Polymer Impregnated Concrete and Polymer Concrete Overlays

by

Dauda A. Ismalia
T. S. Young
Dr. Carl E. Locke

School of CHEMICAL ENGINEERING and MATERIALS SCIENCE

The University of Oklahoma
202 West Boyd
Room 23
Norman, Oklahoma 73019

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16. Abstract

The feasibility of impregnating bridge decks with methylmethacrylate for protection against freeze-thaw deteriorzation and corrosion of the reinforcing steel is reported.

Parameters such as monomer system, monomer loading, drying temperature and time, curing temperature and time, soak time and equipment were investigated and discussed.

A nondestructive method for the determination of the the polymer depth in a polymer impregnated concrete was investigated and reported.

The three methods that are presently used to place polymer concrete overlay on bridge decks were tested and compared with each other.

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Polymer impregnated concrete, feasibility, freeze-thaw deterioration, corrosion of reinforcing steel, monomers, polymer, bridge decks.

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ABSTRACT

Polymer impregnated concrete (PIC) is a proven technique for increasing the service of concrete bridge decks. However, the feasibility of this technique has been a much debated question. Parameters such a monomer system, monomer loading, drying temperature and time, curing temperature and time, soak time and equipment determine the time and cost involved in the application of the technique to bridge decks. The work reported here looks into these parameters as they affect the feasibility of the process.

The most effective and economical monomer system for the process is concluded to be 88.5 percent by weight of methyl-methacrylate (MMA), 1.5 percent by weight of 2, 2'-Azobia (isobutyronitrile) (AIBN), and 10 percent by weight trimethylol-propane trimethacrylate (TMPTMA).

A heat flux of at least 1140 BTU/hr. ft^2 is enough to dry concrete slabs at a drying surface temperature of 260°F and a drying time of six hours and at a heater height of twenty-three inches to twenty-seven inches.

A six-tenth pound per square foot monomer loading and a four hour soak time are sufficient for the polymer depth usually demanded for bridge deck treatments.

A curing temperature range of 150°F to 185°F maintained for an hour is enough to cure the monomer soaked into the deck. Adequate planning and proper timing serve to cut down the time and cost involved with the process.

Polymer concrete overlay is another proven technique for bridge decks protection. There are three different procedures that are used to place polymer concrete overlay on bridge decks. These procedures are looked at briefly in this report and compared to each other according to their feasibilities.

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INTRODUCTION

Many concrete bridge decks which were expected to last for 40 years are requiring major repairs after 5 to 10 years and must be replaced after 15 years (1). The freezing and thawing resulting from the ingression of water into the concrete bridge decks causes cracking or spalling. Roadway surfaces are heavily salted during winter to help clear the roads of ice. With repeated applications (salting), the chlorides penetrate the concrete surface and eventually reach the reinforcing steel. This causes the steel to corrode. Because the rusted steel occupies much more space, pressure is exerted on the concrete and eventually potholes develop as shown in Figure 1.1. This problem is progressive and eventually leads to the complete failure of the structure. There are an estimated 560,000 bridges in the United States. The number of these bridges falling into the category of "Deficient Bridges" and the replacement costs are rising at rates that should cause some concern. Table 1.1 (2) compares the 1968 estimates of deficient bridges to the most current estimates through December 1977. The large increase during this time period might be attributed partly to a more complete inventory of needed bridge projects, but the large increase in the use of deicing chemicals on the road surfaces and the fact that the bridge decks were not protected, played a major role. Because of the high maintenance/replacement cost coupled with the discomfort to the driving public and the reduction of driving safety, highway officials have become increasingly concerned about the growing number of prematurely deteriorated concrete bridge decks. As soon as it was known that the corrosion of the reinforcing steel was the primary cause of bridge deck deterioration, research effort was directed towards developing techniques to stop the intrusion of chlorides into bridge decks and to protect the reinforcing steel from chemical attack. Numerous techniques have been suggested as possibilities. These include:

1. Membrane systems with asphalt overlays
2. Epoxy-coated reinforcing steel bars
3. Low water-cement ratio concrete
4. Internally sealed concrete using wax beads
5. Polymer concrete overlay

Figure 1.1 A Damaged Bridge Deck with Potholes

6. Polymer concrete impregnation
7. Cathodic protection
8. Electrochemical removal of chlorides.

TABLE 1.1 (2)

NUMBER OF DEFICIENT BRIDGES IN USA

Year	Number of Deficient Bridges	Replacement Cost
1968	88,900	$ 14.8 billion
1977	105,500	$ 25.1 billion

A program to protect existing structurally sound bridge decks using any of the above techniques instead of completely replacing them at a later date could save billions of dollars. The potential benefit/cost ratio of repairing and protecting an existing bridge deck versus completely replacing the deck at a later date is about 2.75 to 1 (1). Because of the large potential saving of protecting rather than replacing at a later date FHWA officials and state and local highway officials began looking more intently into these protective systems and pushed for the commercial development of them. Many of the protective systems have been installed on bridge decks and identified to extend their service life. However, very limited performance data on the effectiveness of these protective systems is available. Therefore, it is extremely difficult to determine to what extent presently installed protective systems are effective. Without such information, there is no sound method of determining which technique should be used for a given bridge. The only criteria presently used in selecting a method is feasibility, cost and safety. This is what the work done in this report is about. The primary purpose of the work was to evaluate and develop the Polymer Impregnated Concrete (PIC) technology to a level that would enable the Oklahoma State Highway Department to routinely utilize it at a relatively low cost if it is considered feasible.

LITERATURE REVIEW

A large number of reports on Polymer-Impregnated Concrete (PIC) as a technique for protecting bridge decks has been published. The main objective of this phase of the project was to look at what had been done, identify the parameters which might affect the application of PIC and its economics on bridge decks and then decide on experiments directed towards implementing the technology.

Polymer-Impregnated Concrete

Polymer impregnated concrete involves the polymerization of liquid monomer which has partially or fully saturated the pores of previously cured (hardened) portland cement concrete. In full impregnation, the monomer is forced through the entire bulk of the concrete. In partial impregnation the monomer soaks into a surface layer of the concrete item. In both, the polymerization is then conducted to fill the cracks and voids in the concrete. This review is directed towards the applications of PIC for partial impregnation of concrete bridge decks. The intent is to seal the deck with polymer to a depth of 1" (2.54 cm) or more which would be larger than the 3/4" (1.9 cm) aggregate normally used and sufficient to prevent penetration of the top cover above the rebar. The partial impregnation of concrete bridge decks involves the following steps:

1. The concrete surface is freed of contaminants such as oil, asphalt, and other compounds that would prevent or reduce monomer penetration.
2. The concrete is dried to a depth sufficient to permit the desired monomer penetration.
3. Impregnation of the concrete with monomer to the desired depth.
4. Polymerization of the monomer in the concrete to form the protective barrier.

From the above description of the PIC application to bridge decks it is obvious that the parameters determining the economics of the process are: monomer system, drying time, drying temperature, soaking time, curing time and temperature. All these parameters affect the economics of PIC technology. They must be optimized for any savings in the cost of PIC to be realized.

Effectiveness of PIC

As mentioned in the introduction, long-term performance data of all the protective systems that have been installed on bridge decks are not yet available. To validate the effectiveness of PIC, it will be necessary to collect and analyze performance data of a treated bridge deck over the expected useful life. This will take about 40 years (design life of bridge decks). However, there are certain improvements on the physical and mechanical properties of treated bridge decks that are known to prolong the service life of polymer-impregnated bridge decks. PIC effectively resists penetration by water and salt solutions. This should eliminate the corrosion of the reinforcing steel and provide protection against freeze-thaw damage to the bridge deck. Repeated cycles of freezing and thawing of concrete produces scaling, splitting and cracking of the concrete.

It has been demonstrated that with adequate polymer depth, the freeze-thaw resistance of treated slabs was up 500% for slabs without reinforcing steel (4). With reinforcing steel in the concrete, there was no damage to the PIC treated slabs under freeze-thaw exposure for the duration of the test (200 cycles).

It also has been demonstrated that the corrosion of the bars in untreated slabs was about 25 times greater than for the bars in PIC-treated slabs (4). In another work it was found that the corrosion of the reinforcing steel was completely arrested, freeze-thaw damage was eliminated and there was a dramatic increase in resistance to chemical attack (5). It has also been confirmed that there are improvements on most of the structural properties of treated concrete bridge decks. In one work it was found that PIC gave a threefold increase in compressive strength, twofold increase in tensile strength and an increase in thermal expansion from 4.34 micro cm./cm to 4.93 micro cm./cm (4,5). The abrasion and skid resistance of treated concrete are not reduced. They are improved in some cases (3).

Previous Studies

Generally, all the previous studies done on PIC could be divided into four major catagories:

1. Drying time and temperature
2. Soaking time and polymer depth
3. Curing methods, temperature and time
4. Durability of polymer impregnated concrete.

Drying Time and Temperature

Adequate drying of concrete prior to monomer application is essential to remove moisture from that section of the concrete to be impregnated. The water otherwise would block the penetration of the monomer. The drying has been accomplished by exposing the concrete to external heat sources such as solar energy, ovens, heating blankets,hot air heaters, gas burners and infra red heaters. Most of these were only feasible in laboratory experiments. It has been found that exposing the surface of the concrete to extremely high temperatures can cause damage to the concrete. Slight damage to the concrete has occurred at a drying temperature of 350°F (177°C) (6). To remove the moisture from the concrete, it is necessary to raise the concrete temperature to 212°F (100°C) or higher. The length of drying time is inversly related to the drying temperature. Increasing the drying temperature reduces the drying time. It was found that to dry concrete cylinders to a constant weight at 302, 257, and 221°F (150, 125 and 105°C respectively) (surface temperature) required drying times of 8, 20 and 100 hours (7). In another work, it was found that to obtain 0.5 in. (1.27 cm) polymer depth it is necessary to dry the concrete slab at 300, 275 and 212°F (149, 135 and 100°C respectively) (surface temperatures) for 4.5, 6.5 and more than 24 hours respectively (4). In the same work it was concluded that to achieve 0.5, 1.0, and 1.5 in. (1.27, 2.54 and 3.81 cm respectively) polymer depths, it is necessary to dry the slabs at a surface temperature of 300°F for 5, 8 and 12 hours respectively. It was also found that with an adequate drying temperature and time the relative water content prior to drying has no effect on the polymer depth. The concrete is adequately dried when sufficient moisture has been removed so that the incoming monomer will soak to the desired depth. To avoid cracking the concrete, it is recommended that the rate of temperature change, both during the drying and cooling cycles should not exceed 1.5 degrees F (0.83°C) per minute and the maximum temperature variation over the heated concrete surface should not exceed 20 degrees F (11°C) of the mean concrete surface temperature (4).

Soaking Time and Polymer Depth

The soaking time is the period of time the monomer system is ponded on the surface of the concrete. The polymer depth depends on the monomer penetration into the concrete surface. The polymer depth should increase as the soaking time increases. The various factors determining the time required for a monomer to develop the desired depth of penetration include monomer viscosity, temperature of monomer and concrete, condition of concrete surface, the relative moisture content (R.M.C.) of concrete prior to monomer application, porosity of concrete and time of monomer application (4).

The monomer viscosity controls the penetration rate of monomer into the concrete surface. The penetration decreases as the viscosity goes up for a given soaking time (8).

A higher slab temperature produces a greater monomer penetration. However, as the slab temperature goes up, evaporation of the monomer becomes an important factor.

Textured surfaces are more easily penetrated by the monomer than smooth surfaces (8). A 1/4 in. (0.64 cm) sand layer spread on the concrete surface is used to hold the monomer in place during soaking and to reduce the monomer evaporation from the concrete surface. A polyethylene membrane is also used to minimize evaporation problems during the soaking period.

The amount of monomer absorbed for a given soaking time decreases as the R.M.C. of the concrete prior to monomer application goes up. Also the effect of R.M.C. increases for the greater soaking time (4).

Tests were performed to determine the effect of the quality (porosity) of concrete on absorption of monomer (4). Lower quality concrete absorbed more monomer than higher quality concrete for a given soaking time. For a 60-minute soaking time the concrete with water-cement ratios of 0.54, 0.68 and 0.81 lb/lb absorbed 21, 27 and 33 cc. of monomer respectively (4).

In the same work a relationship between polymer depth in inches, D, and the soaking time in minutes, T, was developed from capillary forces theory for soaking time equal to or less than 8 hours:

$$D = 0.03733 + 0.05859\sqrt{T}$$

Curing Methods, Temperature and Time

There are various methods by which polymerization of monomers can be achieved. However, in polymer concrete impregnation, it is essential that polymerization of the monomer in the concrete occurs only after adequate monomer penetration is achieved. It was found that the use of a chemical accelerator with the monomer produced an inadequate penetration of monomer before polymerization took place. A less reactive monomer system is now used to permit adequate penetration followed by an application of external energy to achieve polymerization.

The external energy source could be radiation or heat. Polymerization by radiation gives slightly better strength properties but for reasons of safety and cost, heat seems to be the most feasible method, especially for field applications (9). The various heat sources that could be used include steam, hot water, solar energy, infra-red heaters, gas fired heaters, electric heating blanket, oven and circulated hot air produced by forced air heaters.

Steam has proved to be a practical and appropriate method for field application. An oven seems to be convenient only for laboratory work. Circulated hot air is feasible for field application if there is no open flame. The electric heating blanket has one disadvantage. The length of time required to build up the temperature to curing temperature is impractical in field application. In one work it took 10 hours to raise the concrete slab temperature from 75°F to 125°F (24 to 52°C) (10). Hot water is effective for both laboratory work and field application. However, if the water is not reheated during curing, the large amount of hot water ponded on the surface of the concrete might be a disadvantage. On days (most likely summer days) when the air temperature gets up to about 103°F (39°C) it has been found that the temperature on concrete bridge decks is about

135°F (57°C) (3). On such days solar energy could be used to cure the monomer soaked into the concrete. However, the use of sunlight is limited by factors such as air-temperature, relative humidity and cloud cover which cannot be controlled. Besides, treatments would have to be on a day-to-day basis, which would make planning very difficult. A study to investigate the potential for using solar energy to provide the required heat in Oklahoma has been done. The result was not promising in respect to providing the required temperature (11).

Another method of curing involves a second reactive monomer system. It has been demonstrated that a monomer system consisting of 92% (wt.) MMA, 4% (wt.) LP and 4% (wt.) DMPT ponded on the surface of a concrete slab polymerized (without the addition of external heat) and generated enough heat to cure the monomer system already soaked into the concrete within 2 hrs. (3). In addition, the sand cover was bonded to the surface of the concrete. This method gives inconsistent results, and in recent investigations additional heat sources have been used in conjunction with it.

Studies have been done to determine the effects of curing temperature and length of curing time on polymer depths. Curing temperatures of 150 and 170°F (66 and 77°C) gave 1.5 and 1.65 inch (3.81 and 4.19 cm) polymer depths respectively. At these curing temperatures the length of curing time had no effect on the polymer depth as long as it was more than 20 minutes (4). No polymerization was achieved at a curing temperature of 130°F (54°C) after 90 minutes curing time.

Polymerization of the monomer soaked into the concrete should be carried to completion. It has been found that the presence of unpolymerized monomer in concrete may have a negative effect on the long term durability of concrete (4).

Durability of Polymer Impregnated Concrete

As mentioned earlier long-term evaluation tests on the performance of polymer impregnated bridge decks are just in progress. However, there is little doubt that polymer-impregnated concrete bridge decks have improved physical and mechanical properties. Tests have been done to confirm this.

Impregnation of polymer into concrete has the primary purpose of providing greater resistance to water penetration and thus reducing the amount of chloride getting to the reinforcing steel. Freezing and thawing of the water inside the concrete and the corrosion of the reinforcing steel caused by chloride are the major causes of bridge deck deterioration. An evaluation technique then should be found to determine the protection against water penetration, freeze-thaw and corrosion of the reinforcing bars provided by PIC.

Treated concrete slabs with varying polymer depths and control slabs have been taken through several freeze-thaw cycles. Slabs with 1/8 in. (0.32 cm) polymer depth sustained up to an average of 79 freeze-thaw cycles compared to 30 cycles for the untreated control slabs (4). There was no damage to those slabs with 2 in. (5.08 cm) polymer depth through 200 freeze-thaw cycles. Tests were done to determine the effects of polymer type and reinforcing steel in the concrete slab on the freeze-thaw resistance. Methyl methacraylate (MMA) was found to be the best choice, and, with reinforcing steel in the concrete, there was no damage to the slabs after 200 freeze-thaw cycles.

Treated slabs and control slabs were subjected to long-term salt-water exposure to determine the degree of corrosion protection of reinforcing bars provided by PIC (4). The corrosion of the bars in the control slabs was about 25 times greater than for the bars in the treated slab. The chloride ion content was measured and found to be about 5 times greater in the control slabs. In another study (12) the following was observed: 1) the chloride permeability of polymer impregnated concrete was virtually zero and 2) the conventional concretes absorbed more than 4 percent water within the first day of soaking while the water absorption of the polymer impregnated concrete was only 0.3 percent. In another work he found that PIC prevented chloride intrusion to a depth of 1 in (2.54 cm) at least for the number of salt applications he tried - 267 times (13).

To evaluate the mechanical properties of PIC, tests were performed on several treated and control slabs (14). Most of the mechanical properties such as strength, stiffness and durability were improved. The degree of improvement depends on the monomer type; for example, impregnation with butyl acrylate (a ductile material) of strength only slightly greater than that of a convectional concrete to a very strong, hard, brittle material such as impregnation with methyl methacrylate (5). The modulus of elasticity was found to be anywhere from 17% greater for butylacrylate to 94% greater for MMA and IBMA than for the control slabs. The slabs treated with IBMA and MMA gave the greatest improvements in compressive and tensile strengths as shown in Table 1.2. The data in Table 1.2 is for fully impregnated concrete. The table also shows that the ratio of compressive strength and modulus of elasticity of the treated slabs to the control slabs increases as the glass-transition temperature of the monomer type goes up. Efforts were made to determine the effect of concrete quality on the mechanical properties of PIC. The compressive strength was found to decrease as the water-cement ratio increases for the control slabs and the slabs treated with IBA. It increases for the slabs treated with MMA. The changes in tensile strength were found to follow the same trend. The moduli of elasticity of the slabs treated with MMA and IBA were found to decrease as the water-cement ratio increased (2,6,10 and 14).

Tests were also conducted on treated slabs to determine the effect of polymer on the abrasion and skid resistance of concrete. On the average, it was found that PIC is not detrimental to the skid resistance and abrasion properties of concrete surfaces (14). Table 1.3 shows test data obtained on skid resistance using different monomer type (15).

Field Applications

Full scale impregnation has been done on several bridge decks. These include two bridges in Denver, Colorado, one in Idaho and one in California under programs sponsored by the Federal Highway Administration with technical assistance provided by the Bureau of Reclamation (19) and two bridges in Texas with technical assistance provided by the University of Texas in Austin. The process has also been demonstrated in New Mexico. The first bridge treatment was done on a small concrete bridge deck (12 feet by 30 feet) located on Center Street on the Denver Federal Center from July 24 to July 27, 1974. The equipment used consisted of a 500 gallon propane gas tank located on the bridge to supply gas for the heaters (gas-fired space heater) a portable generator to supply electric power for the temperature recorder and temperature control system. Eight thermocouples were used to monitor concrete temperatures at six surface locations and at 1- and 2-inch

TABLE 1.2 STRUCTURAL PROPERTIES OF PIC (2)

Monomer	Glass Transition Temperature °C	Compressive Strength, PSI	Tensile Strength, PSI	Modulus of Elasticity PSI (10^6)
Control		5,330	447	3.10
Butyl acrylate	-54	8,317	835	3.63
Isobutyl acrylate	-43	8,775	785	3.74
45% MMA + 55% BA	- 3	12,400		
Butyl methacrylate	20	12,750		4.61
Isobutyl methacrylate	48	15,500	940	6.0
Methyl methacrylate	105	15,250	1,038	6.0

TABLE 1.3 SKID NUMBERS OF POLYMER IMPREGNATED CONCRETE SURFACES (15)

Specimen #	Skid # at 0 Revolution	Skid # at 70,000 Revolution
MMA	78	59
IBMA	73	59
IDMA	71	59
50% MMA - 50% IDMA	76	61
Control	75	57

depths in the concrete. The process conditions were 72 hours drying time (at 225°F (107°C) to 250°F (121°C) surface drying temperature), 18 hours cooling, 16 hours monomer soaking at an application rate of 1.7 to 1.8 lb/ft^2 and 16 hours for polymerization at 180°F (82°C). The monomer system consisted of 95/5 MMA TMPTMA and 0.5 percent AZObis-dimethylvaleronimle (AMVN) catalyst. Core samples showed polymer penetration of 2 in. The second field demonstration was done on Quincy Avenue Bridge located in Cherry Hills Village near Denver, Colorado in October, 1974. It had a riding surface 28 feet wide by 60 feet long. It took about 50 hours drying time (at 225° to 250°F surface drying temperature), 18 hours cooling, 18 hours monomer soaking at an application rate of 1.7 lb/ft^2 and 18 hours for polymerization at 180°F. The same monomer system was used, but is was mixed together with the catalyst and stored overnight in a refrigerated storage area at -20°F (-29°C) and transported to the bridge site the second day. After polymerization it was found that the sand was bonded to the concrete by polymer. Core samples showed 1- to 1 1/2-inch polymer penetration depth. The same procedure used on the Quincy Avenue Bridge was used on Idaho Bridge located on East Hope, Idaho, and California Bridge located over Rattlesnake Creek on State Route 36 near Forest Glen, California. The work done in Texas and New Mexico followed identical procedures as above with less process time and monomer loading. Also, different heating methods were used. Electric infrared heaters and propane gas-fired space heaters were used. The weaknesses in these early demonstration are too much process time, monomer requirements, excessive manpower and equipment costs.

However, it should be emphasized that the application techniques have been continually improved as more field demonstrations are done. More saving should be realized with more research and better planning.

MONOMER SYSTEMS

The monomer mix usually consists of a monomer, an initiator and a cross-linking agent. There are several monomers, initiators and cross-linking agents which could be used. This chapter looks at the selection of the monomer mix components.

Monomer

A monomer is a small molecule which can be chemically linked into a long chain compound of high molecular weight called polymer.

The nature of the polymer impregnated concrete process restricts the choice of monomers to those with double bonds and can be polymezized by a free radical mechanism. In theory any liquid monomer at room temperature which satisfies the above requirement can be used. However, in practice, certain desirable characteristics must be met. These include low viscosity, low volatility, high polymezitation rate, safety in handling, cost and the resultant polymer-impregnated concrete properties. The monomers that have been used in previous studies include:

1. Methyl methacrylate (MMA)
2. Isobutyl methacrylate (IBMA)
3. Isodecyl methacrylate (IDMA)
4. Butyl acrylate (BA)
5. Isobutyl acrylate (IBA)
6. Butyl methacrylate (BMA)
7. 45% MMA + 55% BA

Table 1.4 lists some of the desirable properties for a number of monomers that could be used. Liquid monomers generally have low viscosities at ambient temperature and are suitable for polymer-impregnated applications. The viscosity of the monomer must be low enough to achieve an adequate penetration

TABLE 1.4 (1, 2, 21)
PROPERTIES OF MONOMERS

Name	Cost*/lb	Viscosity CP	Density gm./cc	Boiling Point °C	Polymerization Rate** Ksp at 44°C	Polymer Tg °C
Methyl methacrylate (MMA)	$ 0.46	0.55	0.940	100	27	105
Isobutyl methacrylate (IBMA)	$ 0.59	0.83	0.883	155	-	48
Isodecyl methacrylate (IDMA)	$ 0.91	2.90	0.870	High	44	-41
Butyl acrylate (BA)	$ 0.42	0.86	0.894	147	324	-54
Isobutyl acrylate (IBA)	-	0.77	0.883	145	228	-43
Butyl methacrylate (BMA)	$ 0.59	0.86	0.889	163	41	20
Styrene (S)		0.71	0.900	145	6	100
Stearyl methacrylate	$ 1.37	9.40	0.85	310	-	38

* Cost for bulk quantities based on 1979

** Defined as % Polymerization/hr. = $Ksp\sqrt{[AIBN]}$ Units are $t^{1/2}/moles^{1/2}hr.$

within a reasonable time. From table 1.4 it can be seen that all the monomers that have been used in previous studies have viscosities less than the viscosity of water. Combinations of styrene and polyester have also been tried. However, because of the high viscosity of the polyester, adequate penetration could not be achieved. Fig. 1.2 shows the effect of viscosity on depth of monomer penetration for a given soaking time (4). Low volatility of the monomer is desirable to reduce monomer evaporation which occurs during monomer application and impregnation. Monomer loss due to evaporation has a detrimental effect on the economics of the process and the safety of personnel in the application and storage areas. Successful impregnation requires that the monomer not begin to polymerize until adequate penetration has been realized since this would raise the viscosity and virtually halt further penetration. Once the desired penetration has been reached, it is then necessary for polymerization to proceed at a fairly rapid rate so that excessive time is not required for conversion of monomer into polymer. Obviously, since the monomer constitutes the bulk of the mix, the cost of the monomer affects the economics of the whole PIC technology the most. An expensive monomer could make the process economically unattractive. The polymer type determines the extent of the improvement on the physical and mechanical properties of the polymer-impregnated concrete. The mechanical properties can be varied by the choice of the monomer from rubbery (BA) to glass-like (MMA). The combination of these factors is unique for each monomer and to a large extent determines the suitability of the monomer.

Methyl methacrylate (MMA) is the monomer used for all of the work presented here. The reasons for this include:

1. It has one of the best combinations of the desired characteristics.
2. It has been the most widely used monomer in previous polymer-impregnated concrete studies; and, therefore, considerable information is available.
3. Early attempts at surface treatment were most successful with this monomer compared to other monomers.
4. The greatest improvement in compressive and tensile strengths were obtained with MMA.
5. It is relatively inexpensive and available.

