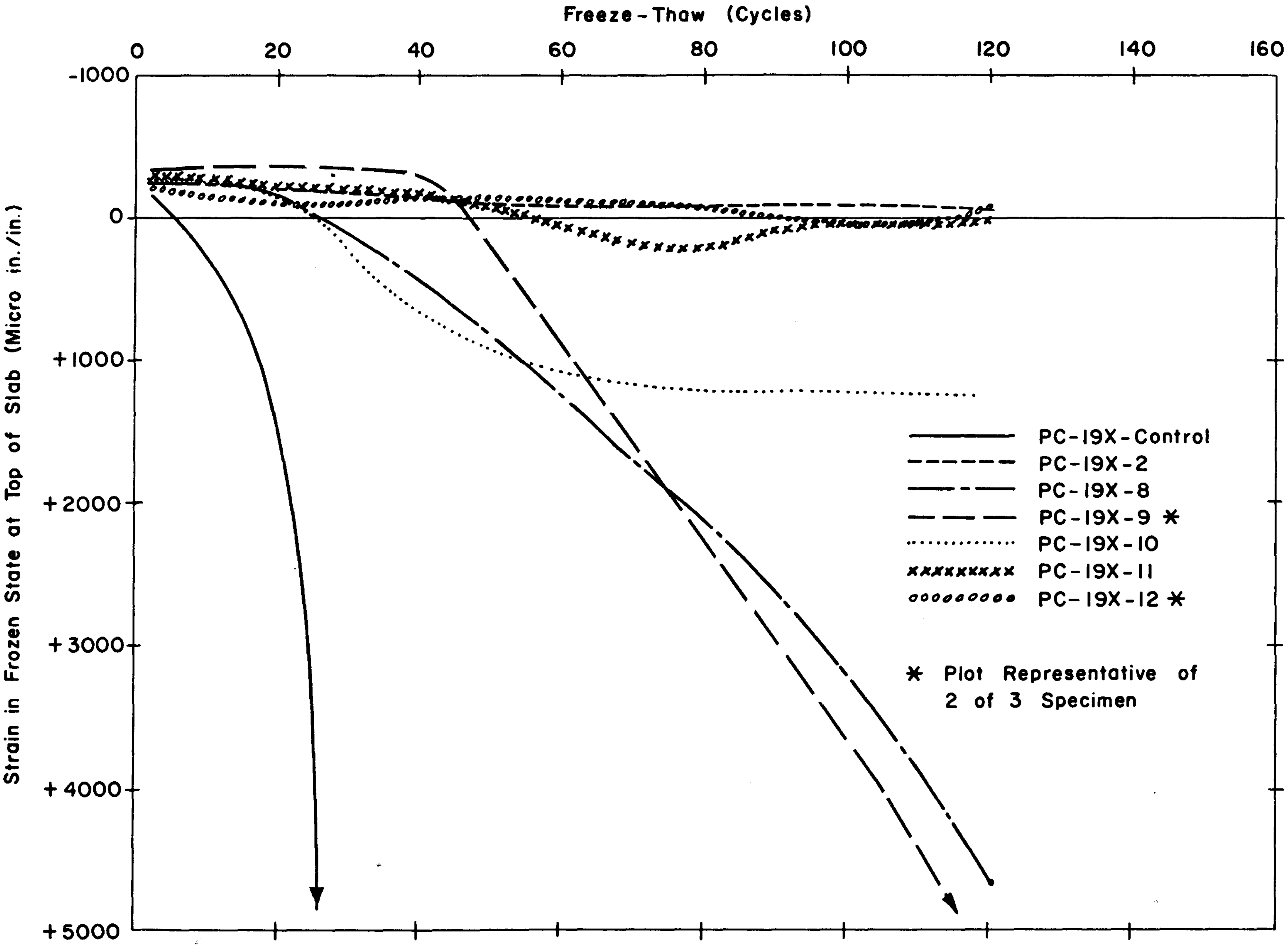

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Figure 9