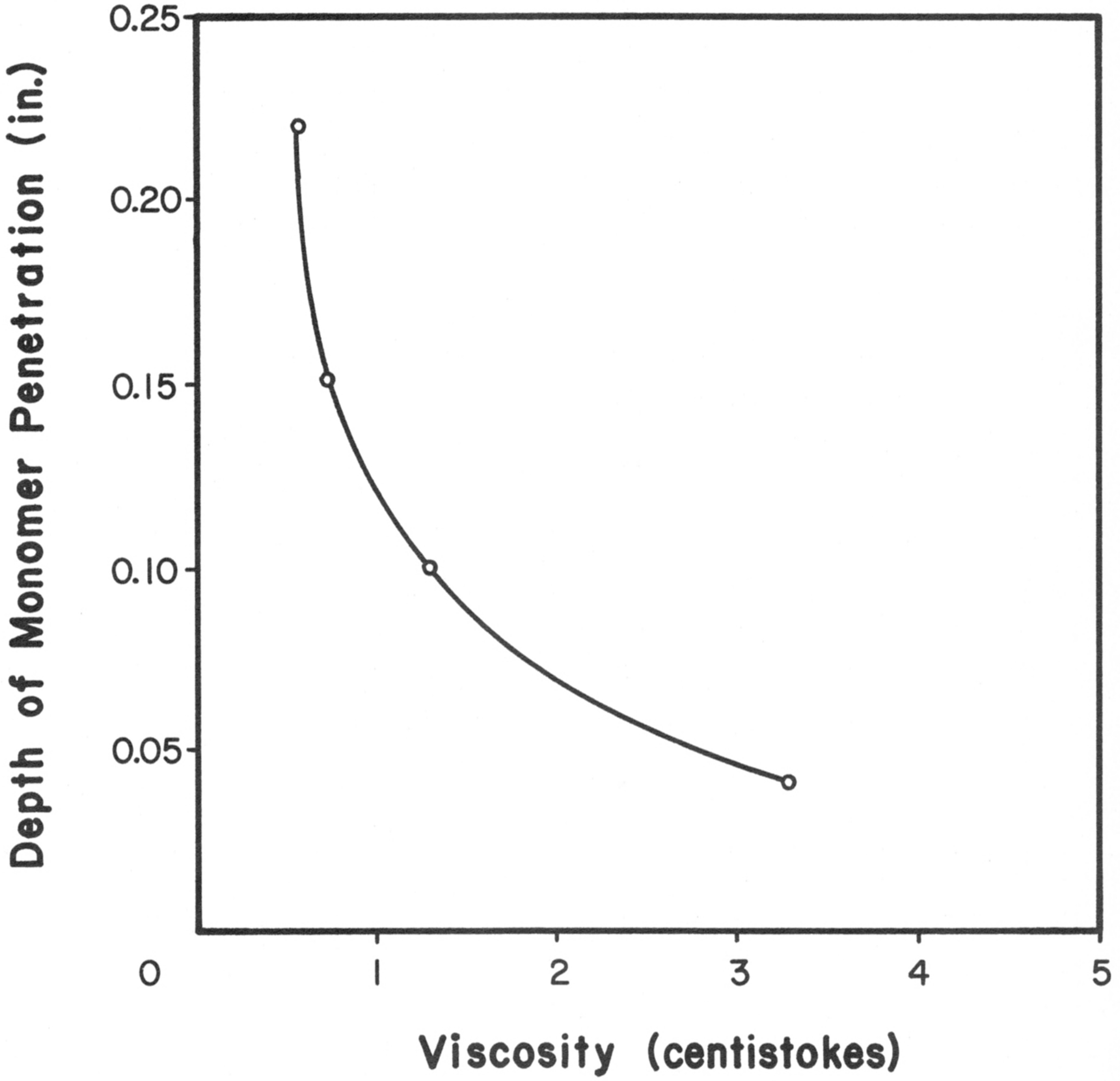


Figure 1.2 Effect of Viscosity on Polymer Depth.

Initiator

An initiator is a compound added to the monomer to start the polymerization. It generates free radicals upon decomposition to begin the reaction. In polymer-impregnated concrete the decomposition is brought about by energy from an external heat source after adequate penetration of the monomer mix. Thus, the initiator employed must be stable at ambient temperature. There are a large number of initiators available in the market and the selection of the proper one depends most on its decomposition temperature. Too high decomposition temperature requires extra heating and too low decomposition temperature may result in an inadequate monomer penetration. Those that have been used in previous works include:

1. Benzoyl peroxide (BP)
2. Lauroyl peroxide (LP)
3. Azobis-isobutyronitrile (AIBN)
4. Methyl-ethyl-Keytone-peroxide (MEKP)
5. Azobis-dimethylvaleronitrile (AMVN)

AIBN was used throughout the work reported here for the following reasons:

1. It gave excellent results in previous works.
2. Though more expensive than common peroxides, AIBN demonstrates excellent stability at ambient temperatures and in the presence of impurities.
3. It has relatively low reaction temperatures, complete monomer-to-polymer conversion and low half life temperatures.
4. It is not shock sensitive.

Benzoyl peroxide (BP) has been the most widely used, but it has the following setbacks:

1. It is flammable and toxic.
2. It is shock sensitive.
3. It is unstable in the presence of the impurities normally encountered in concrete.

In recent works AMVN has been found to give more favorable results compared to AIBN (19).

Crosslinking Agent

A crosslinking agent is a comonomer used to link one-dimensional molecular chains of polymer into a three-dimensional network. It increases the polymerization rate and the molecular weight of the polymer and thus enhances the chemical, temperature and solvent resistance of the polymer impregnated concrete. Crosslinking also increases the stiffness, strength and the brittleness of the polymer (Ref. 10 and 20). The rate of polymerization depends on the type and amount of cross-linking agent. Trimethylolpropane trimethacrylate (TMPTMA) has been the most widely used cross-linking agent, and it was used throughout this work. Fig. 1.3 shows the effect of the amount of cross-linking agent on the time to peak temperature for TMPTMA. The temperature raises and then falls as the polymerization proceeds. The peak temperature is the maximum temperature attained. The viscosity of the monomer **mix** increases slightly as the percentage of TMPTMA increases. Table 1.5 lists a series of viscosity measurements made on mixtures of MMA and TMPTMA (19). Another cross-linking agent that has been used in recent works without much promise is trimethylolpropane triacrylate (TMPTA). (4)

The monomer system used in this work consists of melthyl methacrylate (monomer), AIBN (initiator) and trimethlopropane trimethacrylate (cross-linking agent). The percent by weight of the initiator and cross-linking agent can be varied. The two compositions most frequently used are: (1) MMA with 2.0% (wt.) of the initiator and 15% (wt.) of the cross-linking agent and (2) MMA with 1.5% (wt.) of the initiator and 10% (wt.) of the cross-linking agent. The second composition was used in this work because it is cheaper (less TMPTMA) and (AIBN) and it is less viscous. Table 1.7 shows the monomer system. Specifications and potential suppliers for these materials are given in Appendix A.

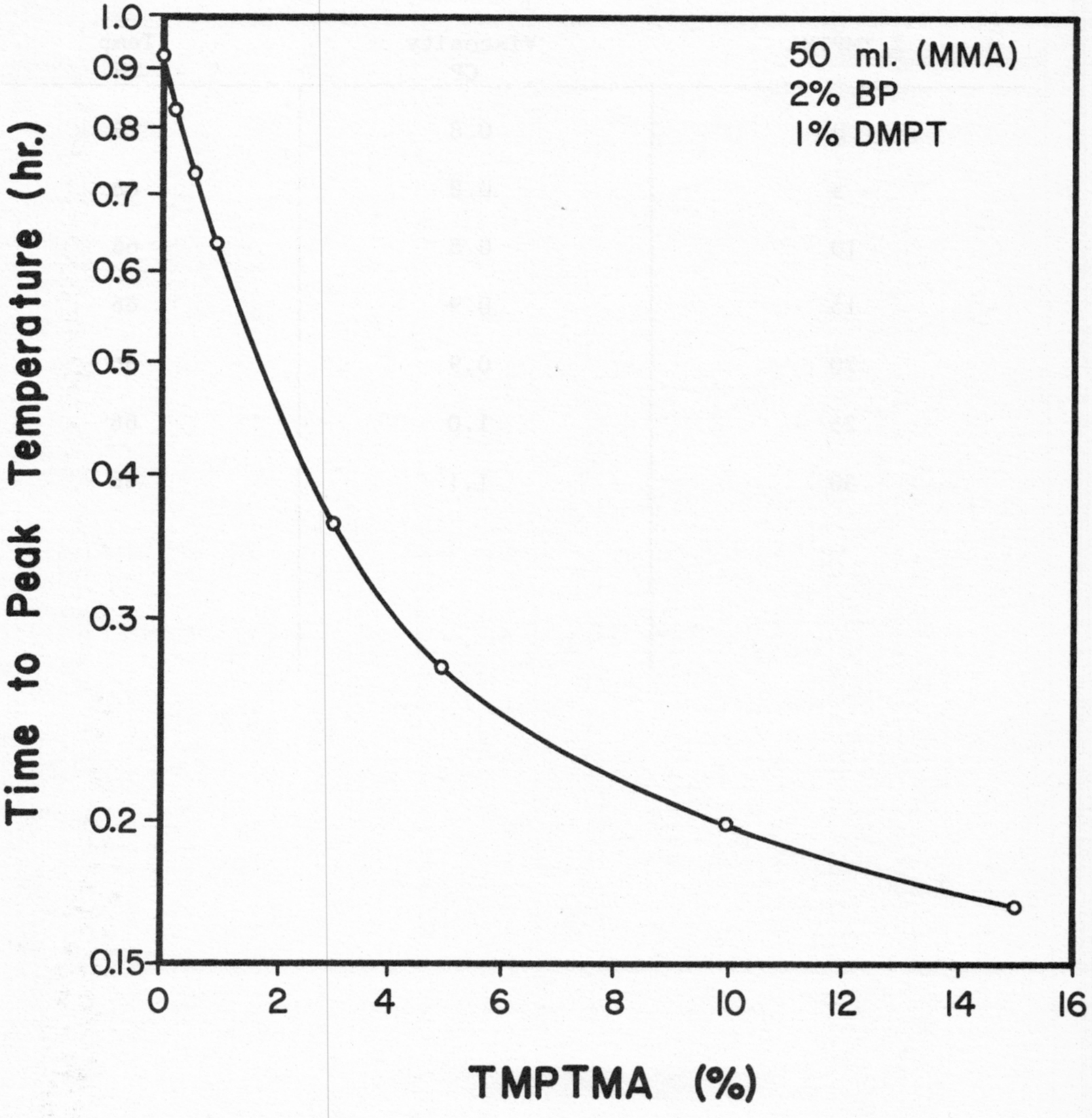


Figure 1.3 Effect of the Amount of TMPTMA on the Time to Peak Temperature (3).

TABLE 1.5 (19)

VISCOSITY OF MIXTURES OF MMA & TMPTMA

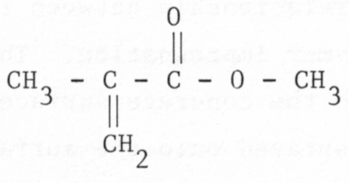
% TMPTMA	Viscosity CP	Temp °F
0	0.8	74
5	0.8	66
10	0.8	66
15	0.9	66
20	0.9	66
25	1.0	66
30	1.1	66

TABLE 1.7

MONOMER SYSTEM

I. MONOMER

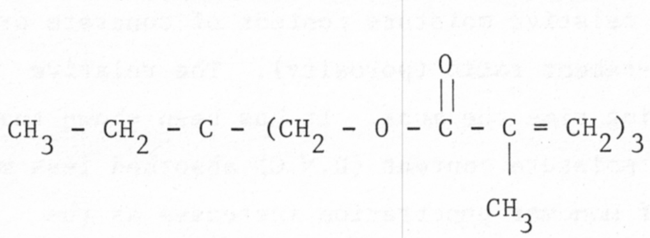
Methyl methacrylate (MMA) 88.5% (wt.)



$CH_3-\underset{\underset{CH_2}{\|}}{C}-\overset{\overset{O}{\|}}{C}-O-CH_3$

II. CROSSLINKING AGENT

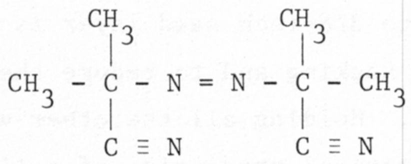
Trimethylolpropane trimethyacrylate (TMPTMA) 10% (wt.)



$CH_3-CH_2-C-(CH_2-O-\overset{\overset{O}{\|}}{C}-\underset{\underset{CH_3}{|}}{C}=CH_2)_3$

III. INITIATOR

$2,2^1$- Azobia (isobutyronitrile) (AIBN) 1.5% (wt.)



$CH_3-\underset{\underset{C\equiv N}{|}}{\overset{\overset{CH_3}{|}}{C}}-N=N-\underset{\underset{C\equiv N}{|}}{\overset{\overset{CH_3}{|}}{C}}-CH_3$

EXPERIMENTAL INVESTIGATIONS

This section summarizes the various experimental studies conducted in this work. It started with laboratory work and then proceeded to scale up work done outside.

Monomer Penetration Study

The primary purpose of this study was to develop the relationship between the soaking time and monomer penetration for partial polymer impregnation. The polymer depth depends on the monomer penetration into the concrete surface. For partial polymer impregnated concrete the monomer is sprayed onto the surface and left to soak into the concrete. The depth of penetration should be expected to increase as the soaking time is increased. The time required for the monomer to reach the desired depth of penetration depends on the viscosity of the monomer, the temperature of the monomer and concrete, the condition of concrete surface, the time of the soaking, relative moisture content of concrete prior to monomer application and the water-cement ratio (porosity). The relative moisture content affects the soaking time the most. It has been shown that concrete slabs with high relative moisture content (R.M.C) absorbed less monomer than low R.M.C slabs. The rate of monomer penetration increases as the water-cement ratio increases. Lower viscosity increases penetration and higher temperature produces higher monomer penetration. Textured surfaces are more easily penetrated by the monomer than smooth surfaces.

Evaporation of the monomer during soaking has proved to be a serious problem for partial PIC. To reduce this problem a 1/4- to 3/8-inch sand layer is usually used to hold the monomer in place during soaking and to reduce the evaporation of monomer from the concrete surface. Holding all the other variables constant, a study was done to confirm theoretical prediction of a linear relationship between depth of monomer penetration and the square root of soaking time from capillary theory.

Experimental Design and Procedure

The experiment was done in the laboratory on several 12" by 12" x 7" concrete slabs prepared by the Civil Engineering Department, University of Oklahoma. They were poured using the standard mix design used by the Oklahoma Department of Transportation for bridge decks (Table 1.8) with broom finish surface and cured in 100% humidity cabinet for 28 days. After curing, the slabs were dried at 230°F for 24 hours. They were enclosed in a polyethylene bag to prevent moisture from re-entering them and left to cool to room temperature (77°F). A 4-inch dam made of wood was sealed with putty to the slabs and a 1/8 inch layer of room-dried sand was spread on the surface of the slabs. Different amounts of monomer systems were applied to the sand. Each dam was covered with polyethylene wrap to inhibit monomer evaporation and the time the monomer system was applied was recorded. The monomer was allowed to soak for as long as it took for the sand to feel dry to the touch. To reduce error, the sand was felt as often as possible. The time the sand felt dry to the touch was recorded. The difference between the two times gave the soaking time. The monomer was polymerized by heating the slab with steam for 2.5 hours. They were then cut open to determine the depth of impregnation/penetration (Fig. 1.4A).

Results and Application

When the slabs were cut open two bands of discoloration were present. The discoloration nearer the surface was gray in color while the one further from the surface was relatively light in color. To be sure the two bands contained polymer a drop of water was applied to three different areas: 1) the gray-colored portion, 2) the light gray colored portion, and 3) the slab interior where there was no discoloration. Both drops from areas 1) and 2) beaded and showed definite contact angles and since the contact angle of water on untreated concrete is zero (which was proved by the drop on area 3) the test indicated that polymer was present in both color bands. The depths (h) in inches of the entire discolored portions were measured and shown in Table 1.9. Fig. 1.4 shows a graph of h in inches vs. the square root of soaking time $(\mathrm{hr})^{1/2}$. The plot indicates a straight line relationship which is in agreement with the theoretical development. Also it is observed from Table 1.9 that the rate of

TABLE 1.8

COMPOSITION OF CONCRETE SLABS

	Weight
Course Aggregate	46.97 to 47.8
Fine Aggregate	30.57 to 33.58
Cement (Type I)	15.45 to 16.55
Water	6.07 to 6.37
Air Content	5.80 to 8.0 (Vol. %)
Water/Cement Ratio:	.393 to .385

TABLE 1.9

PENETRATION VS. SOAKING TIME*

TIME (HOURS)	DEPTH (INCHES)
1.33	0.6
2.25	0.7
4.15	0.9
4.17	1.0
9.58	1.4
22.25	2.0
22.42	2.1

*Different monomer loadings were used.

Figure 1.4A Impregnated Slabs Showing Polymer Depth.

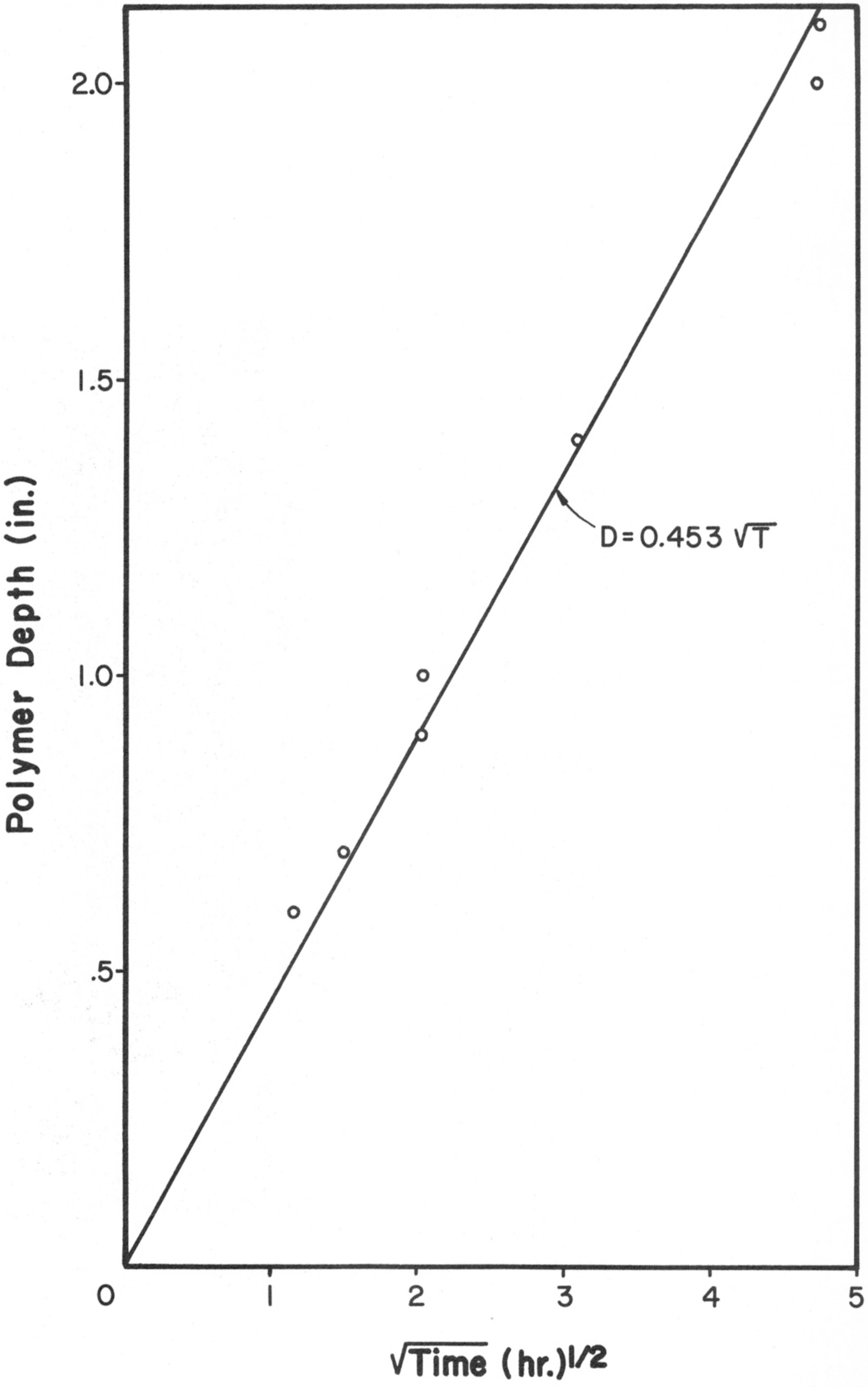


Figure 1.4 Polymer Depth Vs. Square Root of Soak Time.

rate of monomer penetration decreases as the soaking time increases. To put this result to use, the depth of impregnation required is selected and the amount of soaking time necessary to achieve this depth is obtained from Figure 1.4. Since a depth of at least 1 inch of impregnation of bridge deck is usually desired a soaking time of at least 4 hours (from Fig. 1.4) is required. The evaporation problem of monomer during soaking is more pronounced with the longer period of soaking time.

Monomer Loading Study

The monomer loading is defined as the amount of monomer mix in pounds per square foot of the surface to be treated. It was found from the previous section that the depth of monomer penetration increases in proportion to the square root of the soaking time. Since the depth of penetration also depends on the amount of monomer mix available (monomer loading), it should be expected that the soaking time is going to increase with monomer loading and should bear some square root relationship with it. With this in mind the next study was done. The purpose was to determine the time required for a given monomer loading in the sand to completely soak into the concrete.

Experimental Design and Procedure

The same type of slabs as in the previous section were used. The experiment was done in a similar manner to the previous experiment. However, the various monomer loadings were known, and it was not necessary to cure the slabs. The sand was felt to determine the soaking time - this method of determining the soaking time might be expected to introduce an error in the result. Curing of the monomer soaked into the slabs was not done here.

Results and Application

Table 1.10 shows the data. Expecting a square root relationship, a plot of loading (lbs./sq. ft.) vs. the square root of soaking time $(\text{min})^{1/2}$ was made (Fig. 1.5). A straight line was obtained.

TABLE 1.10

LOADING VS. SOAKING TIME

Loading (lb/ft^2)	Soaking Time (minutes)
0.77	100
1.15	150
1.49	229
1.94	347
2.3	431

To apply this result, select the depth of impregnation required and read off the amount of soaking time necessary to give this depth from Fig. 1.4. The maximum monomer loading that can be expected to soak completely into the concrete within the given soaking time is obtained from Fig. 1.5.

As an example, supposing an inch of impregnation is required. An inch (2.54 cm) of impregnation gives 4-hour soaking time (Fig. 1.4), which in turns give 1.5 $lbs/ft.^2$ ($0.733\ gm/cm^2$) monomer loading (Fig. 1.5). Note that its not necessary to use this maximum monomer loading to obtain the desired depth of impregnation/ penetration. This was checked using cured samples (see next section).

Monomer Loading and Depth of Impregnation

This section ties together the work done on monomer penetration vs. soak time and monomer loading vs. soak time. The relationship between the monomer loading and depth of impregnation/penetration is discussed.

Knowing how the two are related to each other one can determine whether it is necessary to use the maximum monomer loading determined in the previous section in order to get the desired depth of impregnation started with.

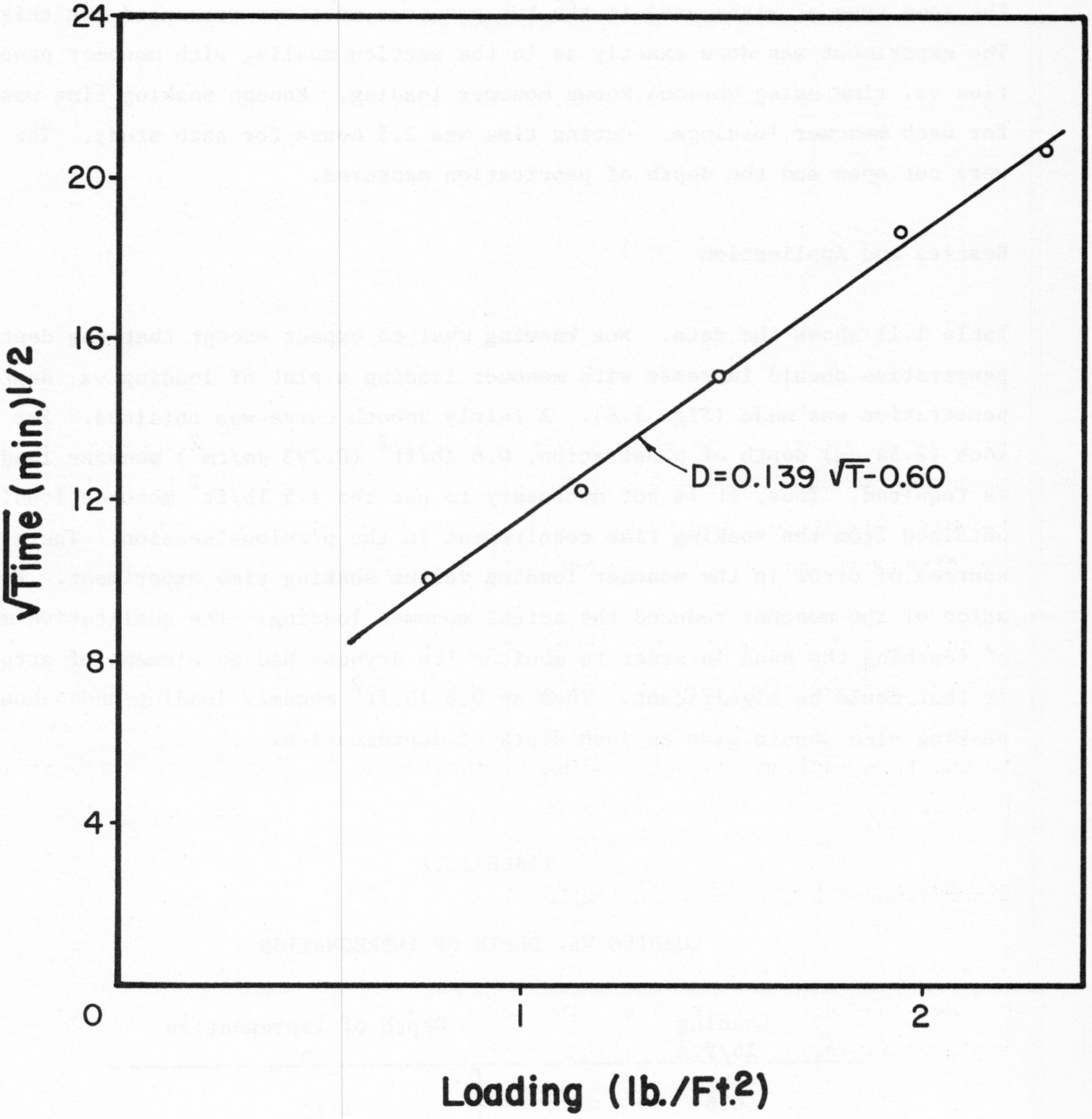


Figure 1.5 Square Root of Soak Time as a Function of Monomer Loading.

Experimental Design and Procedure

The same type of slabs used in the two previous sections were used for this study. The experiment was done exactly as in the section dealing with monomer penetration vs. time using various known monomer loading. Enough soaking time was allowed for each monomer loadings. Curing time was 2.5 hours for each study. The slabs were cut open and the depth of penetration measured.

Results and Application

Table 1.11 shows the data. Not knowing what to expect except that the depth of penetration should increase with monomer loading a plot of loading vs. depth of penetration was made (Fig. 1.6). A fairly smooth curve was obtained. For and inch (2.54 cm) depth of penetration, 0.6 lb/ft^2 (0.293 gm/cm^2) monomer loading is required. Thus, it is not necessary to use the 1.5 lb/ft^2 monomer loading obtained from the soaking time requirement in the previous section. There were sources of error in the monomer loading versus soaking time experiment. Evaporation of the monomer reduced the actual monomer loading. The qualitative method of touching the sand in order to monitor its dryness had an element of error in it that could be significant. Thus an 0.6 lb/ft^2 monomer loading and 4-hour soaking time should give an inch depth of impregnation.

TABLE 1.11

LOADING VS. DEPTH OF IMPREGNATION

Loading lb/ft^2	Depth of Impregnation in
0.6	1.18
0.7	1.38
0.8	1.42
0.9	1.50
1.0	1.54

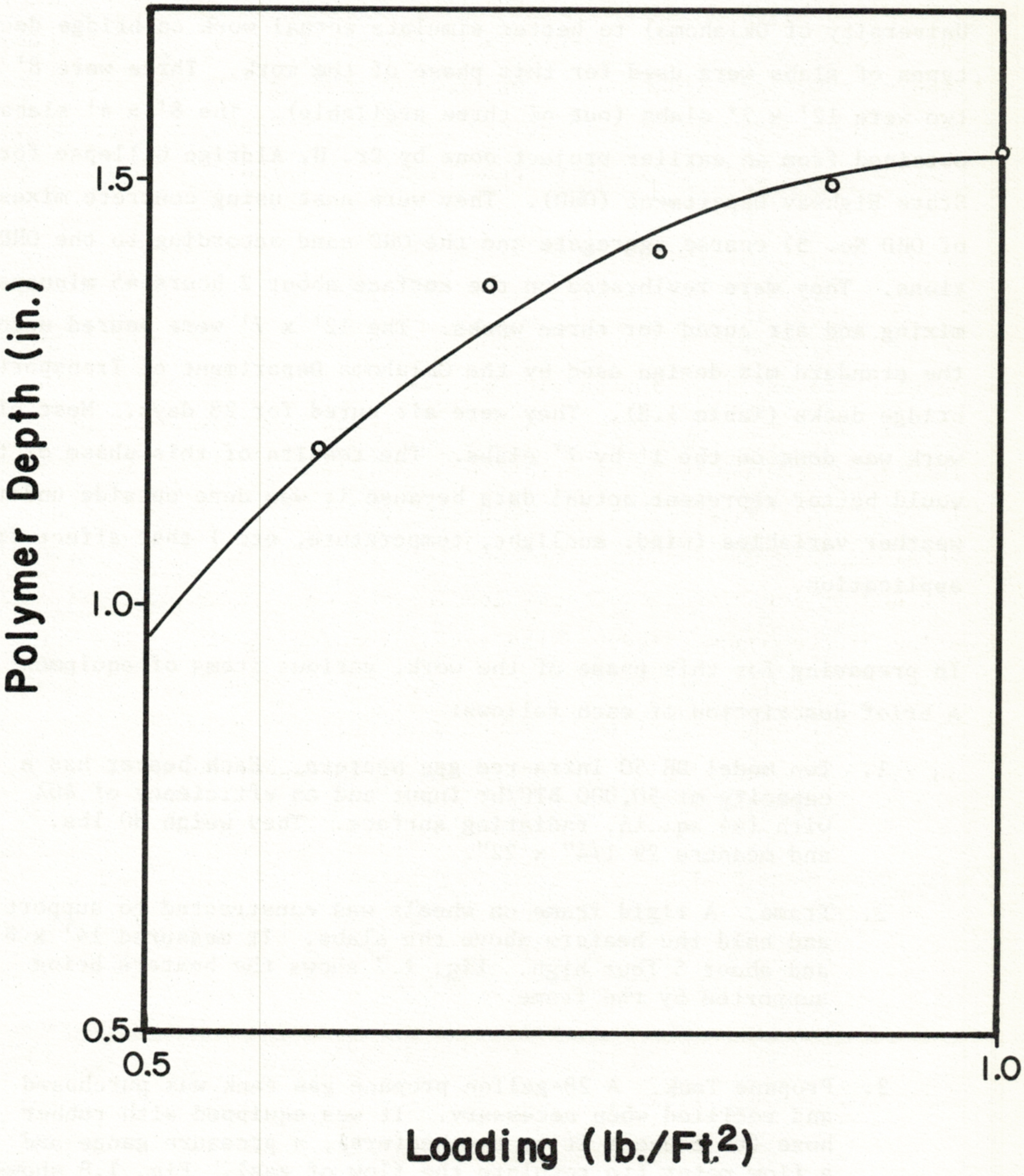


Figure 1.6 Polymer Depth as a Function of Monomer Loading.

Field Tests

From this point on, various investigations were done outside (at North Base of University of Oklahoma) to better simulate actual work on bridge decks. Two types of slabs were used for this phase of the work. Three were 8' by 4' and two were 12' x 7' slabs (out of three available). The 8' x 4' slabs were obtained from an earlier project done by Dr. H. Aldrige Gillepse for Oklahoma State Highway Department (OHD). They were cast using concrete mixes consisting of OHD No. 57 coarse aggregate and the OHD sand according to the OHD specifications. They were revibrated on the surface about 2 hours 45 minutes after mixing and air cured for three weeks. The 12' x 7' were poured according to the standard mix design used by the Oklahoma Department of Transportation for bridge decks (Table 1.8). They were air cured for 28 days. Most of the outside work was done on the 1' by 7' slabs. The results of this phase of the work would better represent actual data because it was done outside under the various weather variables (wind, sunlight, temperature, etc.) that affect field application.

In preparing for this phase of the work, various items of equipment were acquired. A brief description of each follows:

1. Two model DH 50 Infra-red gas heaters. Each heater has a capacity of 50,000 BTU/hr input and an efficiency of 40% with 144 sq. in. radiating surface. They weigh 30 lbs. and measure 29 1/4" x 22".

2. Frame. A rigid frame on wheels was constructed to support and hold the heaters above the slabs. It measured 14' x 8' and about 5 feet high. Fig. 1.7 shows the heaters being supported by the frame.

3. Propane Tank. A 28-gallon propane gas tank was purchased and refilled when necessary. It was equipped with rubber hose (to connect it to the heaters), a pressure gauge and a flow meter (to regulate the flow of gas). Fig. 1.8 shows the tank on a stand.

4. Thermocouple Box. A 115 volt thermoelectric thermocouple box with 12 outlets was purchased (Fig. 1.9) to monitor the temperature of the slabs.

Figure 1.7 Frame and Heaters

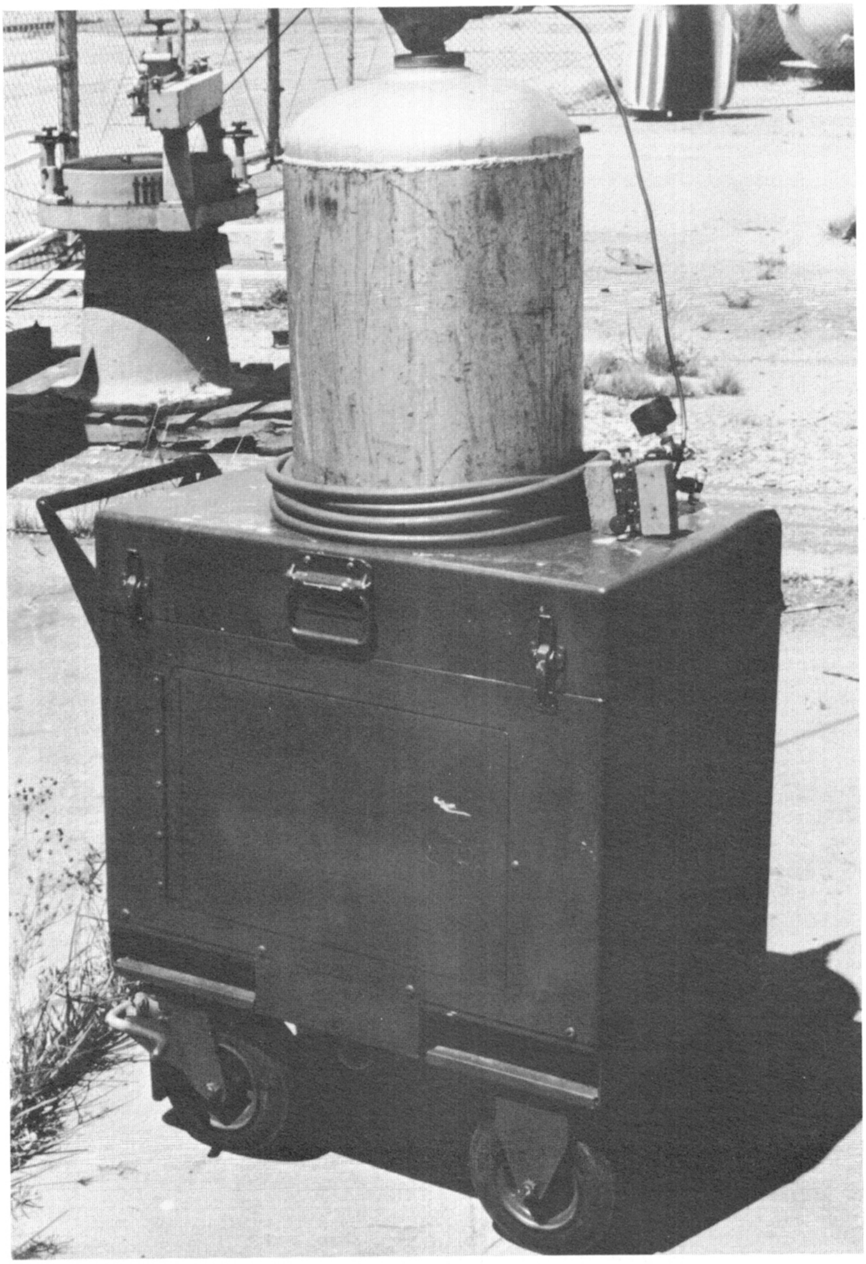


Figure 1.8 Gas Tank

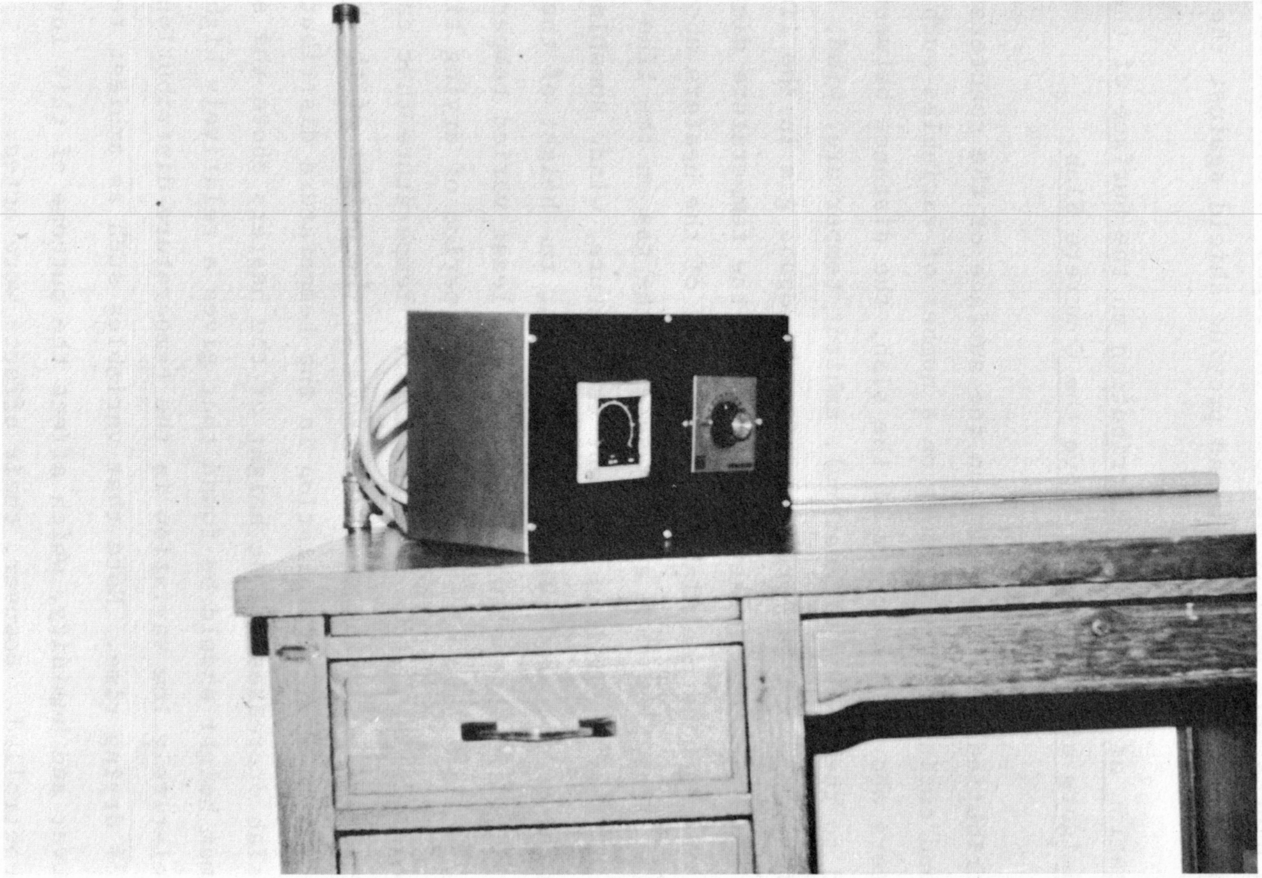


Figure 1.9 Thermocouple Box

5. Applicator. A monomer sprinkler was constructed. It was used to apply the monomer to the sand in fine spray. 1/11" holes spaced about 1" apart were drilled on it. It was connected with a 1/2" tubing to a 5-gallon container usually placed on top of the frame to provide the necessary head when in use (Fig. 1.10).

Concrete blocks were used to surround the edges of the concrete slab and stacked high enough to keep the heat in and provide shield against the wind.

Investigation of Temperature Distribution on the Surface of the Slabs with Respect to the Heights of the Heaters Above the Concrete Slab.

The distribution of temperature on the surface of the concrete slab during the drying and curing cycles depends on a number of variables such as the height of the heaters above the surface of the slab, the distance between the heaters (related to the number of heaters), ambient temperture, wind, humidity, cloud cover, flow rate and the pressure of the propane gas in the line. This study was done to determine the relationship between the temperature distribution on the surface of the concrete slab and the height of the heaters above the surface of the slabs. The flow rate and pressure of the gas on the line were kept constant and the weather conditions (ambient temperature, wind, sunshine, etc) were noted. The results of the study were sought so that the height of the heaters above the surface of the slab that would develop the least varied temperature distribution on the surface of the slab after a certain period of drying time could be estimated. It is obvious that the maximum temperature that can be obtained for a given period of drying time decreases as the height of the heaters above the slab is increased. The variation in the temperature distribution on the surface of the slab decreases as the height of the heaters above the slab is increased. An optimum height should be found that gives a relatively high maximum temperature and a relatively low variation in the temperature distribution after a given period of drying time. Note that variables such as ambient temperature, wind, cloud cover and humidity, which affect the outcome of this investigation, could not be controlled. However, their effects were noted.

Experimental Design and Procedure

The test were done on an 8' x 4' and 12' x 7' slab and on hlaf (6' x 7') of the 12' x 7' slab.

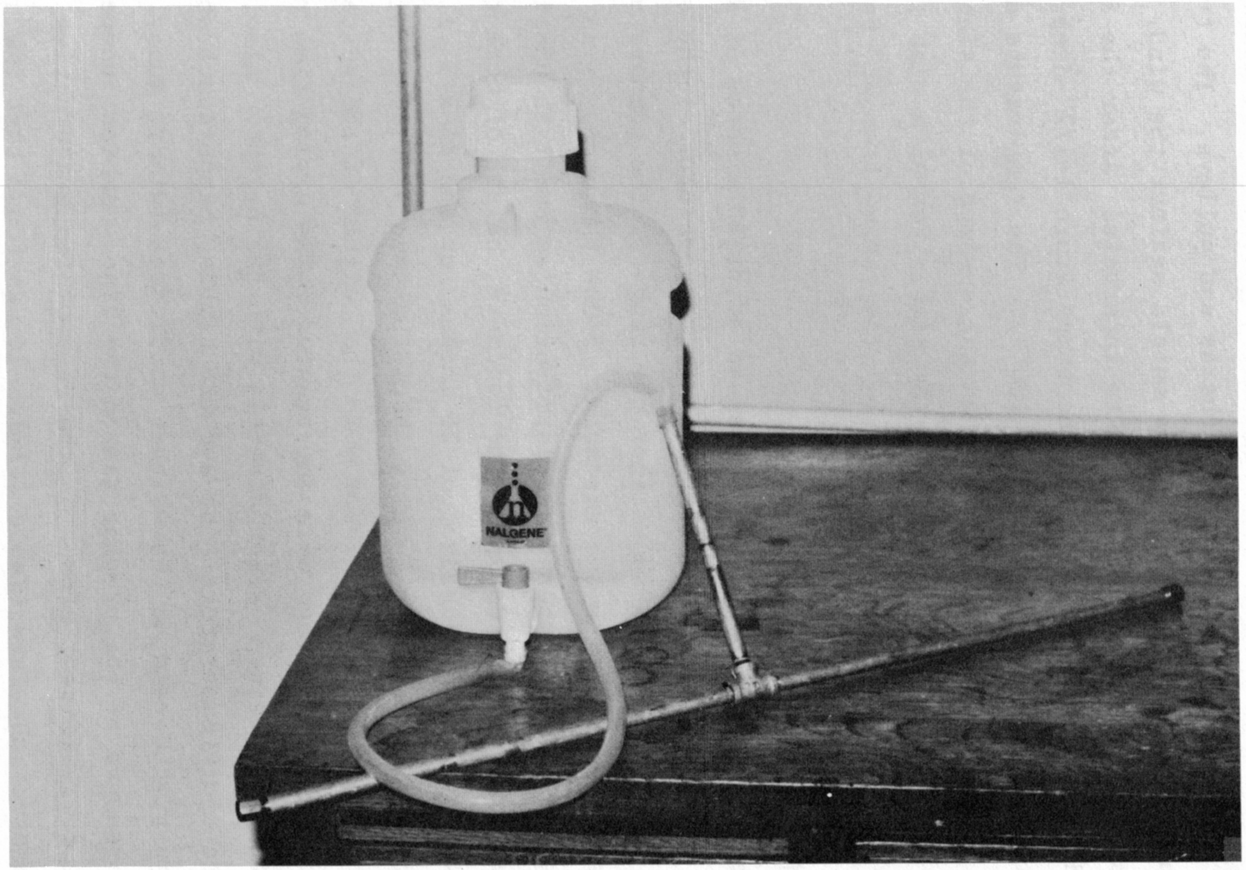


Figure 1.10 Applicator

To simulate the actual field application condition, the test concrete slab was swept clean and surrounded by concrete blocks to reduce heat loss during the drying. Thermocouples were placed on the surface of the concrete slab and about 1-1/2" deep into the slab (to give an idea of the temperature gradients in the concrete slab) and held in place with portland cement grout. A 3/8" layer of sand was spread evenly on the surface of the slab. The heaters were mounted on the frame using chains and pulleys. The frame was covered on the sides and top to provide a shield against the wind. Temperature measurements were made at 15-minute intervals. After the first test it was found that, given enough time, the temperature 1-1/2" deep into the slab got the required value (at least 100°F). The temperature distribution at this depth had the same range as on the surface of the slab. and no further thermocouples were placed inside the slab. For each slab the height of the heaters from the surface of the slab was varied from 22" to 28".

Results and Application

Table 1.12 contains the data obtained after 90 minutes of drying time. Figures 1.11 to 1.13 are plots of the average temperatures of the surface of the slabs with time. The table shows that the range of the temperature distribution varies inversely with the distance. Since the emphasis is on keeping the variation in the temperature distribution as small as possible (± 20°F is recommended) to avoid damaging the concrete, height of more than 27 inches for the 12' x 7' slab, a height of 26 inches for the 8' x 4' slab and a height of 23 inches for the 6' x 7' slab should be used providing only the two heaters are used (Table 1.12). These were the heights of the heaters above the surface of the slabs when they were impregnated. The drying time required to achieve a given temperature varied directly with the height. Also, it was found that the rate of temperature rise and the highest temperature obtained for a given drying time depend on the weather conditions (windy, sunny, cloudy, etc.) and the pressure of the propane gas on the line. Ambient temperature seems to have quite a significant effect on the rate of temperature rise and the maximum temperature obtained (Table 1.12). It was found that the higher the ambient temperature the faster the rate of temperature rise and the greater the maximum temperature for a given drying time.

TABLE 1.12

TEMPERATURE VS. HEIGHT

Height inches	Ambient Temperature °F	Lowest Temperature °F	Highest Temperature °F	Mean of Temperature Distribution °F	Range °F Highest-Mean
Size of Slab: 8' x 4'					
22	80	195	240	196	44
23	85	200	250	224	26
26	94	190	230	206	24
Size of Slab: 7' x 6'					
23	80	142	170	157	13
27	90	130	155	142	13
Size of Slab: 12' x 7'					
23	80	89	170	112	58
25	85	88	148	105	43
27	85	97	155	119	36

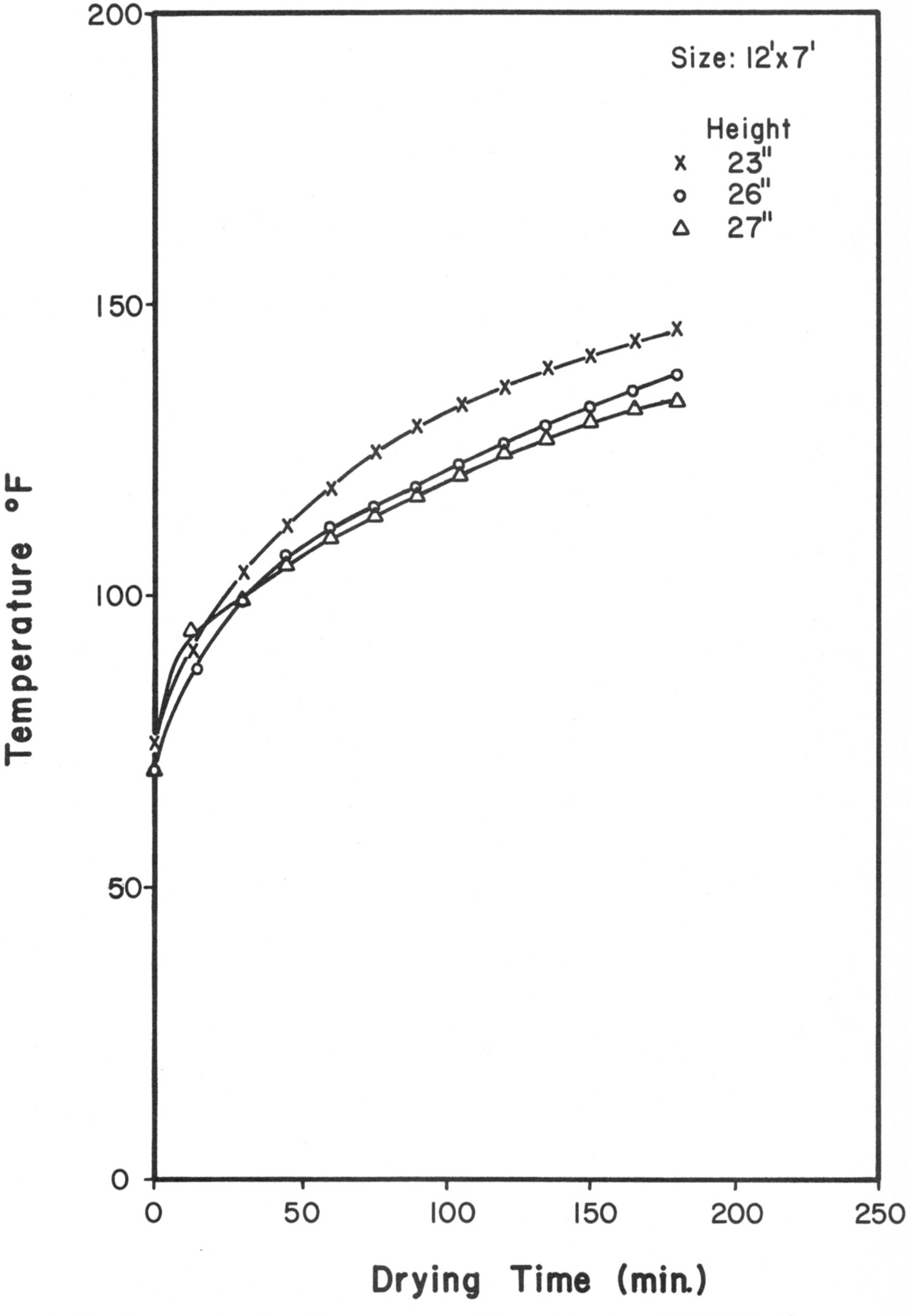


Figure 1.11 Average Surface Temperature of Concrete as a Function of Drying Time.

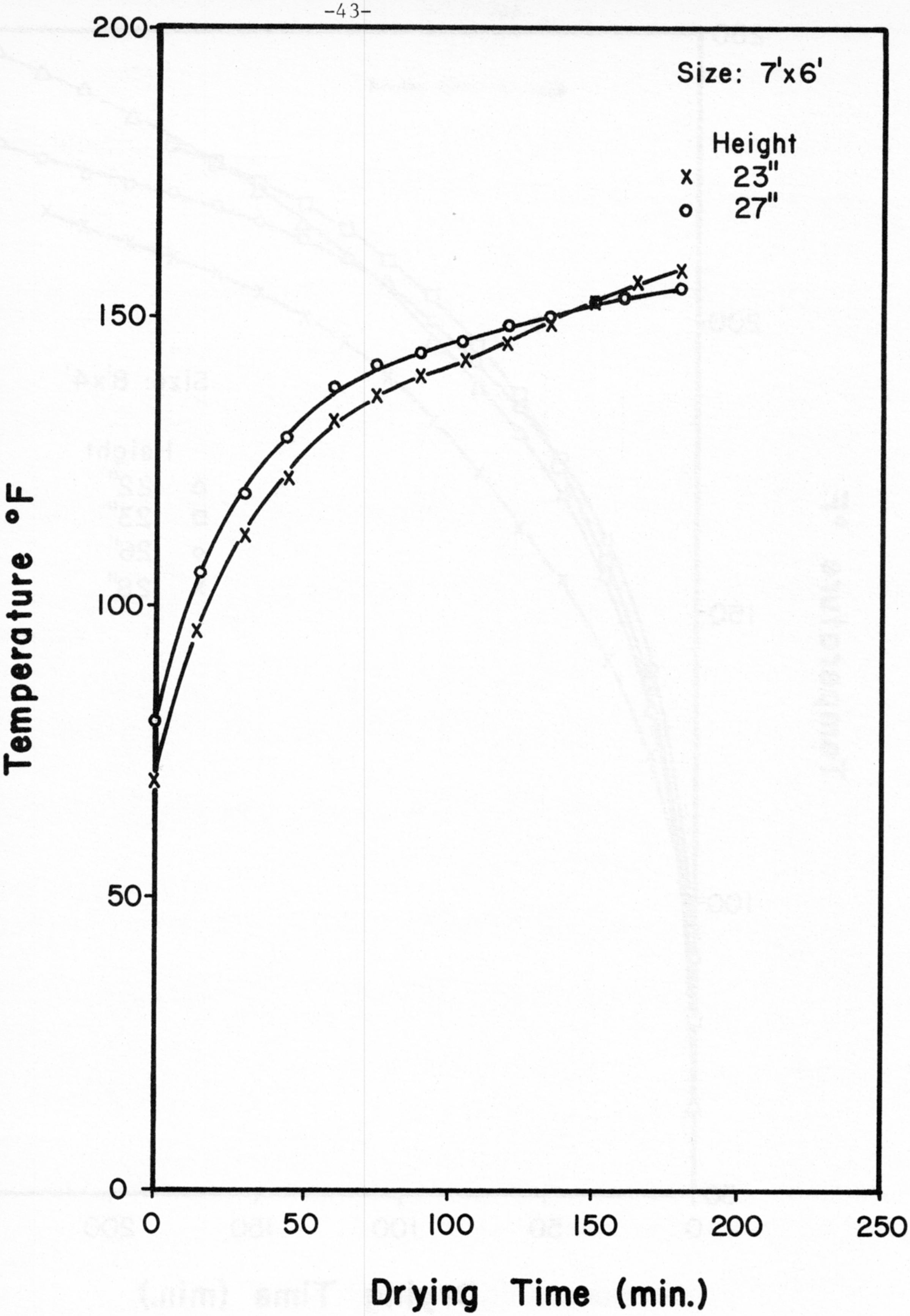


Figure 1.12 Average Surface Temperature of Concrete as a Function of Drying Time.

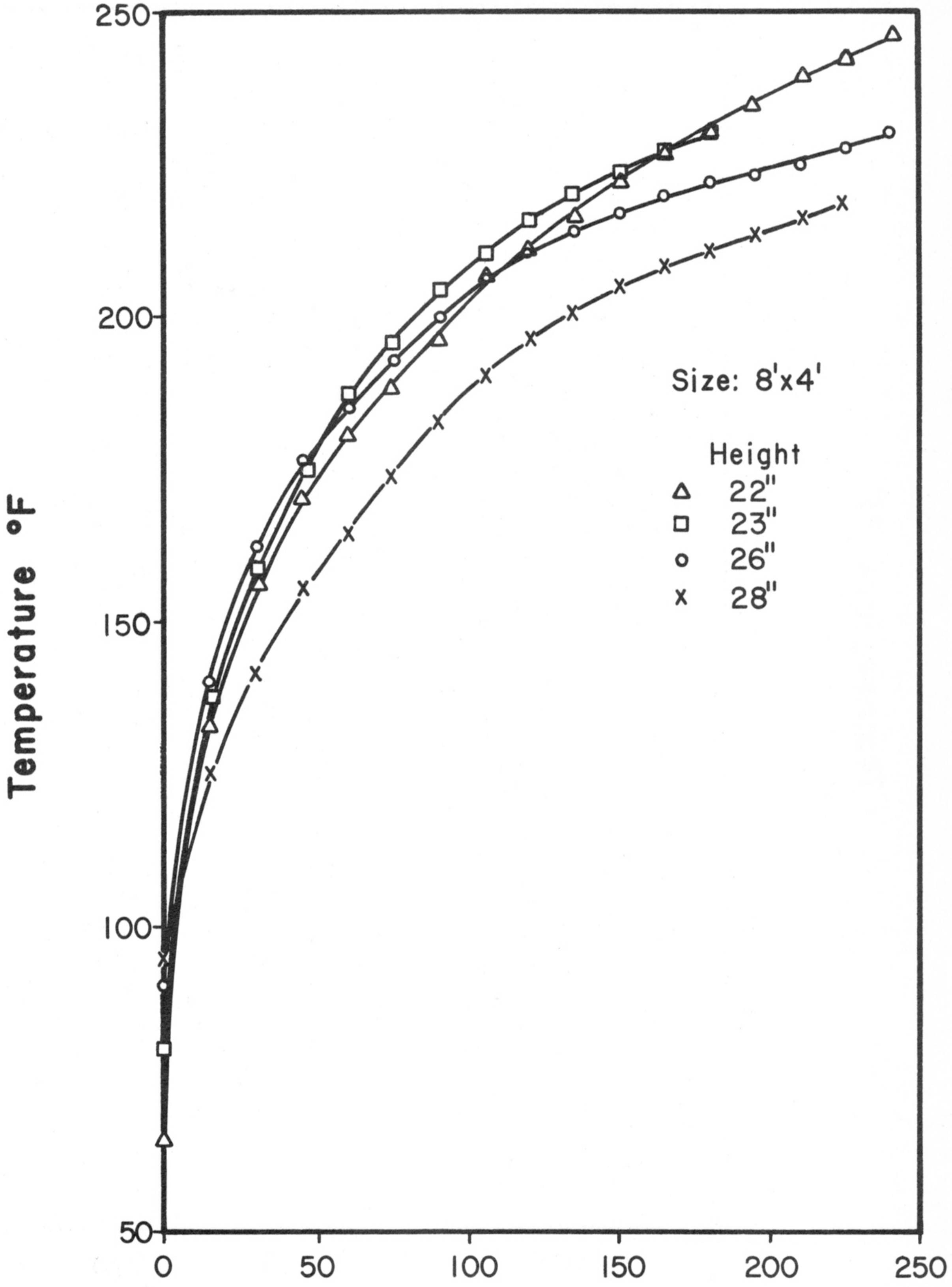


Figure 1.13 Average Surface Temperature of Concrete as a Function of Drying Time.

Determination of the Minimum Heat Flux Required for the Drying Cycle

The surface area of the concrete slabs to be dried using a given number of heaters determines the spacing between the heaters which in turn influences the variation in temperature distribution on the surface of the slab. The minimum heat flux required for the drying cycle could be estimated from a knowledge of the surface area of the slab that could be dried effectively for a given number of heaters. The decision is based on the largest surface area that meets the requirement that the range of the temperature distribution on the surface of the slab not exceed 20°F.

Experimental Design and Procedure

The experiment was set up as in the previous section. The height of the heaters above the surface of the slab was kept the same at 27 inches. Attempt was made to keep the flow rate and pressure of the propane gas constant. The study was done over a period of about two weeks. There were changes in such variables as ambient temperature, wind, humidity, and cloud cover that could not be controlled. Using the two heaters available, the surface area of the concrete slab to be dried was varied, thus varying the spacing between the heaters. A drying period of two hours was used for each study.

Result and Application

Table 1.13 shows the data. Because of the effect of the changes in the variables mentioned above that could not be controlled, the result is slightly different from what was expected. The range of the temperature distribution was expected to increase with the surface area. From the data and taking all the various factors that influenced the result into consideration, the 5' x 7' size was chosen as an optimum area.

The two heaters (Model DH 50) used required an input of 50,000 BTU/hr each, and have an efficiency of 40% as supplied by the manufacturer.

$$\text{Minimum heat flux} = \frac{2(50{,}000\ \text{BTU/hr})\ (.4)}{(5 \times 7)\ \text{ft}^2}$$

$$\approx 1140\ \text{BTU/hr} - \text{ft}^2$$

TABLE 1.13

TEMPERATURE VS. SIZE

Size	Lowest Temperature °F	Highest Temperature °F	Mean Temperature °F	Range °F
4' x 7'	150	200	173.3	26.7
5' x 7'	140	190	182	8
6' x 7'	120	200	160	40
9' x 7'	110	170	145	25
12' x 7'	95	160	119	41

To use this result, the surface area of the concrete to be dried is measured and the number of heaters needed is estimated by calculating the BTU/hr required. As an example, for a 16' by 16' section to be treated using evenly spaced heaters 27" above the concrete surface:

Energy needed = 1140 x 16 x 16 = 291,840 BUT/hr

$$\# \text{ of Model DH 50 heaters} = \frac{291,840}{50,000\ (.4)}$$

$$\approx 15 \text{ heaters}$$

Investigation of the Depth of Impregnation with Respect to Curing Temperature

Polymerization of monomer is an exothermic reaction. For partial polymer-impregnation after the polymerization is initiated by the external heat source, the exotherm is developed and causes the rate of polymerization to increase. The higher the temperature is on the surface of the concrete slab for a given cure time, the longer the polymerization would have been going on. Deeper polymer depths should be obtained with the higher surface temperatures.

Experimental Design and Procedure

The investigation was done on a half (6' x 7') of one of the 12' x 7' slabs. Using the set up described in the section dealing with temperature distribution vs. height, the slab was dried for 6 hours (at this time the temperature on the surface of the slab varied from 140°F to 240°F). It was covered (to prevent moisture from re-entering) and left to cool down overnight. Six-tenths pound per square foot monomer mix loading was applied to the dried sand-covered concrete before sunrise (to prevent polymerization by radiation) the next day. A polyethylene cover was placed on the monomer saturated sand to reduce monomer evaporation and the top of the surrounding concrete blocks enclosure was covered to prevent solar radiation from reaching the monomer-saturated sand. The monomer mix was allowed to soak into the concrete for a period of 4 hours. The sand was checked to make sure it was dry enough to prevent it from polymerizing during the curing cycle. The concrete slab was cured for two and a half hours and the temperature on the surface of the slab was monitored every 15 minutes. Of particular interest was the temperature distribution at the end of the curing cycle. After curing, test core samples were taken and etched with dilute acid (five parts water to one part HCl) to determine depth of impregnation (Figure 1.14A). Effort was made to identify the core samples with the temperatures of the surface of the slab after the drying cycle.

Result and Application

The result is shown in Table 1.14. A plot of polymer depth vs. temperature was made (Fig. 1.14). As evident from the table there was no impregnation at those spots which did not get heated above 140 °F. Also, core samples from those spots with temperature above about 190 °F had no polymer on top (probably due to monomer loss from evaporation).

In order to achieve impregnation to a specified depth, a minimum curing temperature of 125 °F (4,7) must be reached at this depth. To reach this temperature different curing time is required for different curing surface temperature. It could be seen from the result that apparently at 140 °F the temperature right below the surface of the concrete slab did not have enough time to reach

125 °F. Thus, at a surface temperature of 140 °F if a longer period of curing time was allowed for the temperature inside the slab to reach 125 °F to initiate polymerization (as long as the monomer could be protected from evaporating) polymerization of monomer could be achieved. It is obvious from Fig. 1.14 that the effect of curing temperature on the polymer depth becomes less significant once polymerization is initiated. There is a gradual decrease in the slope of the curve.

TABLE 1.14

POLYMER DEPTH VS. TEMPERATURE

Surface Temperature °F	Polymer Depth in
205	1.10
190	1.06
185	0.98
∿ 150	0.47
∿ 140	0

Investigation of Polymer Depth with Respect to Monomer Loading

Although this investigation was already done in the laboratory, it was repeated outside with a little modification to simulate field applica;tion better. The modification involved the soaking time. In the laboratory the monomer mix was allowed to soak for as long as it took for the sand to be dried enough with each monomer loading. Here the same soaking time (4 hours) was allowed for each monomer loading.

Experimental Design and Procedure

The experiment was done exactly as in the previous section using 0.6, 0.8 and 1.0 lb/ft^2 monomer mix loading and a soaking time of 4 hours.

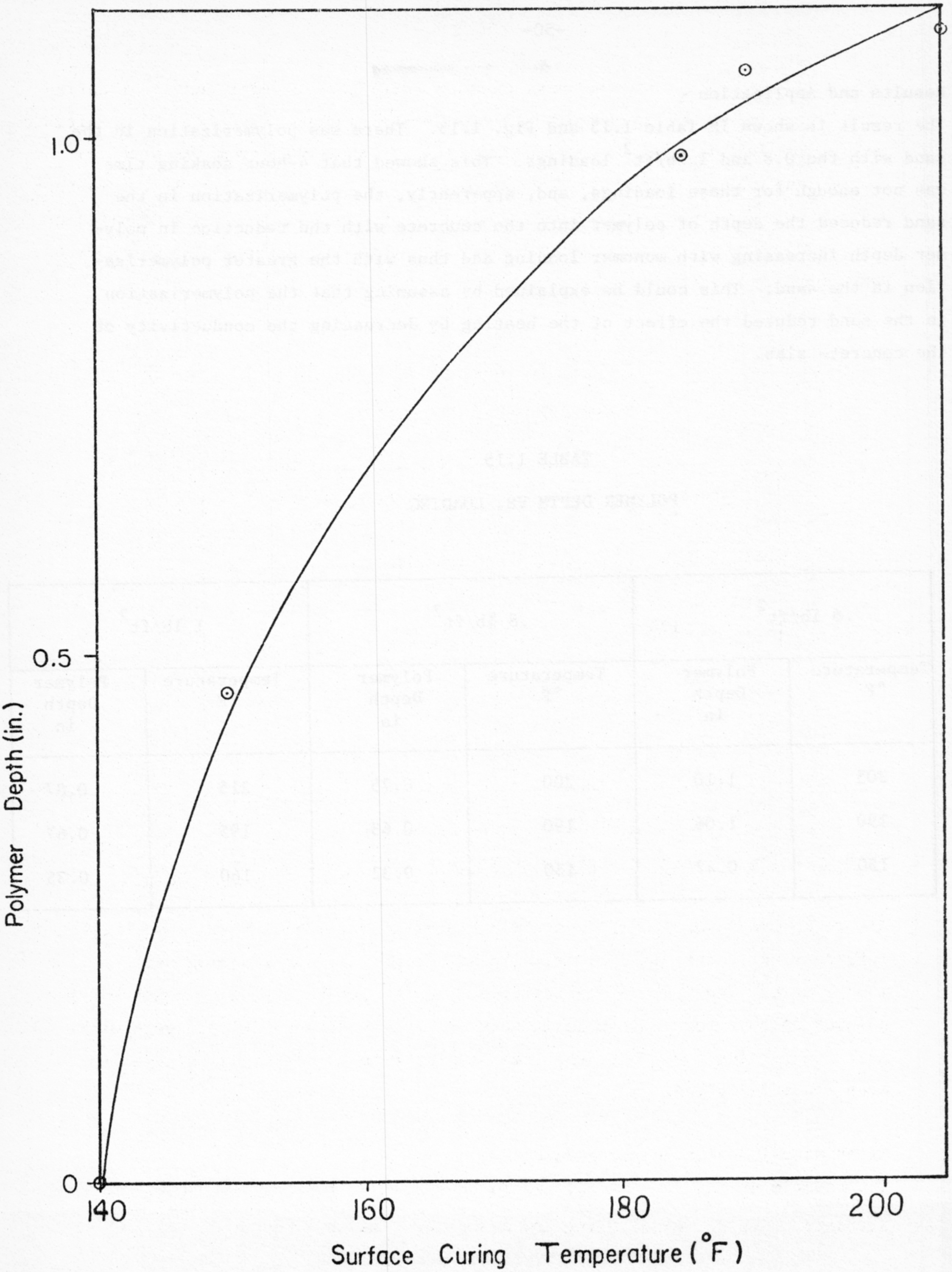


Figure 1.14 Polymer Depth as a Function of Curing Temperature

Results and Application

The result is shown in Table 1.15 and Fig. 1.15. There was polymerization in the sand with the 0.8 and 1 lb/ft^2 loadings. This showed that 4-hour soaking time was not enough for these loadings, and, apparently, the polymerization in the sand reduced the depth of polymer into the concrete with the reduction in polymer depth increasing with monomer loading and thus with the greater polymerization in the sand. This could be explained by assuming that the polymerization in the sand reduced the effect of the heating by decreasing the conductivity of the concrete slab.

TABLE 1.15

POLYMER DEPTH VS. LOADING

.6 lb/ft^2		.8 lb/ft^2		1 lb/ft^2	
Temperature °F	Polymer Depth in	Temperature °F	Polymer Depth in	Temperature °F	Polymer Depth in
205	1.10	200	0.75	215	0.87
190	1.06	190	0.63	195	0.67
150	0.47	150	0.32	160	0.35

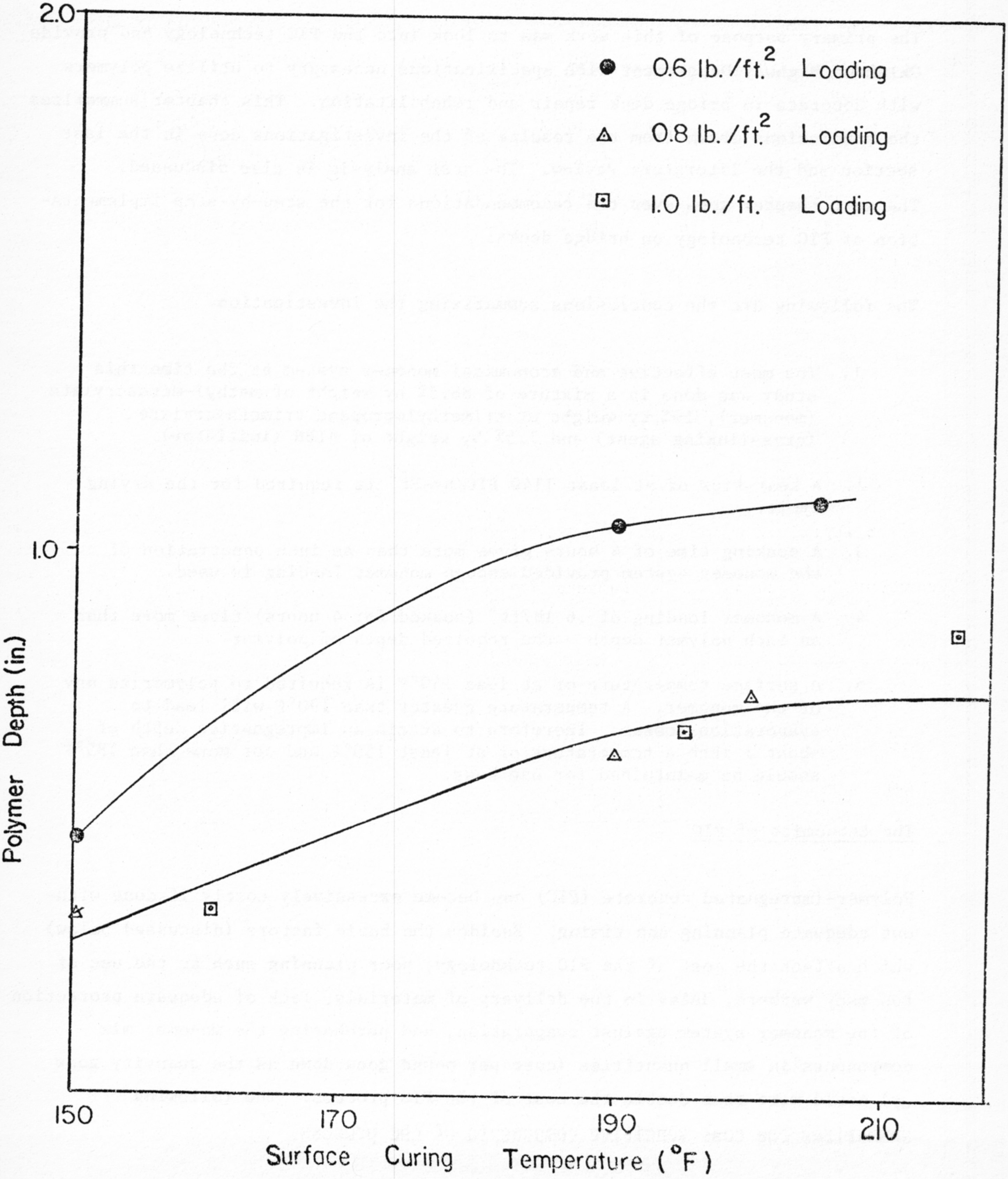


Figure II.15 Polymer Depth as a Function of Curing Temperature and Monomer Loading.

CONCLUSIONS

The primary purpose of this work was to look into the PIC technology and provide Oklahoma Highway Department with specifications necessary to utilize polymers with concrete in bridge deck repair and rehabilitation. This chapter summarizes the conclusions drawn from the results of the investigations done in the last section and the literature review. The cost analysis is also discussed. The next chapter goes over the recommendations for the step-by-step implementation of PIC technology on bridge decks.

The following are the conclusions summarizing the investigation.

1. The most effective and economical monomer system at the time this study was done is a mixture of 88.5% by weight of methyl-methacrylate (monomer), 10% by weight of trimethylopropane trimethacrylate (crosslinking agent) and 1.5% by weight of AIBN (initiator).
2. A heat flux of at least 1140 BTU/hr-Ft^2 is required for the drying cycle.
3. A soaking time of 4 hours gives more than an inch penetration of the monomer system provided enough monomer loading is used.
4. A monomer loading of .6 lb/ft^2 (soaked for 4 hours) tives more than an inch polymer depth - the required depth of polymer.
5. A surface temperature of at leas 140°F is required to polymerize any of the monomer. A temperature greater than 190°F will lead to evaporation losses. Therefore to attain an impregnation depth of about 1 inch a temperature of at least 150°F and not more than 185°F should be maintained for one hour.

The Economics of PIC

Polymer-impregnated concrete (PIC) can become excessively costly if done without adequate planning and timing. Besides the basic factors (discussed below) which affect the cost of the PIC technology, poor planning such as the use of too many workers, delay in the delivery of materials, lack of adequate protection of the monomer system against evaporation, and purchasing the monomer mix components in small quantities (cost per pound goes down as the quantity goes up) could more than double the cost of the PIC process. The following summarizes the cost sensitive components of the process.

1. Monomer System

Any of a number of monomers could be used for the partial impregnation of bridge decks. The fact that the polymer-impregnated concrete (PIC) becomes excessively costly if an expensive monomer is used is the primary factor governing the selection of a monomer. Also the use of more than the necessary amount of the initiator and crosslinking agent could significantly increase the cost. An optimum monomer loading (the least monomer loading that gives the required polymer depth) should be used. The use of a higher loading requires more soaking time (more working hours) and thus adds to the cost.

2. Drying Time

There is an optimum drying time (the least number of hours) required to give a certain polymer depth. Increasing this time means more working hours and thus adds to the cost. In our investigation we found a drying time of 6 hours is sufficient for the polymer depth usually desired in partial impregnation of bridge decks. Previous reports list drying times of anywhere between 8 and 60 hours.

3. Equipment

Equipment is the largest initial cost of the PIC technology. However, most of the equipment (heaters, frame, applicator, temperature monitoring device, gas tank, etc.) could be reused. The more they are used the less the cost of the PIC technology on per unit area basis.

RECOMMENDED FIELD APPLICATION TECHNIQUES

This section summarizes the recommendations for the step-by-step implementation of polymer impregnated concrete on bridge decks. The material is intended to provide Oklahoma Highway Division sufficient information to permit successful field application. The partial impregnation process is composed of the following major steps:

1. Concrete surface preparation.
2. Drying the concrete.
3. Impregnation of the concrete with monomer.
4. Polymerization of the monomer soaked into the concrete.

These various steps would be fully discussed but first essential initial preparation leading to the successful implementation of these steps would be discussed. Due to the difficulties and risks involved in handling large amounts of monomer the concrete bridge deck might have to be divided into and treated in sections. However, it is recommended to purchase and have available all the monomer, crosslinking agent and the initiator needed for the whole area to be treated. A recommended size of each section to be treated is about 256 ft. After deciding on the area of each section, estimations for equipment and material (monomer system) are made.

Equipment

The number of heaters required is estimated. Using our result of 1140 Btu/hr. ft^2 and assuming propane gas fired heaters (Model DH 50) would be used, then the number of heaters is estimated as follows:

$$\text{\# of heaters} = \frac{256 \times 1140}{50{,}000\ (.4)} = 15$$

Note: The heaters have an efficiency of 40%. It is recommended to have one or two extra heaters for standby or backup equipment repair.

A rigid frame to support the heaters over the section of the bridge deck to be treated is next constructed and provided with covers (made of an insulating material) on the sides and top to shield it from the wind and to keep the heat in. The height of the frame should be kept as low as possible (the distance between the heaters and the surface of the bridge deck varies from about 22" to 26"). It is recommended that the cover for the frame be formed of semirigid material with heat insulating properties, be fire resistant and capable of withstanding exposure to high temperatures (250 to 300°F) without melting or cracking. The enclosure could be provided with wheels to permit moving it from one section to another of the bridge deck.

An applicator connected with rubber tubing to a 25 gallon container (enough to hold all the monomer mix needed for each section) is next constructed. The applicator and container should be clean and free of rust and other impurities. They must not be made of copper or copper alloys, or plastics which are attacked by the monomer. A sand spreader for screening the sand to about 3/8" is constructed.

A temperature sensoring device and thermocouple wires need to be purchased. A good supply of sand and propane gas should always be at hand.

Materials

Next, it is necessary to estimate the amount of the monomer mix and the amount of the various components of the monomer mix required for each section to be treated. Using 0.6 lbs/ft^2 of monomer mix loading on a 16' x 16' section:

$$\text{Amount of monomer mix} = 0.6\ \text{lbs/ft}^2 \times 256\ \text{ft}^2$$
$$= 153.6\ \text{lbs}$$

$$\text{Amount of MMA} = (0.885\ \text{wt. fraction})\ (153.6\ \text{total wt})$$
$$= 135.94\ \text{lbs}$$
$$= 61716.76\ \text{g}$$
$$= 64.97\ \text{liters}$$
$$= 17.20\ \text{gallons}$$

Amount of TMPTMA =
(0.10 wt. fraction) (153.6 total wt.) = 15.36 lbs
= 6973.44 g
= 6.64 liters
= 1.75 gallons

Amount of AIBN =
(0.015 wt. fraction)(153.6 total wt.) = 2.30 lbs
= 1046.0 g

The MMA and TMPTMA must meet the following specifications:

<u>MMA</u>

Formula	$CH_2 = C(CH_3)\ COOCH_3$
Inhibitor	12 - 25 p/m hydroquinone (HQ)
Molecular weight	100
Assay (Gas Chromatography), %	99.8 minimum
Density	0.95 g/c.c
Boiling Point	212°F (100°C)
Flash Point (Tag, ASTUM D1310)	55°F (13°C)

<u>TMPTMA</u>

Formula	$(CH_2 = CCH_3\ COOCH_2)_3CCH_2CH_3$
Inhibitor	100 p/m hydroquinone (HQ)
Assay %	95.0 minimum
Density	1.06 g/cc
Flash Point (Cleveland, ASTM D92)	Greater than 300°F (149°C)

The formula of the AIBN, 2,2-azobis-(isobutyronilrile) is $C_8H_{12}N_4$.

Storage

The MMA and TMPTMA shall be stored in their original shipping containers or in other clean, uncontaminated containers. Maximum storage temperature shall not exceed that recommended by the manufacturer or 85°F, whichever is lower. The storage area shall provide protection from direct sunlight, fire hazard and oxidizing chemicals. Adequate ventilation shall be provided to prevent build-up of monomer vapor in the storage area. The storage containers may be equipped with electrical ground cables for additional precaution.

The various steps would now be discussed.

Concrete Surface Preparation

For successful impregnation the concrete must be clean and rid of compounds that might reduce its permeability. Curing compounds such as latex, resin base and linseed oil and contaminants such as oil, asphalt, and rubber are removed by sandblasting. Leaves, grass and other trash should be swept from the surface of the concrete bridge deck.

Drying

After the concrete surface to be treated has been cleaned, it is uniformly covered with a 3/8" thick layer of sand using the sand spreader to screen it to the required height. The sand need not be dry, but it must be composed of low-absorptive particles passing a No. 16 seive and with not more than 5% passing a No. 100 seive. The enclosure is moved over the sand-covered concrete surface. Temperature sensors (thermocouples taped or bonded with epoxy to the concrete) are uniformly located on the concrete surface to monitor concrete temperatures. The temperature on the surface of the bridge deck is gradually raised up to about 260°F (at a rate not greater than 2 degrees F. per minute). The concrete is then dried at this temperature for 6 hours. Effort should be made to maintain uniform temperature distribution on the concrete surface during the heat up and drying period to minimize differential expansion of the concrete which might lead to cracking. After drying, the concrete is cooled down to 100°F or less. A recommended practice is to dry the concrete and leave it overnight to cool down. The enclosure is left on the bridge deck to prevent moisture from reentering the concrete which would otherwise necessitate repeating the drying cycle.

Monomer Mixing

After the required amounts have been estimated the MMA and TMPTMA are measured into a closed mixing vessel. They are mixed together either by agitating with an explosion proof electric mixer or one powered by an explosion proof compressed air motor. Another technique is to stir the mixture with a wooden rod or bubble low-pressure compressed air through the mixing vessel. The MMA and TMPTMA could be purchased pre-mixed and stored for short periods prior to use. The catalyst (AIBN) is thoroughly mixed with the monomer system just before applying the monomer to the bridge deck.

Impregnation

The monomer mix is then applied using the applicator to provide a fine spray and to make sure that the sand is uniformly saturated to a slight excess. A polyethylene membrane is placed over the monomer-saturated sand to reduce evaporation and a 4-hour soaking time should be allowed. It is recommended that the monomer application be made during the time period sunset to sunrise to reduce the chances of premature polymerization by solar radiation. A polyethylene membrane could be used to shield the treated surface (it should not be in direct contact with the monomer-saturated sand) from solar radiation. After 4-hour soaking time, a final inspection of the sand must be made to make sure the sand is not too wet or too dry. As a guide, the sand should be slightly damp to the touch without free-standing monomer.

Polymerization

Polymerization of the monomer impregnated into the concrete is done by gradually increasing the treated concrete surface temperature to at least 150°F and less than 185°F. This temperature range is maintained for an hour. The equipment and procedures used for this step are the same as for the drying cycle.

Core Samples

Small diameter test cores are taken from the treated area and inspected to determine depth of polymer. A polymer depth of at least an inch is recommended. The grinding action of the core drill may make visual inspection difficult. In such cases the core could be etched by dilute acid - one part bench acid to five parts water. The core is left in the acid for a minute or two. A non-destructive resistivity measurement made from the surface of the concrete was developed in this project and can be used to determine the polymer depth in partial impregnated concrete. This procedure is discussed in a separate section. This procedure would be preferable to the core type test.

Safety Considerations

Special precautions must be taken in handling MMA. Safety manuals are available from the manufacturers and suppliers. This must be obtained and studied thoroughly before use of the material is attempted. MMA liquid is volatile, and flammable, and slightly toxic. MMA vapor forms an explosive mixture with air and must be protected from excessive heat, sparks and other sources of ignition. There should be no smoking in and around storage areas and other areas where MMA is being used. Mixing should be done in shaded ventilated areas free of ignition sources. The mixing vessels should be grounded to prevent static electricity sparks. Metal stirring rods in metal containers should be avoided. MMA is toxic if taken internally. Eyes are sensitive to the monomer and protective goggles should be worn. MMA may irritate sensitive skin. Rubberized gloves, aprons and boots should be worn to protect personnel. Skin exposed to MMA should be promptly washed with soap and water. The monomer system should be used once the catalyst (AIBN) is added to prevent bulk polymerization. If extended storage of catalyzed monomer system is necessary, it should be done at a very low temperature (about 0°F) and protected from sunlight. If monomer disposal is necessary, it can be done by either incineration or bulk polymerization. Bulk polymerization is done by adding a catalyst and a promotor or heat to the monomer in open top containers and allowing the monomer to polymerize. The resulting inert polymer can be disposed of like any other material.

MEASUREMENT OF DEPTH OF IMPREGNATION OF POLYMER IMPREGNATED CONCRETE

A. Introduction

Previous studies have indicated a penetration depth of 3/8 to 1 inch of PIC appears adequate to prevent chloride penetration into the concrete and subsequent corrosion of reinforced steel. However, it is not easy to control and measure the penetration depth during the construction of a partial PIC pavement.

In appearance, the polymer inpregnated concrete is very much like conventional concrete. But, upon close inspection PIC may be distinguished by the presence of polymer impregnation occurred is a little darker than the rest of the concrete.

There are several ways that have been used to determine the depth of polymer in PIC:

(1) By cutting the slab or taking a core sample to get the visual depth by seeing the color difference between the impregnated layer and the untreated concrete.

(2) By water absorption test on the cutting surface. Water absorption in the impregnation region decreases as much as 95%.

(3) By acid etching. The core sample is soaked in the diluted HNO_3 or HCl solution for one to two minutes. The acid will etch the unimpregnated concrete (making a darker color) and will not etch PIC.

Methods (1) and (2) are widely used to measure the depth of polymer in PIC. However, these methods are destructive and time consuming. It is desired that a nondestructive testing method be developed for this purpose.

This section describes a study on the development of a new, nondestructive method for impregnation depth determination. This method involves the measurement of the electrical resistivities of different locations on the PIC surface. The resistivity data are treated by an integral method to determine the penetration depth of polymer. Theoretical backgrounds and experimental procedures will be given in the next two chapters.

B. Theory and Literature Review

The Theory of the Four-Electrode Resistivity Method

This theory is illustrated in Figure 1.16, and the equation for resistivity will be derived here.

The four electrodes are equally spaced at distance a. If there is a hemispherical symmetry at radius r from A or D, the current density at distance r from A or D will be equal to the current divided by the durface area of hemispher, or = $I/2\pi r^2$. By ohm's law

$$\frac{dv}{dr} = \frac{I}{2\pi r^2}\rho \tag{1}$$

$$\Delta v = \int_{r_1}^{r_2} \frac{I\rho}{2\pi r^2}\,dr = \frac{-I\rho}{2\pi}\left(\frac{1}{r_2} - \frac{1}{r_1}\right) \tag{2}$$

Let Δv_1 be the potential difference between electrode B and C due to the current entering from A, $r_2 = 2a$, $r_1 = a$

$$\Delta v_1 = \frac{-I\rho}{2\pi}\left(\frac{1}{2a} - \frac{1}{a}\right) = \frac{I\rho}{4\pi a} \tag{3}$$

Similarly, let v_2 represent the potential difference between electrode B and C due to the current leaving at electrode D,

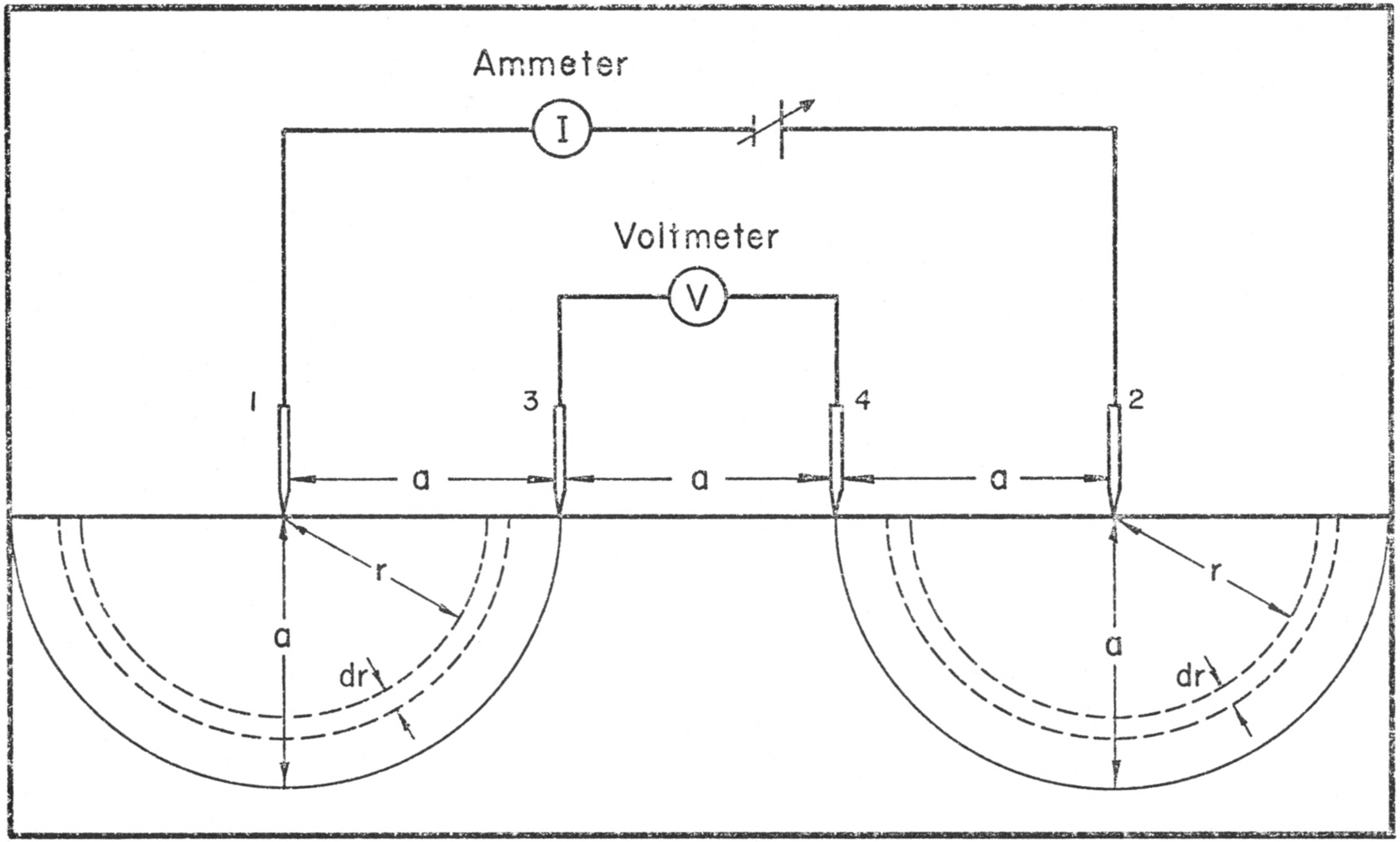
$$\Delta v_2 = \frac{-I\rho}{2\pi}\left(\frac{1}{2a} - \frac{1}{a}\right) = \frac{I\rho}{4\pi a} \tag{4}$$

so the total potential difference between electrode B and C,

$$\Delta v_{\text{total}} = \Delta v_1 + \Delta v_2$$

$$= \frac{I\rho}{4\pi a} + \frac{I\rho}{4\pi a}$$

$$= \frac{I\rho}{2\pi a} \tag{5}$$



a = distance between electrodes; r = distance from electrode A or D

I = current in circuit

Δv = potential difference between electrodes B and C

FIGURE 1.16 Theory of the Four-Electrode Resistivity Method

Hence,

$$\rho = 2\pi a \frac{\Delta v_{total}}{I} = 2\pi aR \tag{6}$$

This is the equation used in the four electrode methods to measure the average resistivity from the surface to a depth which equals the spacing between the electrodes. As the electrode spacing is expanded to involve greater depth, the bottom of the hemispherical zones may involve layers of differing electrical resistivities. This produces a trend toward lower or higher overall resistivity and gives an indication of depth to the layer producing the resistivity change.

The Electrical Resistivity of Concrete

Hammond and Robson (22) found that the electrical resistivity of concrete is highly dependent upon the moisture content. The investigation of electrical resistivity also showed that "moist" concrete is essentially an electrolyte having a resistivity of the order of 10^4 ohm-cm, a value in the range of semiconductors. The oven-dried concrete at 105°C was found to have a resistivity of the order of 10^{11} ohm-cm, a good insulator (23). The water content of "moist" concrete was not stated in their experiment.

This large increase in resistivity of concrete on removal of water is interpreted to mean that electric current is conducted through moist concrete essentially by ionic conduction by ions in the evaporable water. It can therefore be expected that any increase in water and ions present decreases the resistivity of concrete.

Henry (24) found that the electrical resistivity of concrete increases with age and with decreasing water-cement ratio. Figure 1.17 shows the resistivity variation of a fresh portland cement concrete.

The Electrical Resistivity of Polymer

The electrical resistivity of most polymers is primarily influenced by the temperature and degree of polymerization, while being relatively independent of molecular weight and degree of crystallinity. Type and percentage of fillers are known

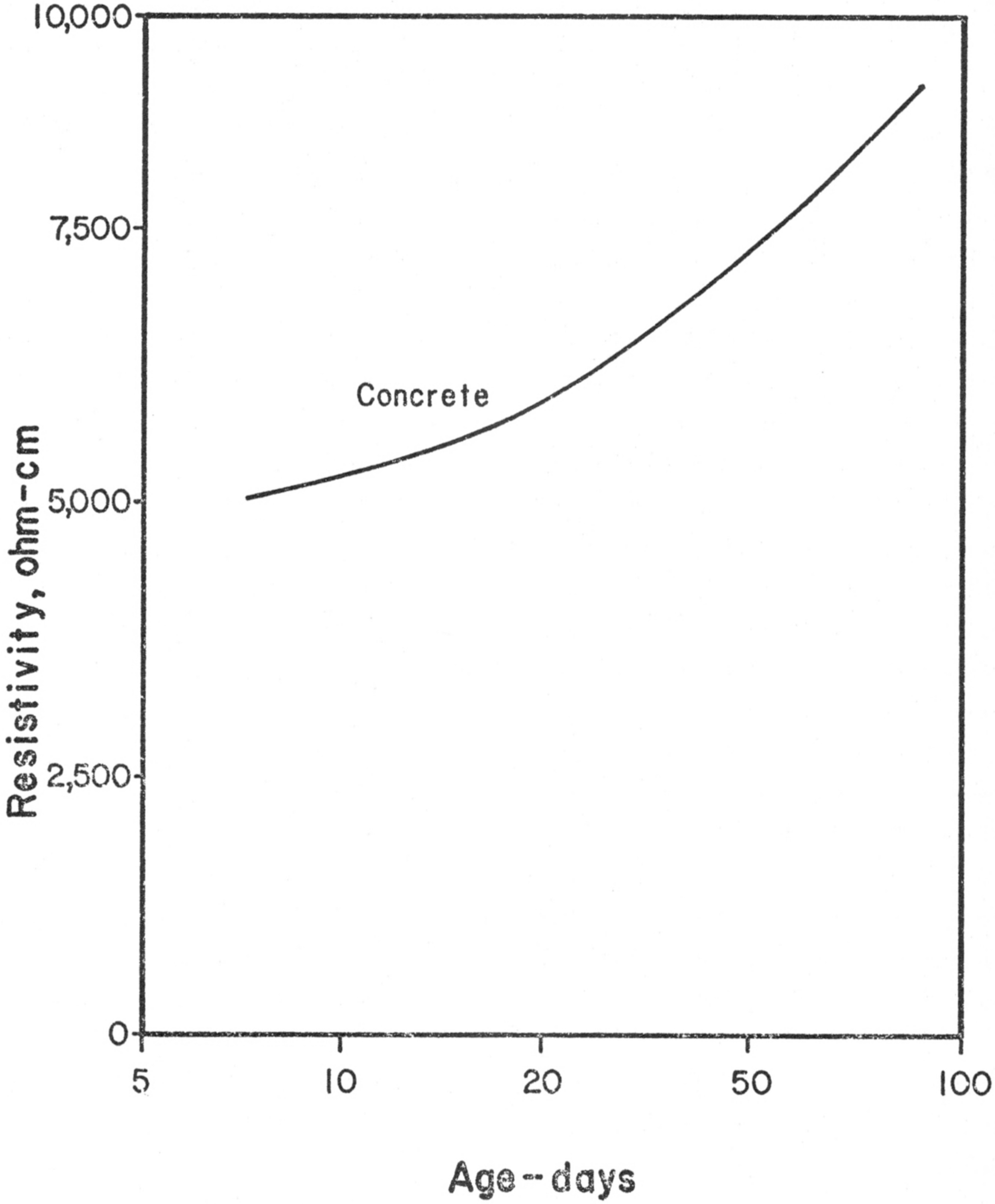


FIGURE 1.17 Influence of Prolonged Moist Curing on Resistivity of Concrete(25)

to affect the transport of electric currents in polymers. There are other factors, for instance, polarity and impurity, also affect the resistivity of polymer.

In this experiment, methyl methacrylate was used as the material of impregnation. Polymethyl methacrylate has a resistivity of 10^{14} ohm-cm, at 25% RH, 23°C (25).

Moore Cumulative Curve Method of Depth Determination

Moore used this method to investigate the thickness of concrete pavement and rebar location. The basic theory of the four electrode resistivity method has been discussed earlier. Using Equation 6, $\rho = 2a\pi v/I$, the resistivity can be calculated. The nature of the test is that the effective depth is equal to the electrode spacing for a particular setting of the electrodes.

Moore set the four electrodes at one inch spacing for the initial readings of current and potential change and increased the spacing in one inch increments for successive readings extending to a total depth of three to six inches below the bottom of the pavement.

Concrete pavement has a resistivity which usually differs from that of the underlying soil or base layers and the reinforcing steel.

Figure 1.18 shows data for tests made on a reinforced concrete pavement. The resistivity values are plotted against electrode spacing or depth as shown by the dashed-line curve. The solid-line curve is a plot of the cumulative data from the dash line curve. The first point on the solid line is the same value as the first point of the dashed-line curve. The second point is the sum of the resistivities for the first and second points, the third point is the sum of the resistivities for the first three points, etc. Using a constant increment of depth, i.e., one inch, the solid-line curve constitutes a graphical integration of the dash-line curve. The straight lines which are combined with cumulative data points give the intersections which indicate the depth of different layers. Obviously, the downward trend of resistivity is due to the lower resistivity of the sand, gravel layer, and reinforcing steel.

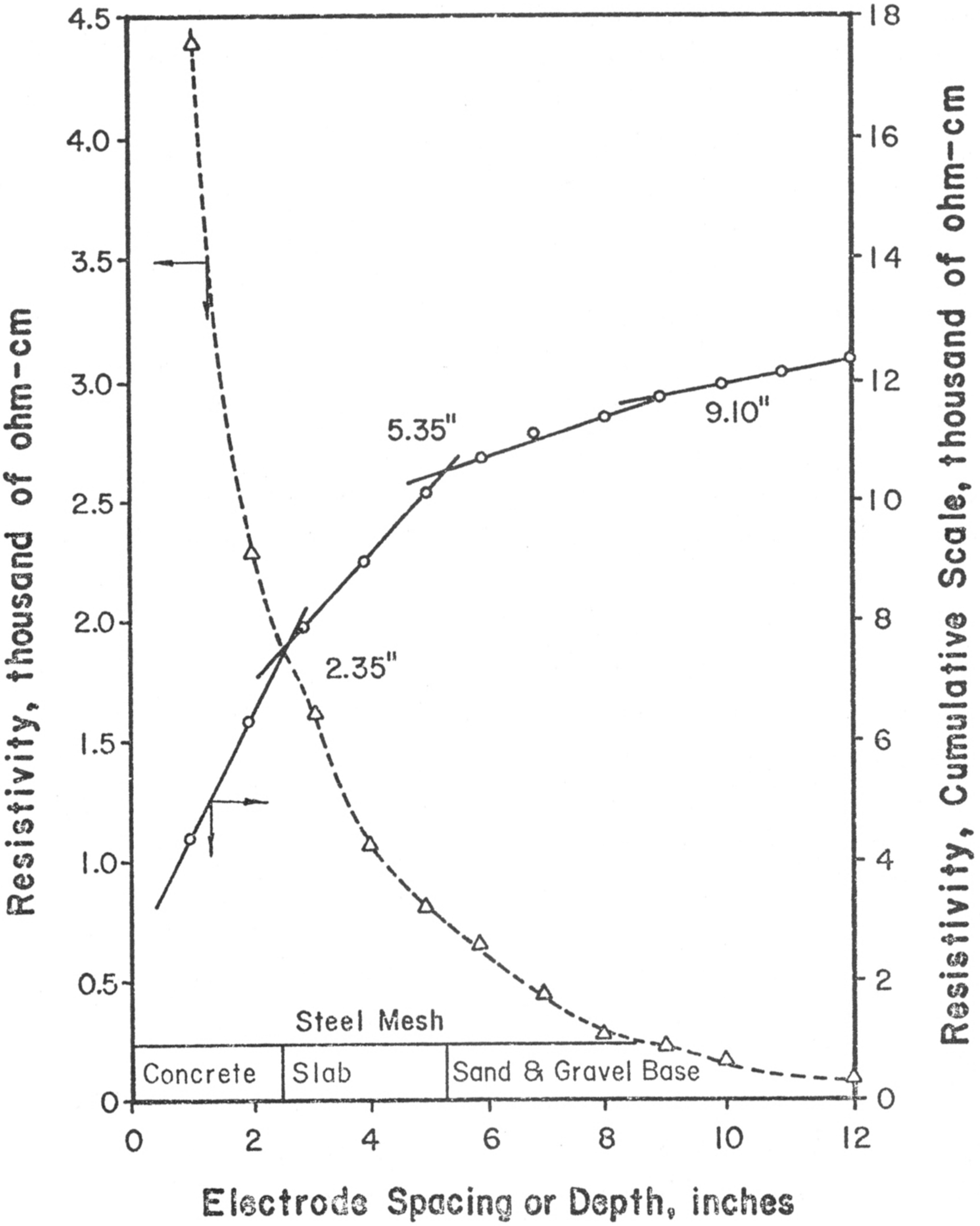


FIGURE 1.18 Earth-Resistivity Test over Reinforced Concrete Slab - 5 inches Thickness on Sand and Gravel Base.(26)

Moore did 68 thickness measurements of different locations, and the standard error of estimate (SE) is 0.226 inch (the average thickness of the pavement is 9.55 inches).

C. Experimental

Resistivity Measurement (Laboratory Test)

All the PIC slabs had the dimensions 12" x 6" x 7" and had been stored in the laboratory over three months. The resistivity measurements were made using a D.C. current source. The applied voltage ranged from 10 to 90 volts. The apparatus is shown in Figure 1.19. The resistivity measurements were made by applying D.C. voltage to the outside electrodes. An electrometer was used to measure the voltage drop through the known resistance, and a second electrometer was used to measure the electric potential between two inner electrodes.

Theoretically, the current flowing between these electrodes can be indicated directly by an electrometer. The two electrometers interfered with each other and caused a false and unstable reading in current. The Two electrometers connected as in Figure 1.19 eliminated this phenomena. The current was measured by observing the voltage drop across a known resistance.

Since the resistivities of polymer impregnated concretes are high, the known resistance for measuring the current has to be set high to have a meaningful reading of voltage drop across the resistance. The resistance used in this study ranged from 10^5 to 10^7 ohms.

Electrode: The electrodes used in Moore or other methods to measure the concrete and earth resistivity are not suitable in this experiment.

(1) These electrodes are too big in size. In this experiment, the four electrodes sometimes must be placed at less than one centimeter spacing.

(2) Moore's electrodes are plugged with stiff clay to allow a very slow movement of solution to wet the concrete surface. However, this method failed in the test. Another electrode

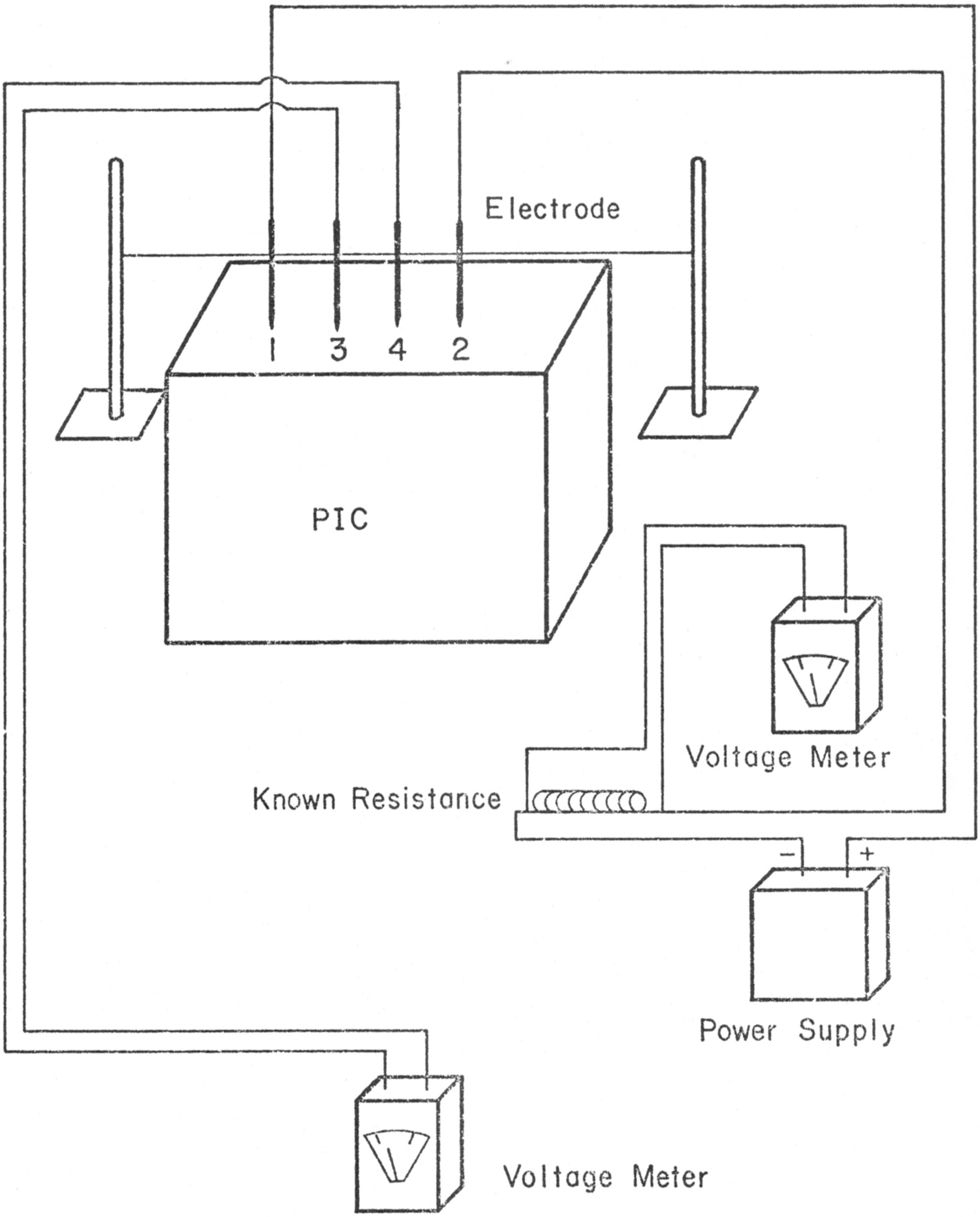


Figure 1.19 Apparatus for Resistivity Measurement.

was made using glass tubing and plugged with a sponge. It was found that $CuSO_4$ solution in this electrode was weeping and causing an unstable reading of voltage drops during the test.

(3) The electrodes can not be inserted into the medium and provide a good contact.

(4) The polymer impregnated concrete has higher resistivity than the earth, which means it is easier to measure the resistivity of the earth.

Due to the factors stated above, an electrode was designed having small size, good contact with PIC surface, and no weeping or flowing of $CuSO_4$ solution occurred near the electrode. A pen-type copper-copper sulfate reference electrode is shown in Figure 1.20.

Resistivity measurements were made with the spacing between electrodes at one to six centimeters in one centimeter steps. The measurement was initiated by marking a point in the central part of the concrete slab, a straight line was drawn through the point and chosen as the center. Four electrodes were placed equidistant about the center point in the straight line. The potential difference between the two inner electrodes was recorded and the voltage drop through the known resistance was measured. The voltage measurements were used with Equation (6) to calculate the resistivity. Resistivity versus depth with Moore's method of depth determination was plotted.

The depth of polymer impregnation was determined visually to compare to the depth measured by resistivity. A curve was marked along the color difference line on the slab which was cut prior to the resistivity measurement and a straight line was drawn to get the average impregnation depth. Sometimes it was difficult to see the slight color difference between the impregnated material and the unimpregnated portland cement concrete.

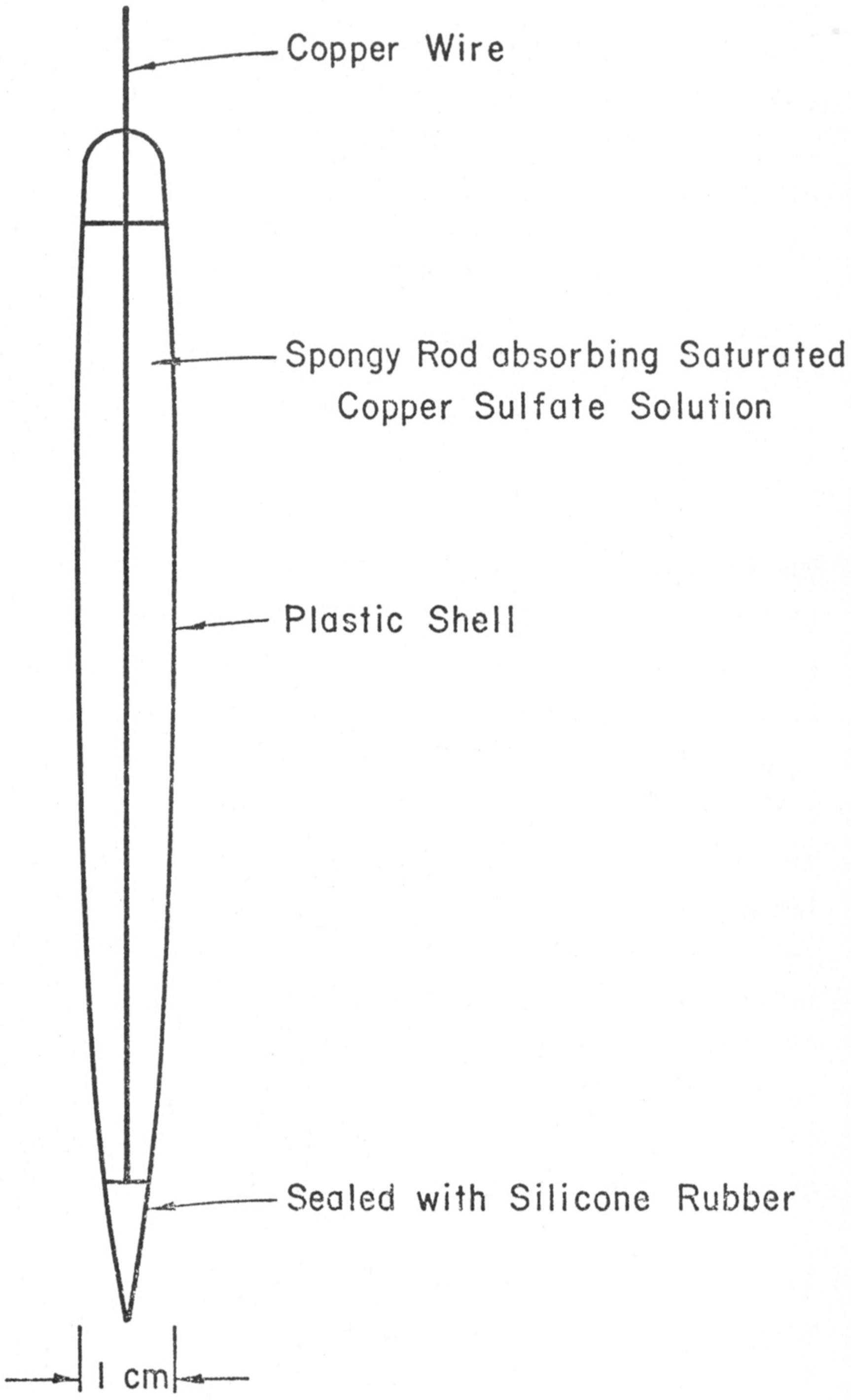


Figure 1.20 Pen-Type Electrode.

Resistivity measurements were also made along the cut cross-section with a constant three centimeter electrode spacing. The electrodes were moved at one centimeter steps measured from the impregnated surface of the slab. This measurement was made in order to determine the depth of polymer impregnation by means other than visual. Figure 1.21 illustrates the resistivity measurement on the cut cross section of PIC.

Polarization may occur during the measurement due to the D.C. current used. This phenomena can be studied by interchanging the current carrying wires which are connected to the positive and negative poles. The results of this test showed there were no significant difference in data when the polarity was reversed.

Resistivity and Moisture Content: Since moisture content affects the resistivity of concrete greatly, the investigation was made on concrete slabs with different moisture levels. An unimpregnated concrete slab was put into the oven to dry for 24 hours and then was wrapped with aluminum foil. It was then cooled to room temperature, and the resistivities were measured at different electrode spacings.

An unimpregnated concrete slab was soaked in water for two weeks, taken out of the water, and wrapped with plastic film except the top surface. As soon as the surface was dry, the resistivity values were recorded as a function of separation between electrodes.

Out-Door Test

Resistivity measurements were also done on two large partial impregnated polymer concrete slabs (12' x 7' x 1') located at North Base. This measurement was made to provide more information on an actual application since the environment was similar to that of the pavement on the bridge decks.

The apparatus for out-door resistivity measurement was slightly modified so that they could be more portable. The modified apparatus is shown in Figure 1.22. With the help of a switch, both the potential drop between the inside electrodes and the current flowing through the outside electrodes could be measured almost simultaneously with only one electrometer.

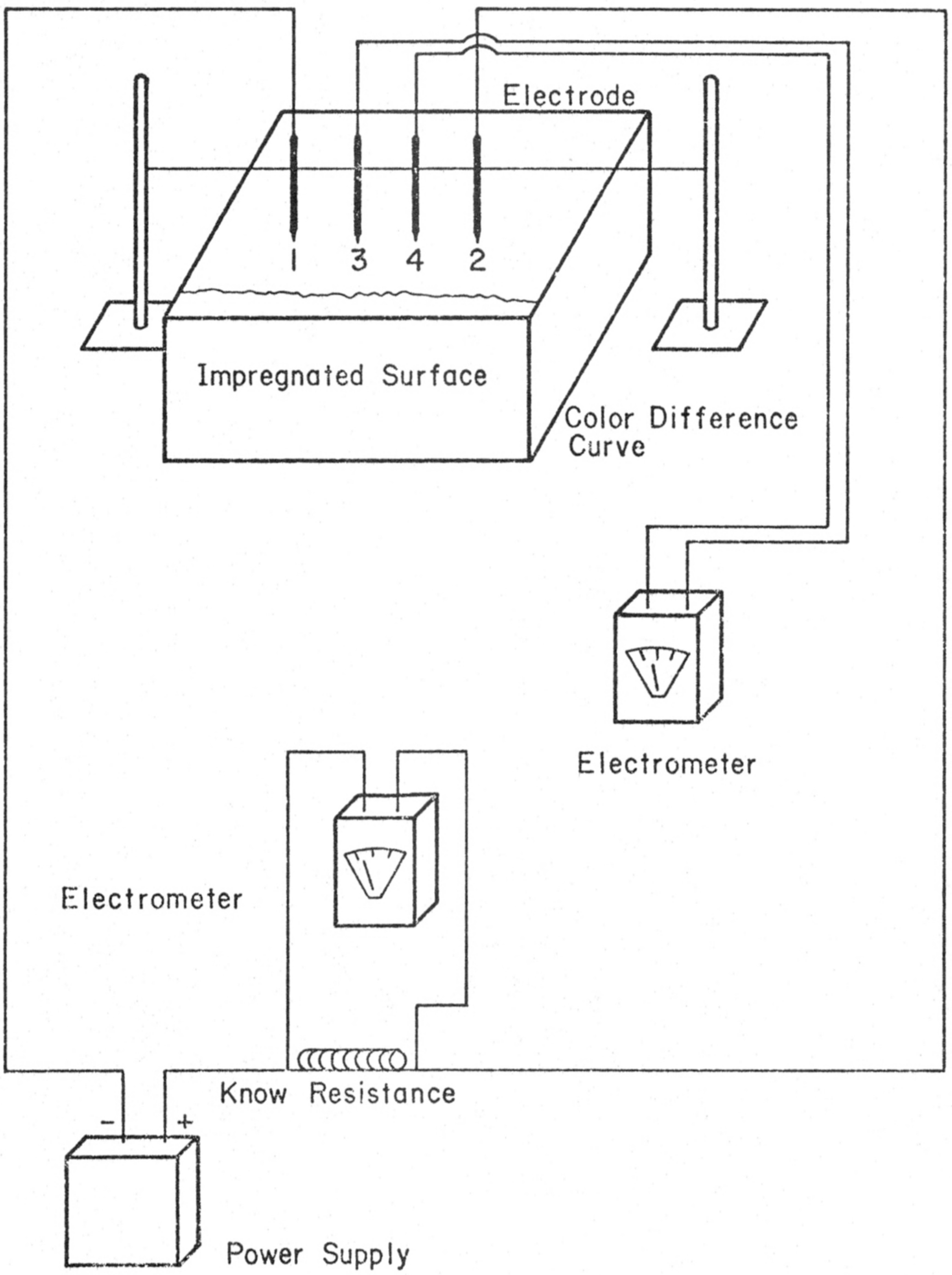


FIGURE 1.21 Resistivity Measurements on Cut Surface (Spacing between electrodes was held constant and measurements were made at various distance from the impregnated surface)

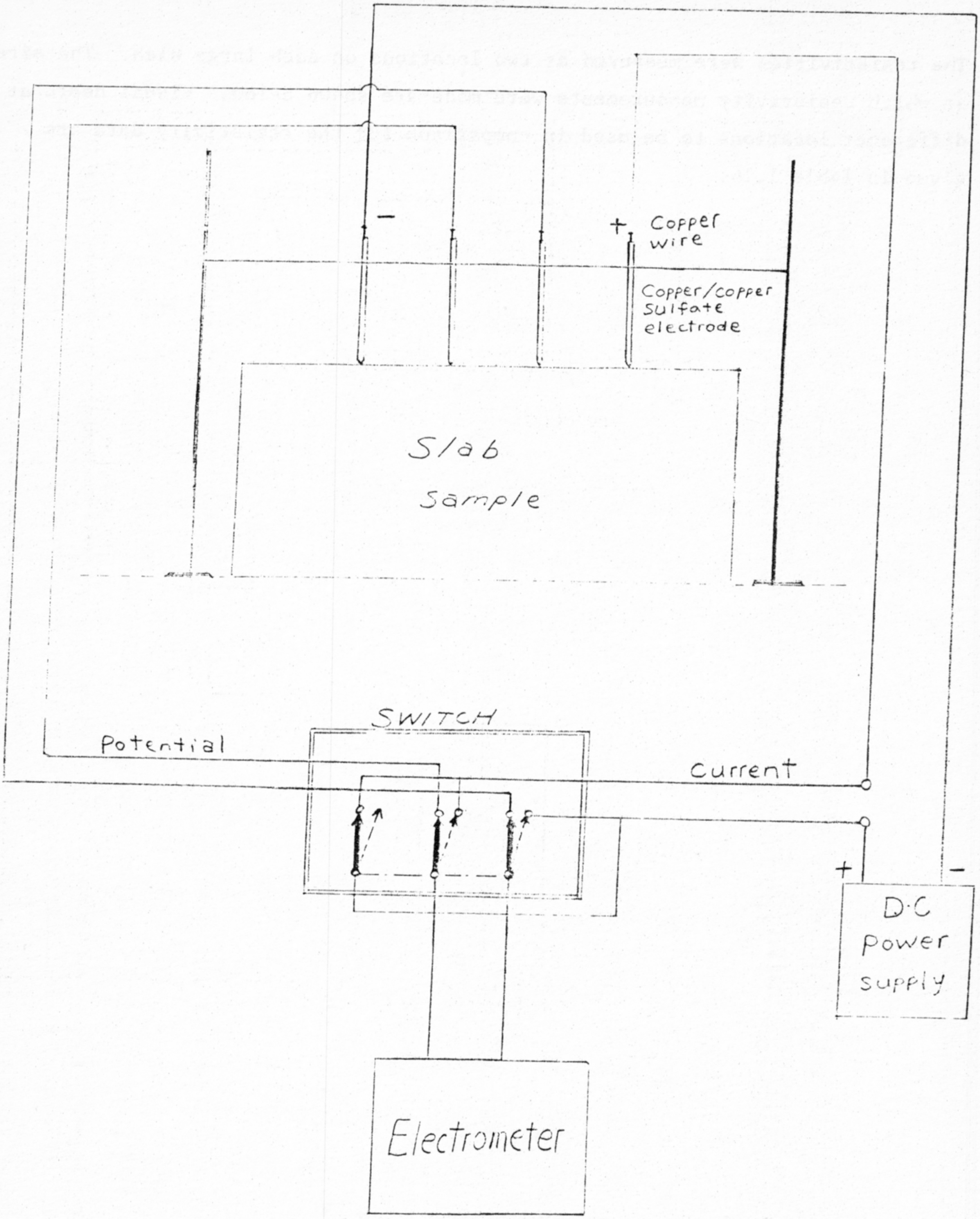


Figure 1.22 Apparatus of Resistivity Measurement.

The resistivities were measured at two locations on each large slab. The sites at which resistivity measurements were made are shown below. Visual depth at differenct locations to be used in comparison for the resistivity data are given in Table 1.16.

TABLE 1.16

	Position	Visual Depth (cm)
Slab No. 1	1	2.8
	2	2.7
	3	2.8
	4	2.5
	5	0.0
	6	1.2
	7	1.0
	8	0.4
Slab No. 2	1	-
	2	1.0
	3	0.8
	4	.05
	5	.9

D. Results

Moore Cumulative Curve Method of Depth Determination

Table 1.17 lists one set of data for resistivity measurements made on a typical slab and show the sum of resistivity. The experimental data for all measurements are in the Appendix.

Resistivities of impregnated slabs as a function of electrode spacing are shown in Figures 1.23 - 1.28. The sum of resistivities are also shown in those figures. According to the Moore Cumulative Curve Method, the intersection of the resistivity sums is indicative of the depth at which the resistivity changes. In the partial impregnated concrete this point should be the depth of penetration of the polymer.

TABLE 1.17

Resistivity and Sum of Resistivity

Electrode Spacing, cm	Resistivity ohm-cm	Sum of Resistivity, ohm-cm
1	2×10^8	2.00×10^8
2	6.7×10^8	8.70×10^8
3	1.5×10^8	1.02×10^9
4	1.3×10^7	1.03×10^9
5	4.5×10^6	1.03×10^9
6	2.0×10^7	1.05×10^9
7	2.5×10^7	1.08×10^9

Slab No. 10B

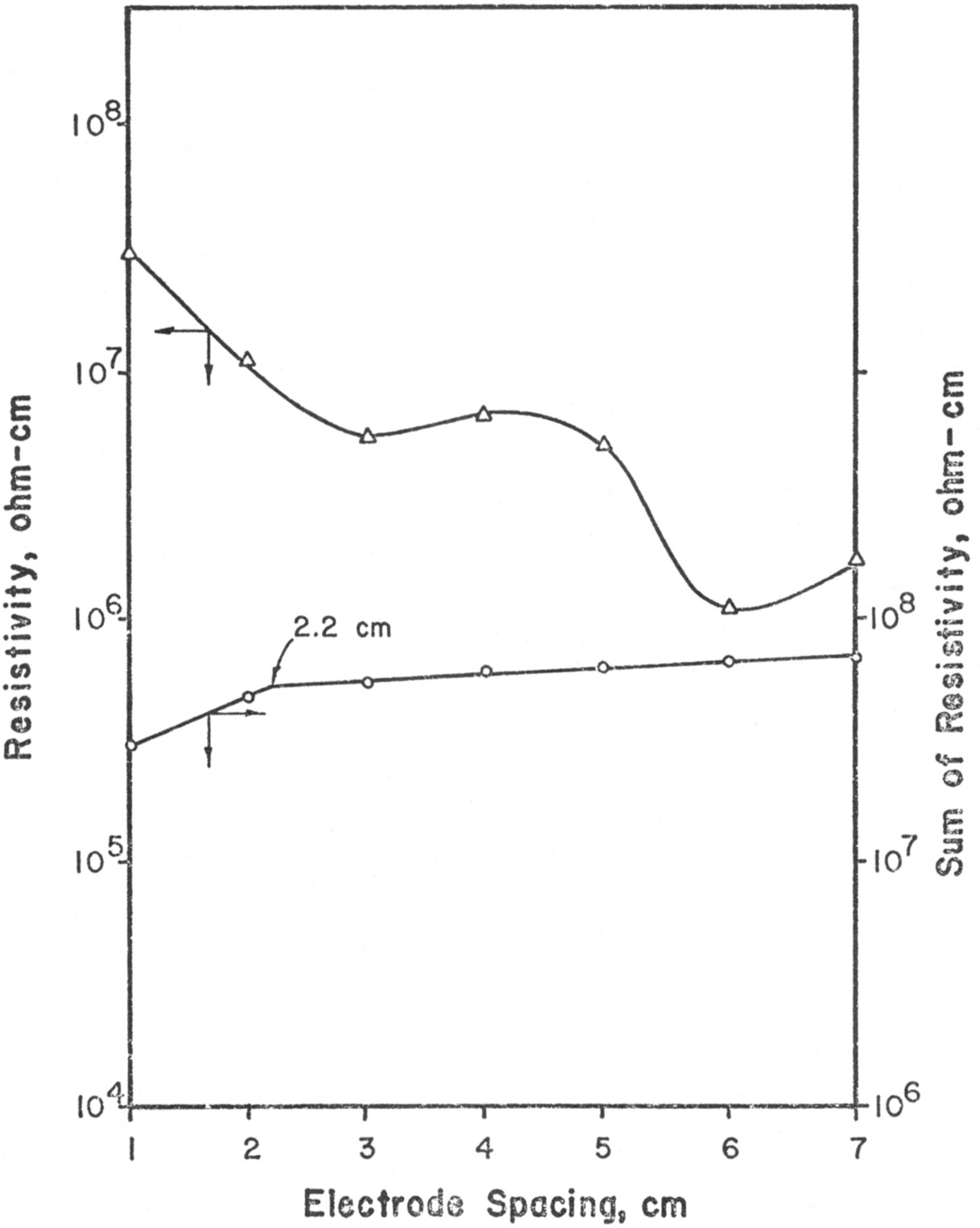


Figure 1.23 Depth Determination by Moore Method

Slab No. 9C, loading: 0.6 lb/ft^2

average visual depth: 2.1 cm

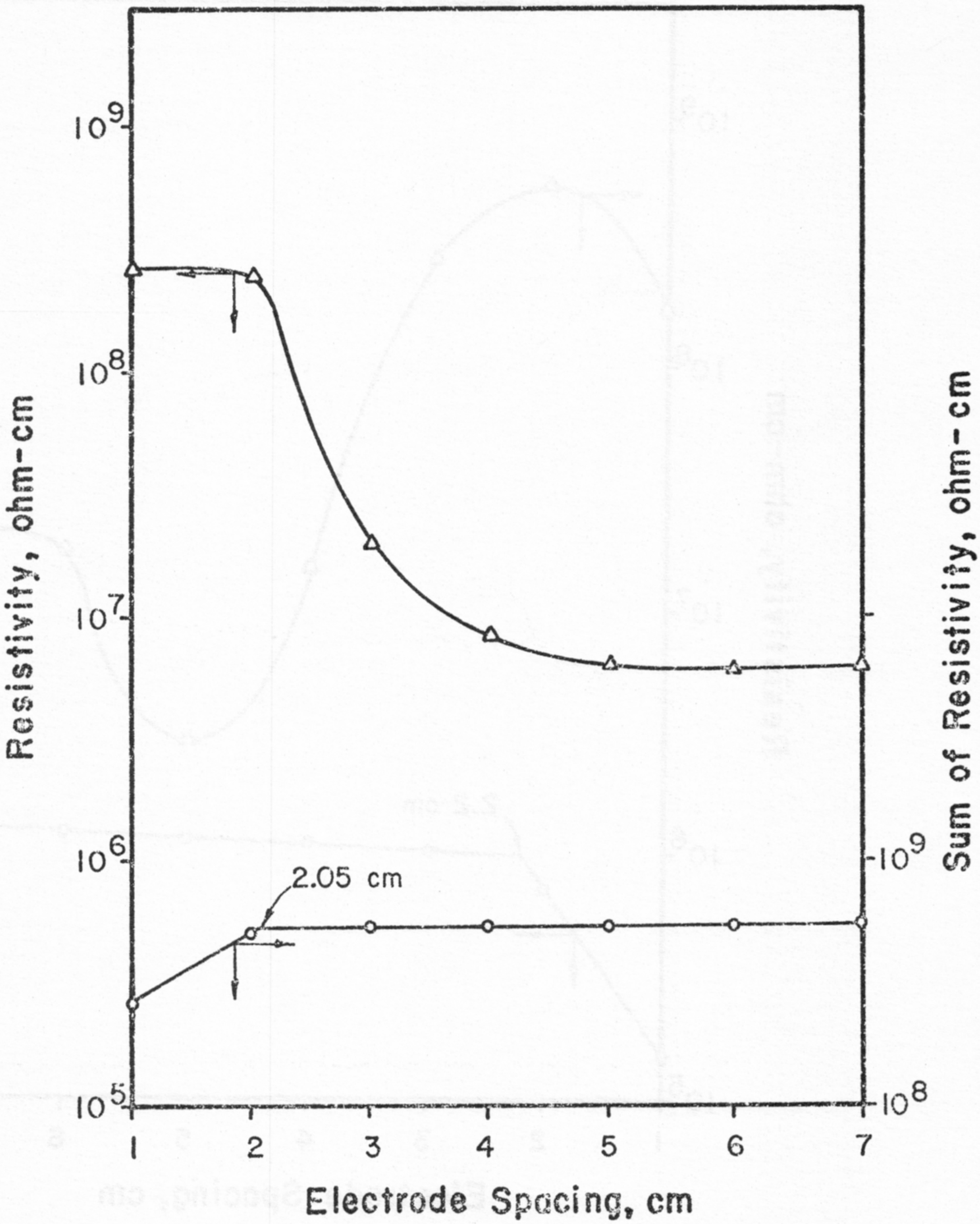


Figure 1.24 Depth Determination by Moore Method

Slab No. 5B, loading: 0.7 lb/ft^2

average visual depth: 2.2 cm

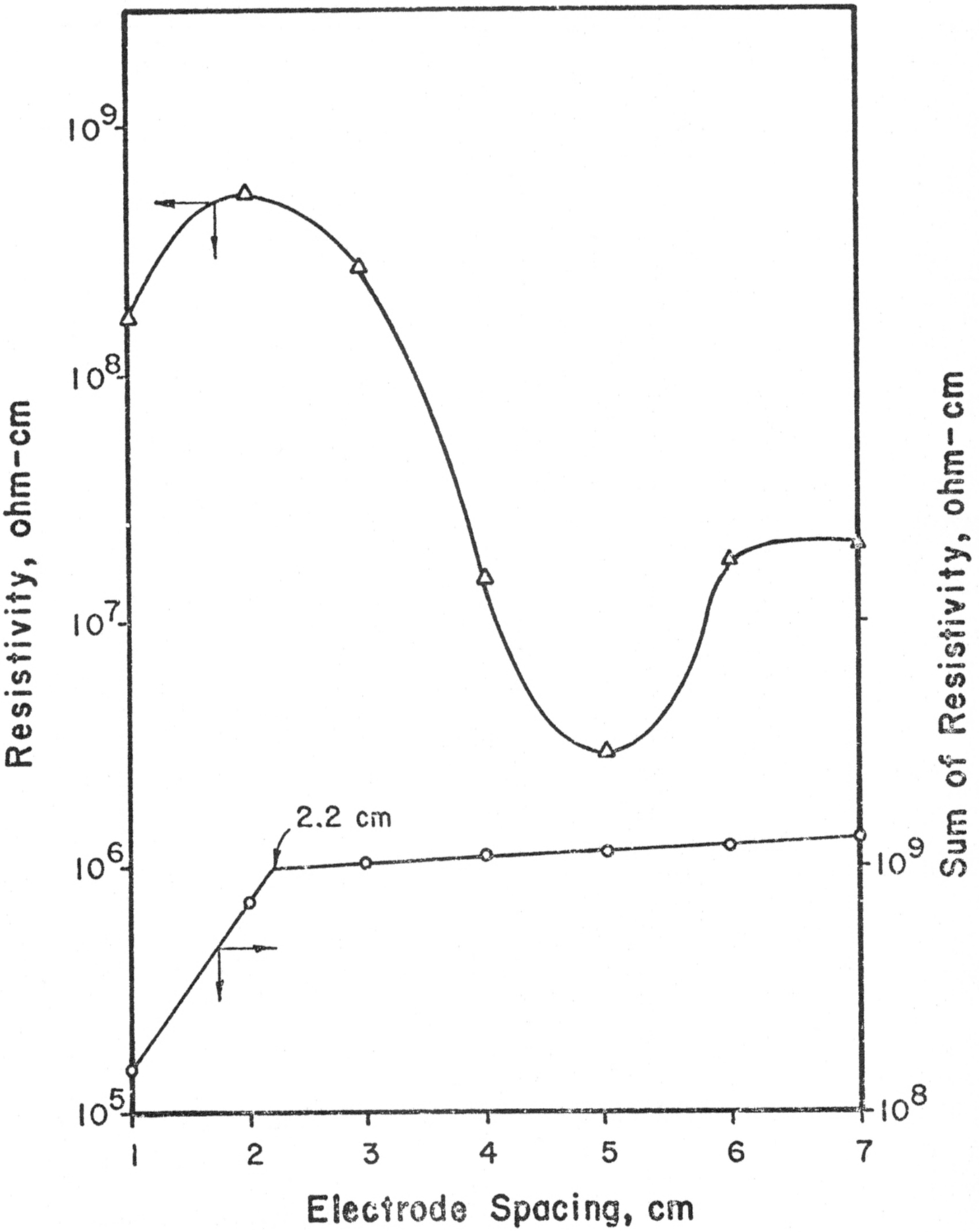


Figure 1.25 Depth Determination by Moore Method

Slab No. 11B, loading: 0.8 lb/ft^2

average visual depth: 2.4 cm

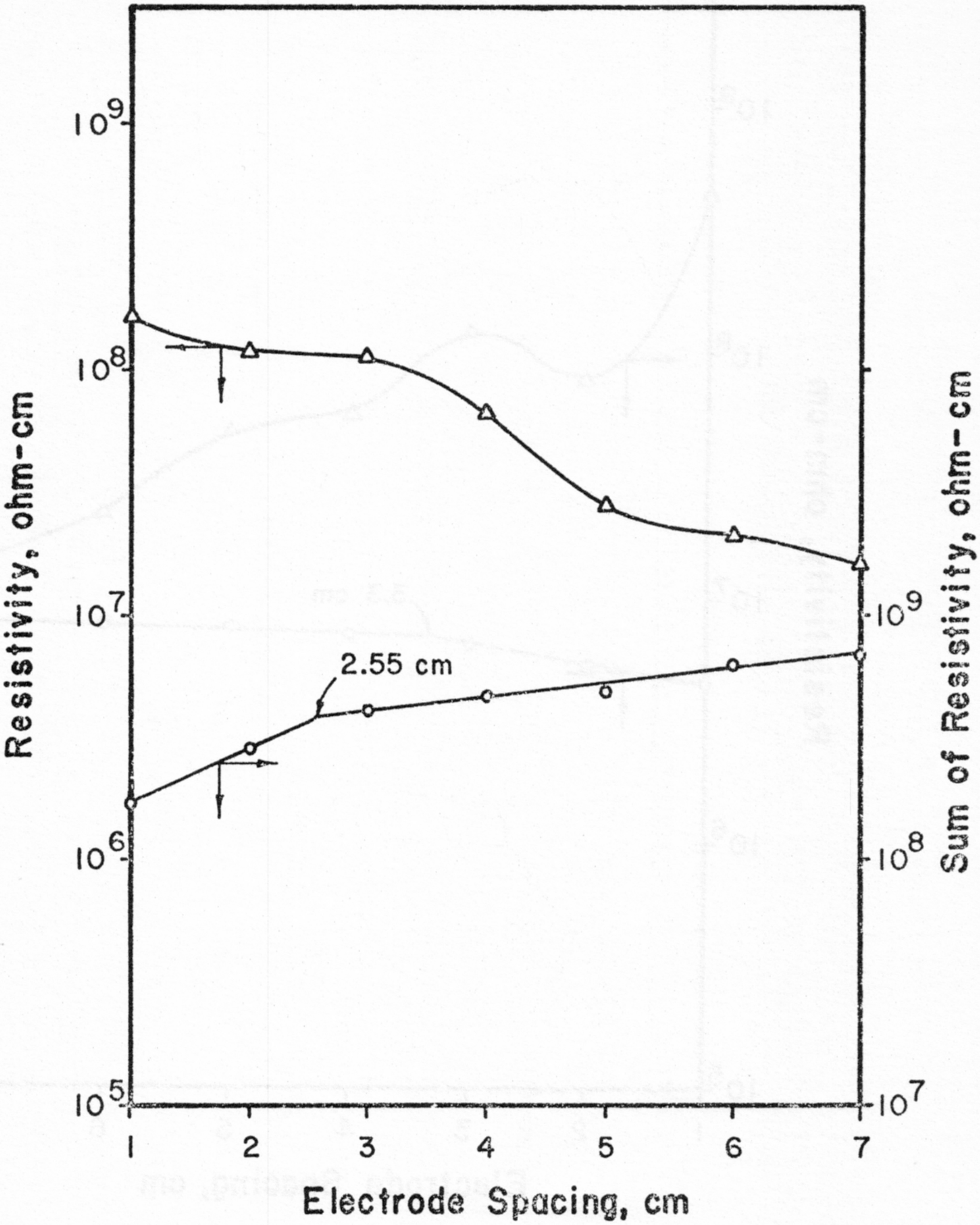


Figure 1.26 Depth Determination by Moore Method

Slab No. 4B, loading 0.9 lb/ft^2

average visual depth: 2.7 cm

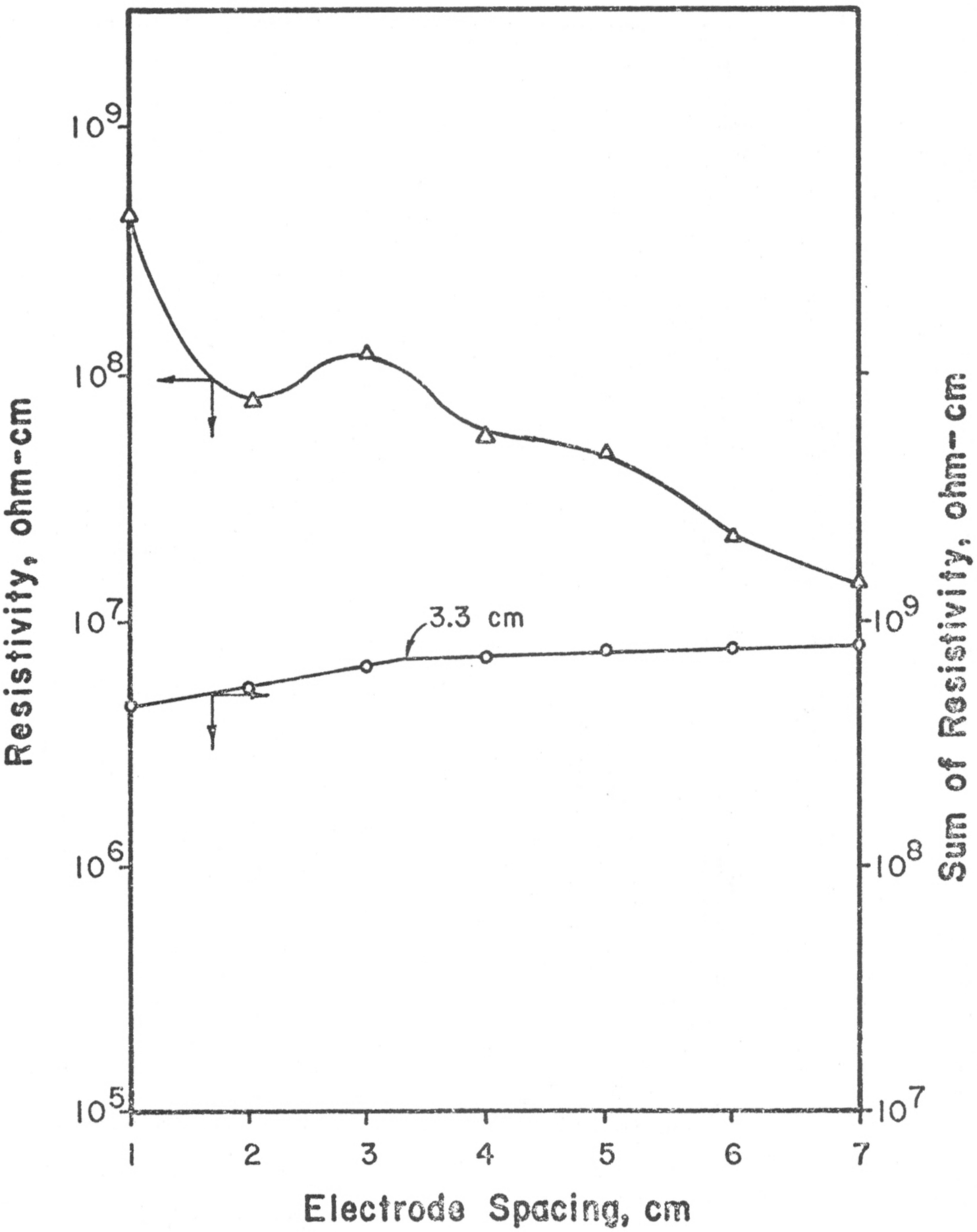


Figure 1.27 Depth Determination by Moore Method

Slab No. 4A, loading: 1.0 lb/ft^2

average visual depth: 3.0 cm

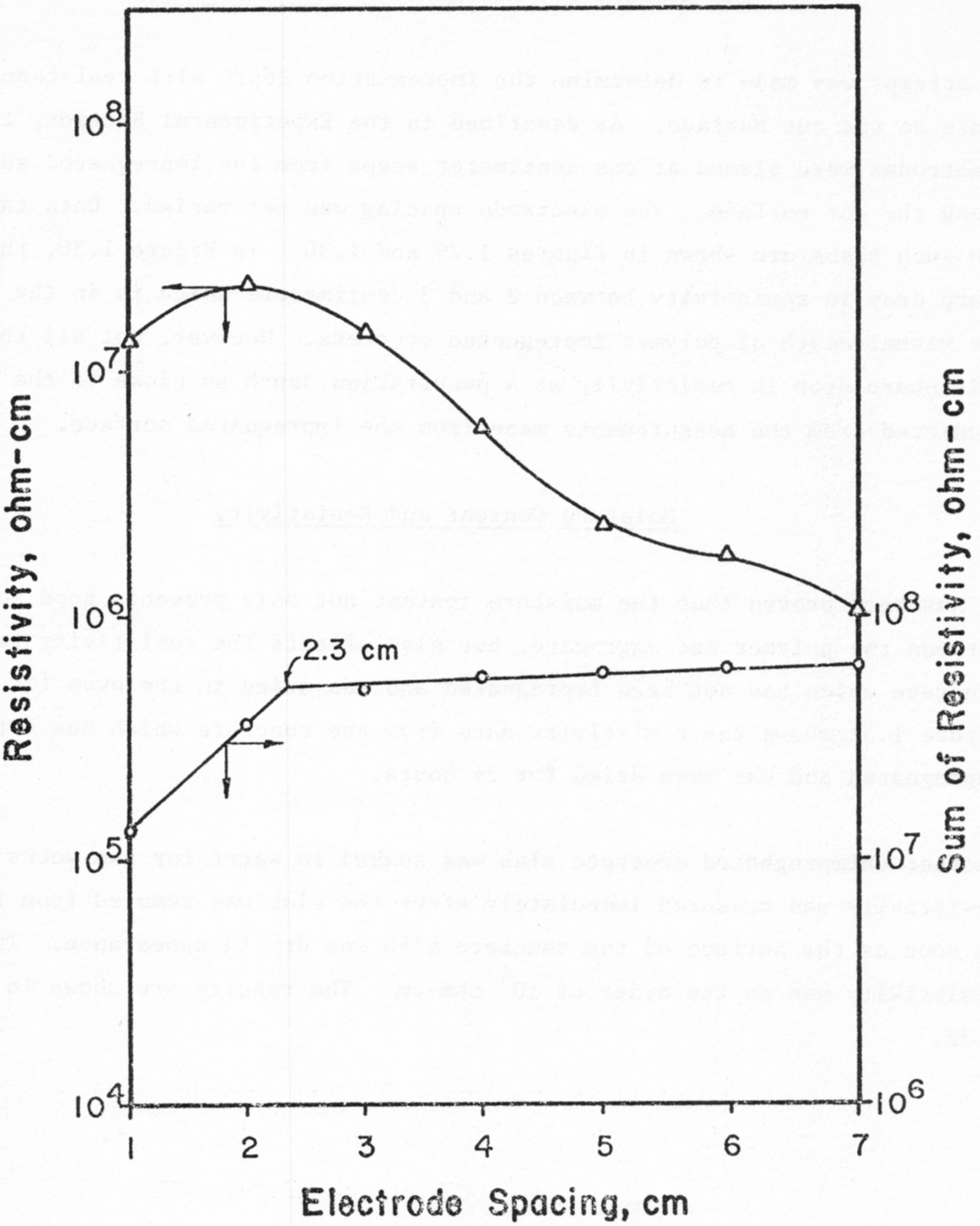


Figure 1.28 Depth Determination by Moore Method

Slab No. 12B, loading: 0.6 lb/ft^2

average visual depth: 2.2 cm

The Resistivity Measurement on Cut Surface

An attempt was made to determine the impregnation depth with resistance measurements on the cut surface. As described in the Experimental Section, the electrodes were placed at one centimeter steps from the impregnated surface along the cut surface. The electrode spacing was not varied. Data taken from two such slabs are shown in Figures 1.29 and 1.30. In Figure 1.30, there is a sharp drop in resistivity between 2 and 3 centimeters which is in the range of the visual depth of polymer impregnated concrete. However, not all the data had this sharp drop in resistivity at a penetration depth so close to the value predicted from the measurements made from the impregnated surface.

Moisture Content and Resistivity

It has been proved that the moisture content not only prevents good bonding between the polymer and aggregate, but also effects the resistivity test on the concrete which had not been impregnated and was dried in the oven for 24 hours. Figure 1.31 shows the resistivity data from the concrete which has not been impregnated and was oven dried for 24 hours.

Another unimpregnated concrete slab was soaked in water for two weeks. The resistivity was measured immediately after the slab was removed from the water as soon as the surface of the concrete slab was dry in appearance. The resistivity was on the order of 10^4 ohm-cm. The results are shown in Figure 1.32.

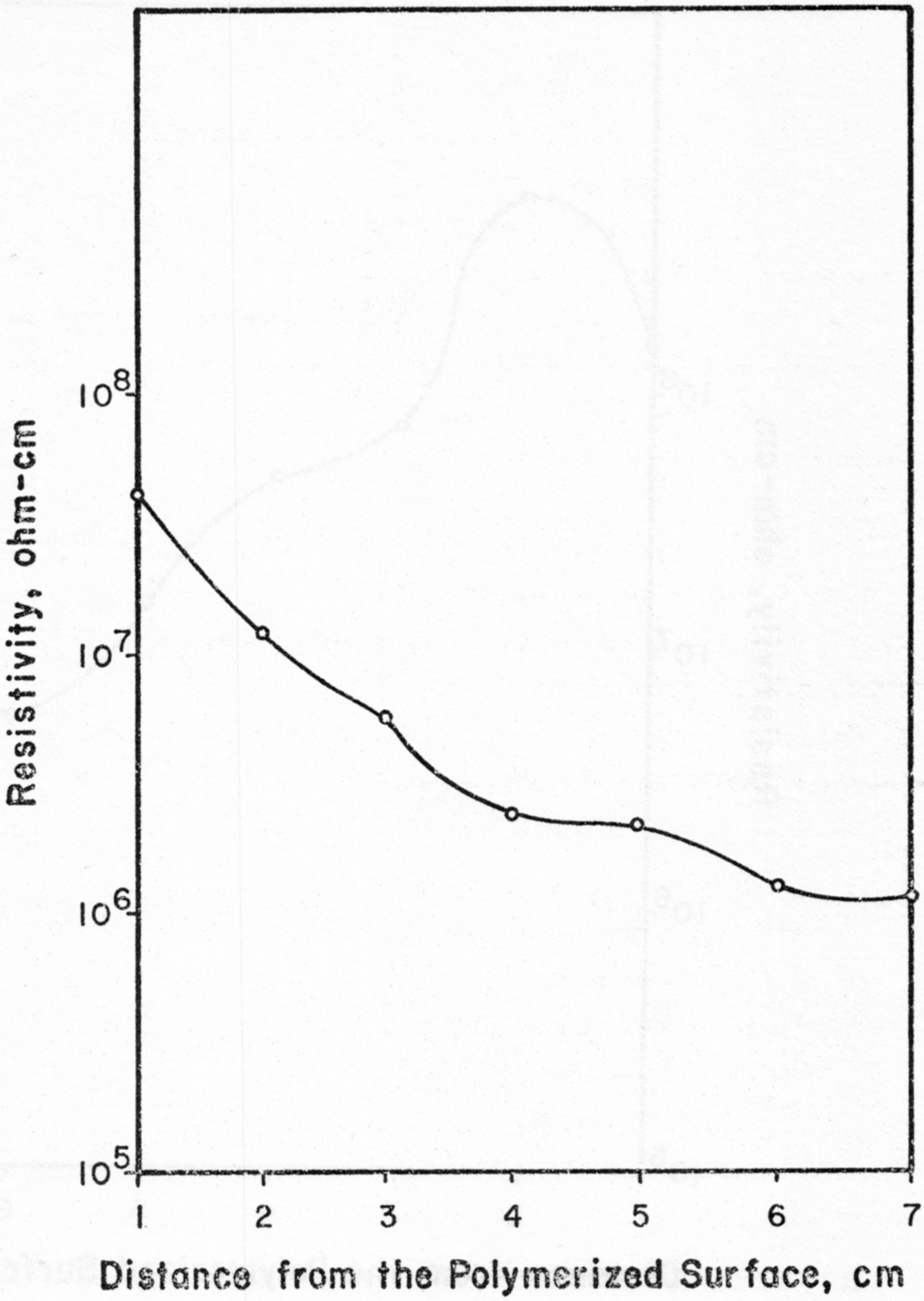


Figure 1.29 Resistivity on the Cut Surface

Slab No. H1, loading: 0.6 lb/ft^2

average visual depth: 2.1 cm

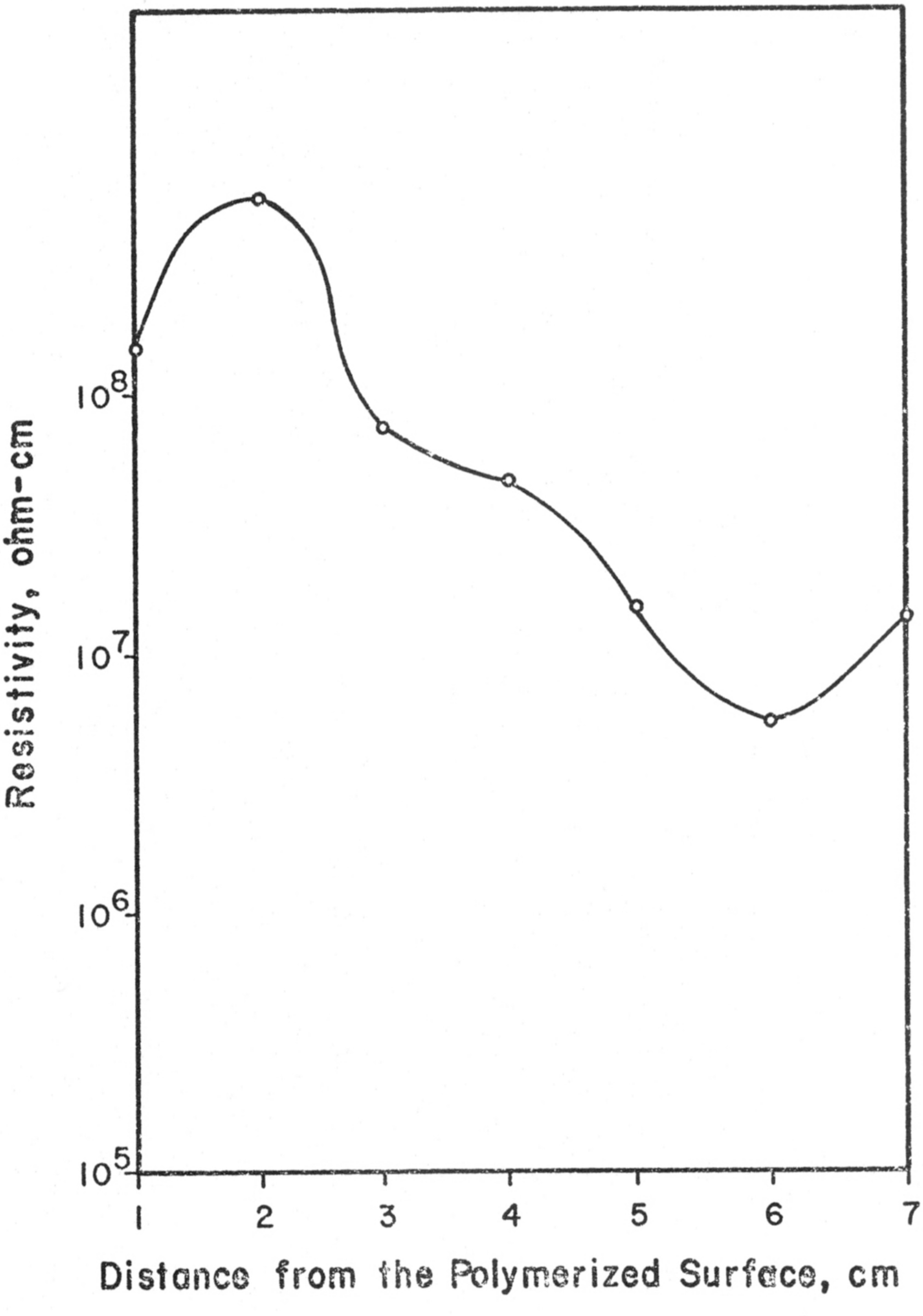


Figure 1.30 Resistivity on the Cut Surface

Slab No. 13A, loading: 1.0 lb/ft^2

average visual depth: 3.0 cm

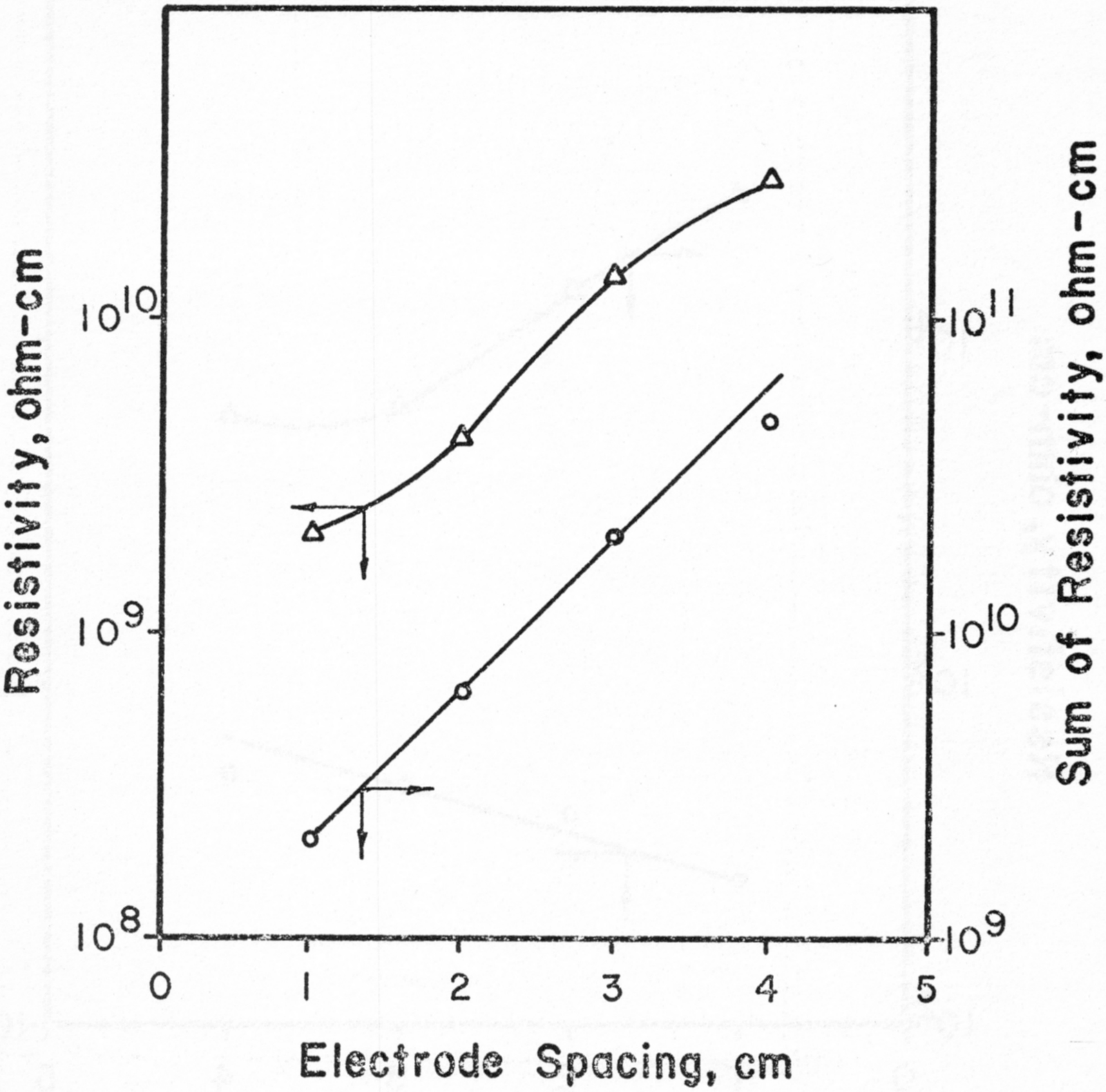


Figure 1.31 Resistivity and Cumulative Resistivity Data of Unimpregnated Concrete Slab after Oven Drying for 24 Hours

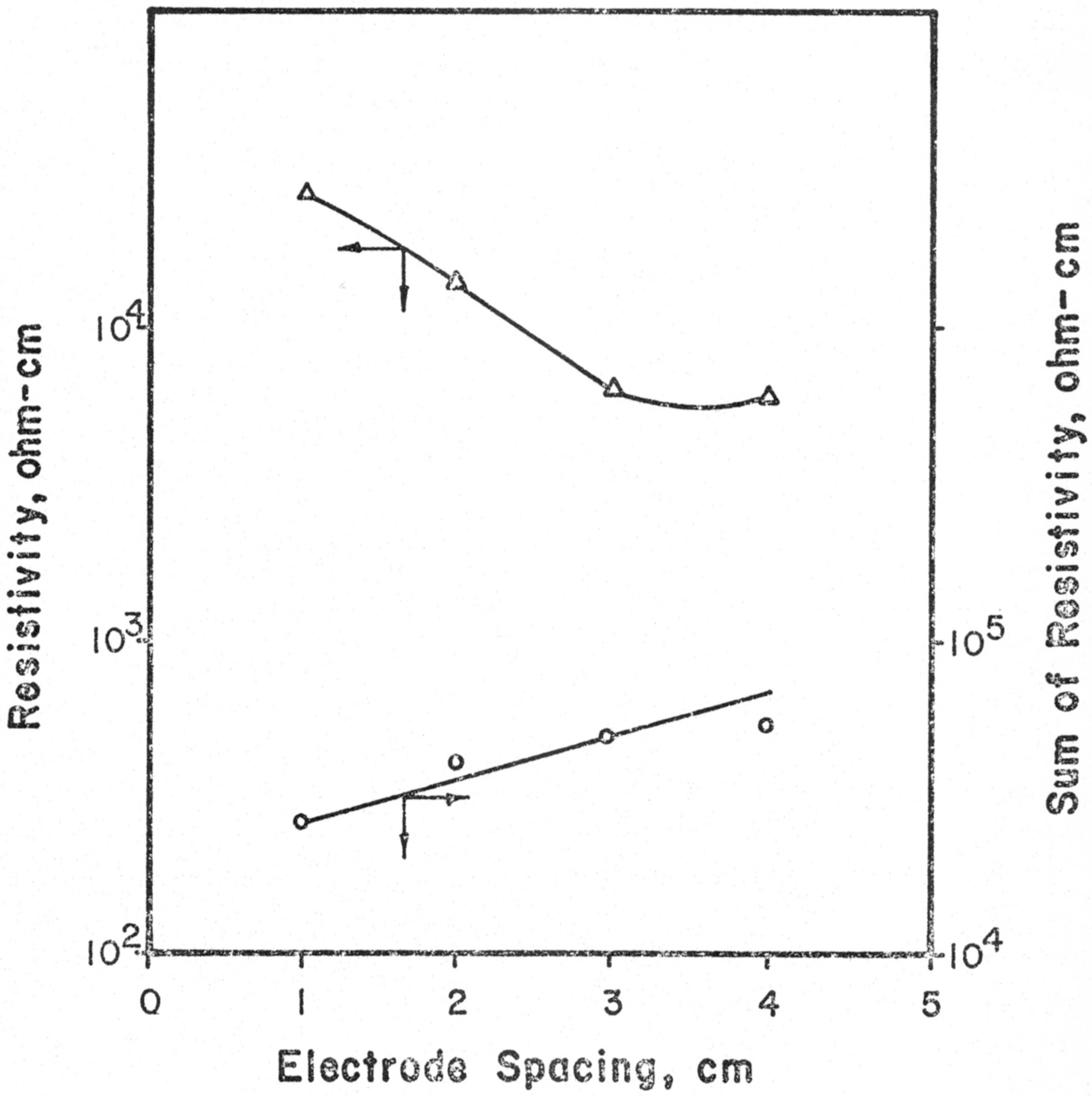


Figure 1.32 Resistivity and Cumulative Resistivity Data of Unimpregnated Concrete Slab after Soaking in Water for 2 Weeks

Maximum Resistivity and Polymer Loading

The resistivity of the polymer impregnated layer was found to vary with polymer loading. The data are shown in Figure 1.33. The maximum resistivity varies from 10^7 to 10^9 ohm-cm. The value at the maximum loading might indicate that the major portion of the pore space is filled with the polymer.

Penetration Depth and Polymer Loading

Figure 1.34 is a plot of penetration depth (visual depth) versus polymer loading. Obviously, the penetration depth increases with an increase in polymer loading.

Table 1.18 shows the values of visual depth and depth determined by Moore method for different loadings. The standard error of estimate (SE) is 0.103 cm.

Moisture Content and Penetration Depth Determination

It was also observed that after the slabs had been stored for six months, their resistivities changed significantly. The resistivities measured from several aged slabs were found to be higher than that obtained six months earlier, especially those measured at large electrode spacings. The resistivities of unimpregnated concrete portion were found to be in the magnitude of 10^8, which was much higher than that measured earlier. The penetration depth could not be determined by Moore Method under this condition.

However, after the aged slab had been soaked in water for eleven days, the resistivity of the unimpregnated portion dropped to $10^4 \sim 10^5$ ohm-cm. The resistivity of this slab (No. 9C) was measured again four days after it was removed from the water bath, and a clear intercept was obtained on the cumulative resistivity plot (Fig. 1.35). The penetration depth determined by resistivity method was 2.1 cm, very close to that obtained six months earlier (2.2 cm).

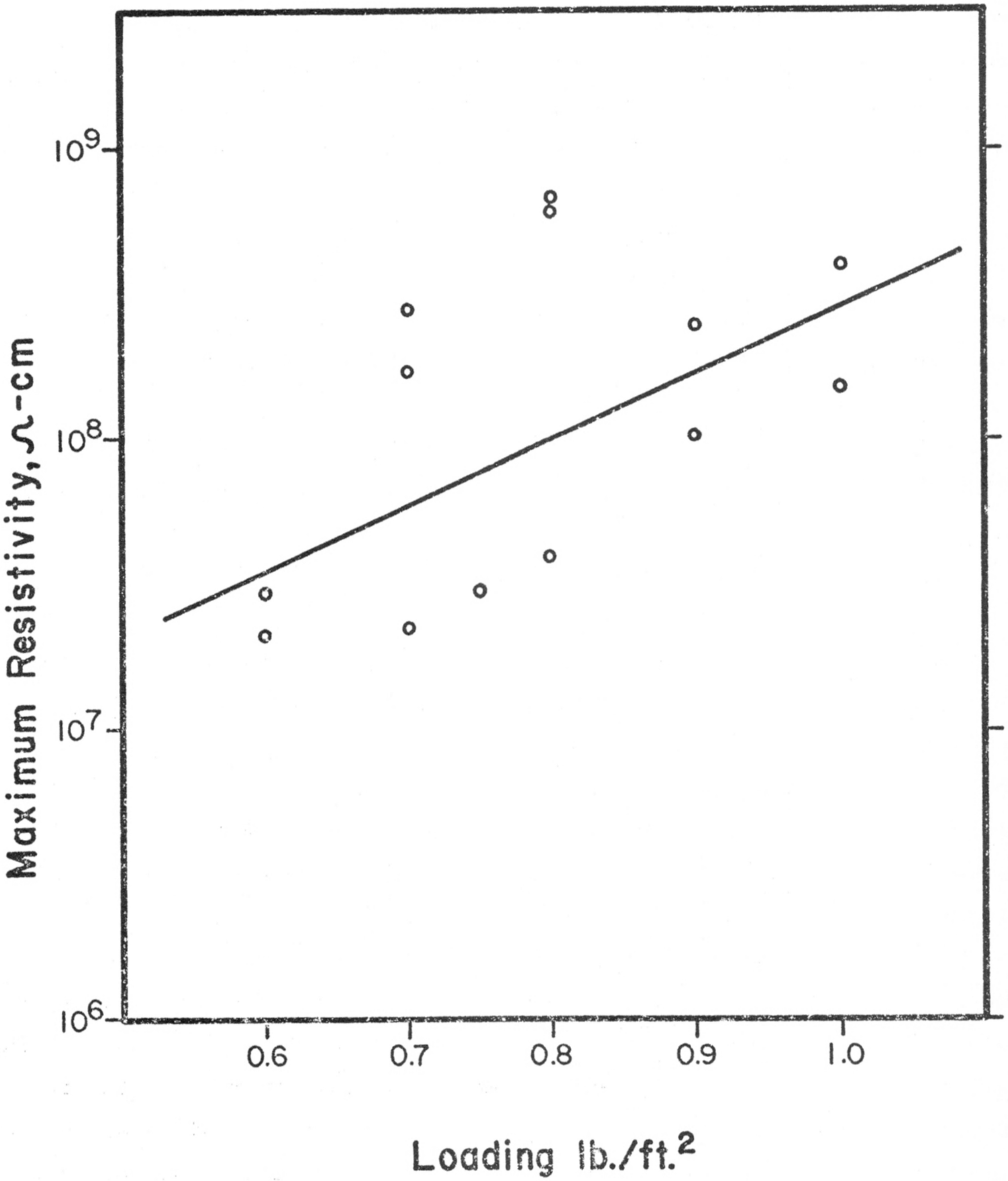


Figure 1.33 Variation of Maximum Resistivity with Monomer Loading

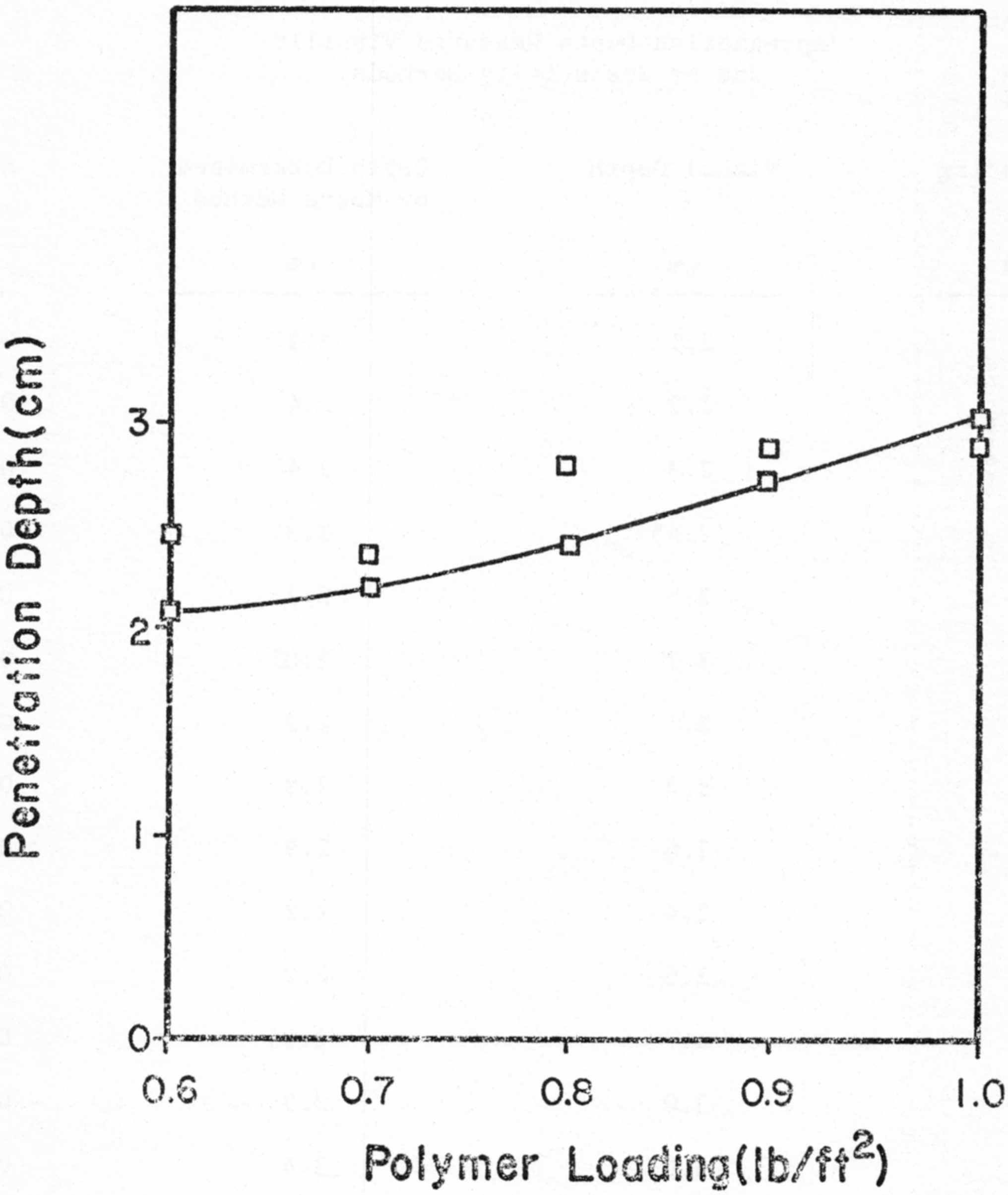


Figure 1.34 Penetration Depth and Polymer Loading

TABLE 1.18

Impregnation Depth Measured Visually and by Resistivity Methods

Polymer Loading (lb/ft^2)	Visual Depth cm	Depth Determined by Moore Method cm	Δcm x
0.6	2.1	2.2	0.1
0.6	2.2	2.4	0.2
0.6	2.3	2.4	0.1
0.6	2.45	2.3	0.15
0.6	2.5	2.7	0.2
0.7	2.2	2.05	0.15
0.7	2.4	2.3	0.1
0.7	2.2	2.0	0.2
0.75	2.8	2.9	0.1
0.8	2.4	2.2	0.2
0.9	2.6	2.2	0.4
0.9	2.7	2.55	0.15
1.0	3.0	3.3	0.3
1.0	3.0	3.4	0.4

Average Δcm, $\overline{X} = 0.196$

$$\Sigma\,(\overline{X} - x_i)^2 = 0.1373$$

$$\text{Standard Error of Estimate} = \sqrt{\frac{(\overline{X} - x_i)^2}{N - 1}} = 0.103 \text{ cm}$$

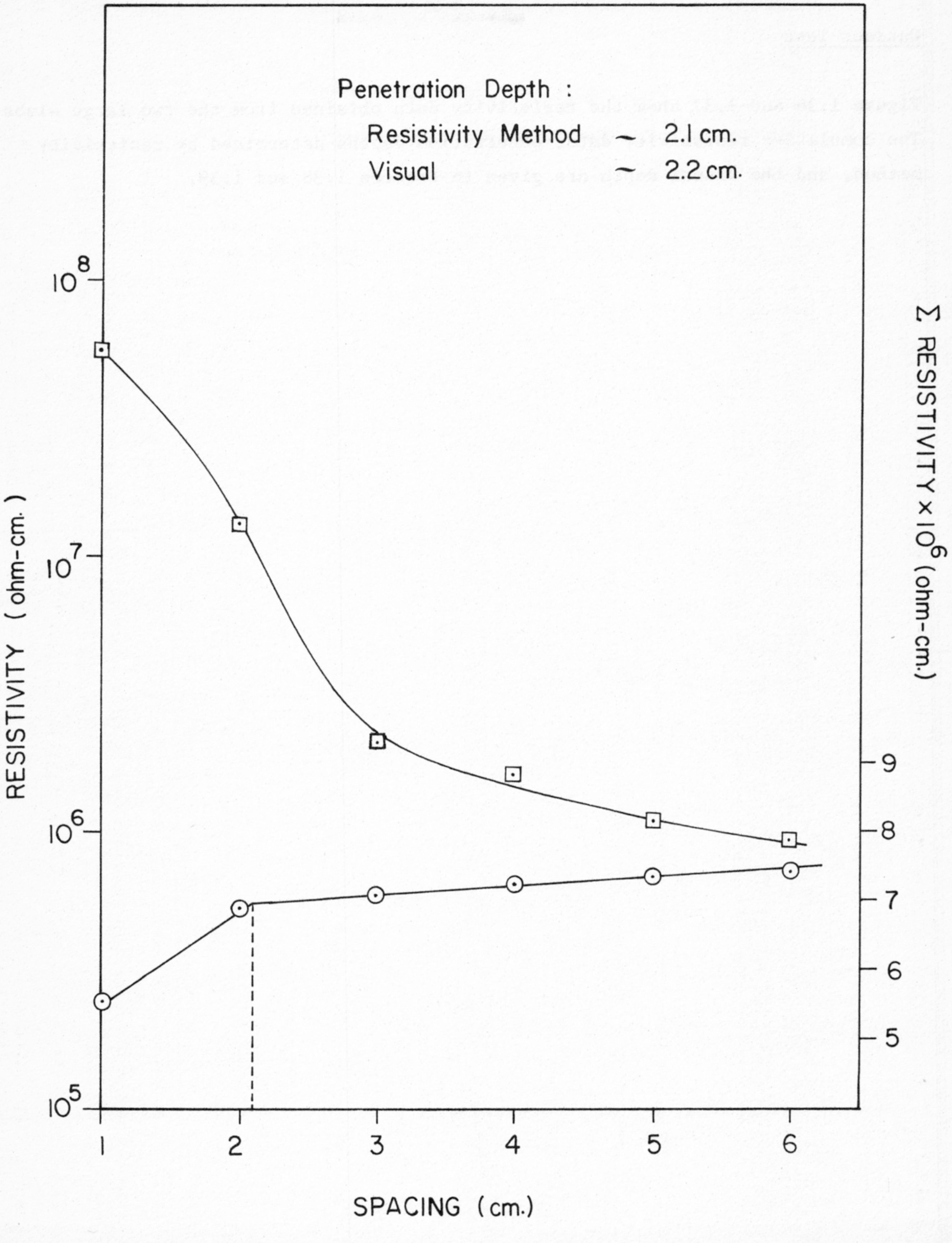


Figure 1.35 Depth Determination by Moore Method - Slab No. 9C

Outdoor Test

Figure 1.36 and 1.37 show the resistivity data obtained from the two large slabs. The cumulative resistivity data, penetration depths determined by resistivity method, and the visual depth are given in Figures 1.38 and 1.39.

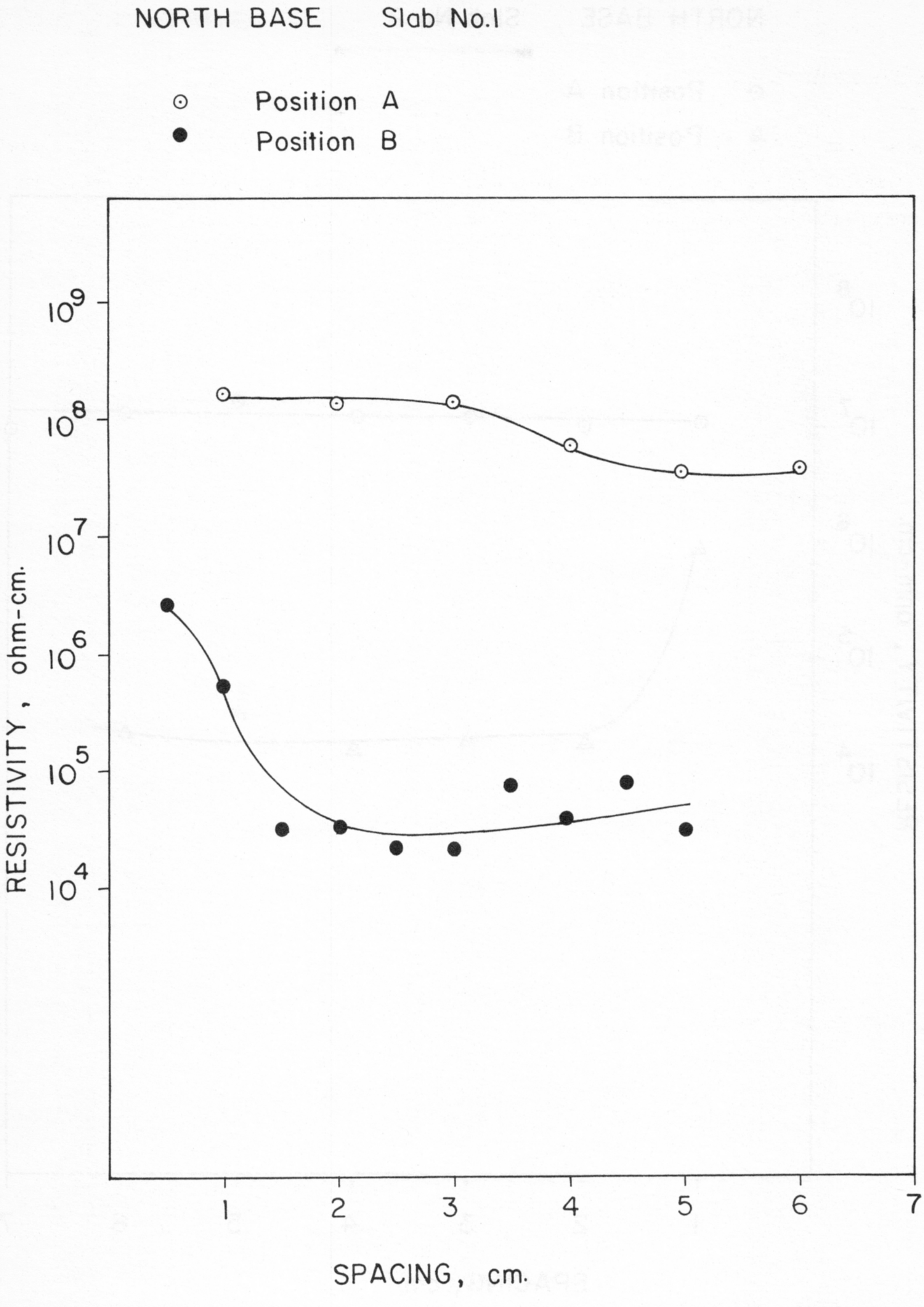


Figure 1.36 Resistivity vs. Spacing

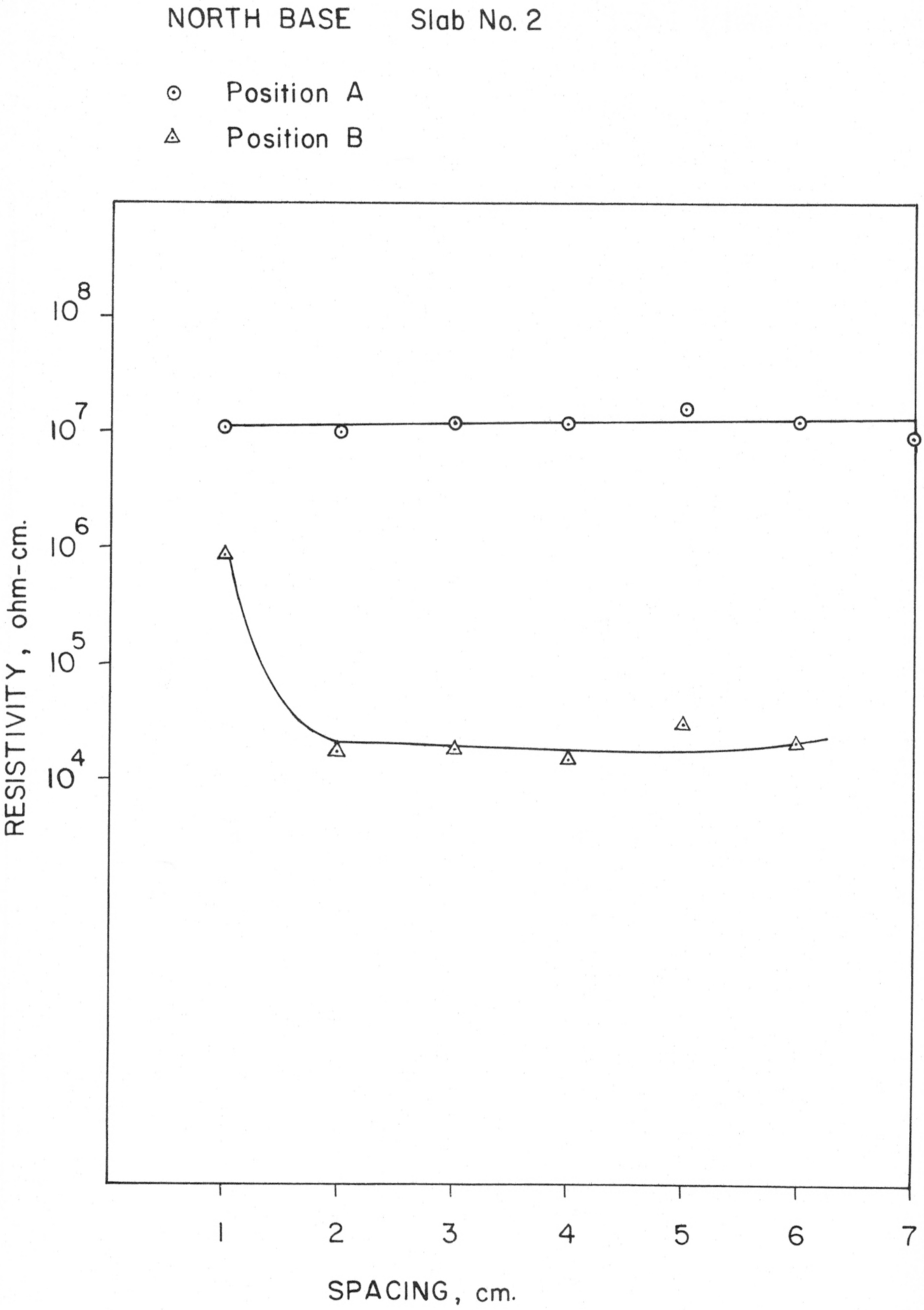


Figure 1.37 Resistivity vs. Spacing

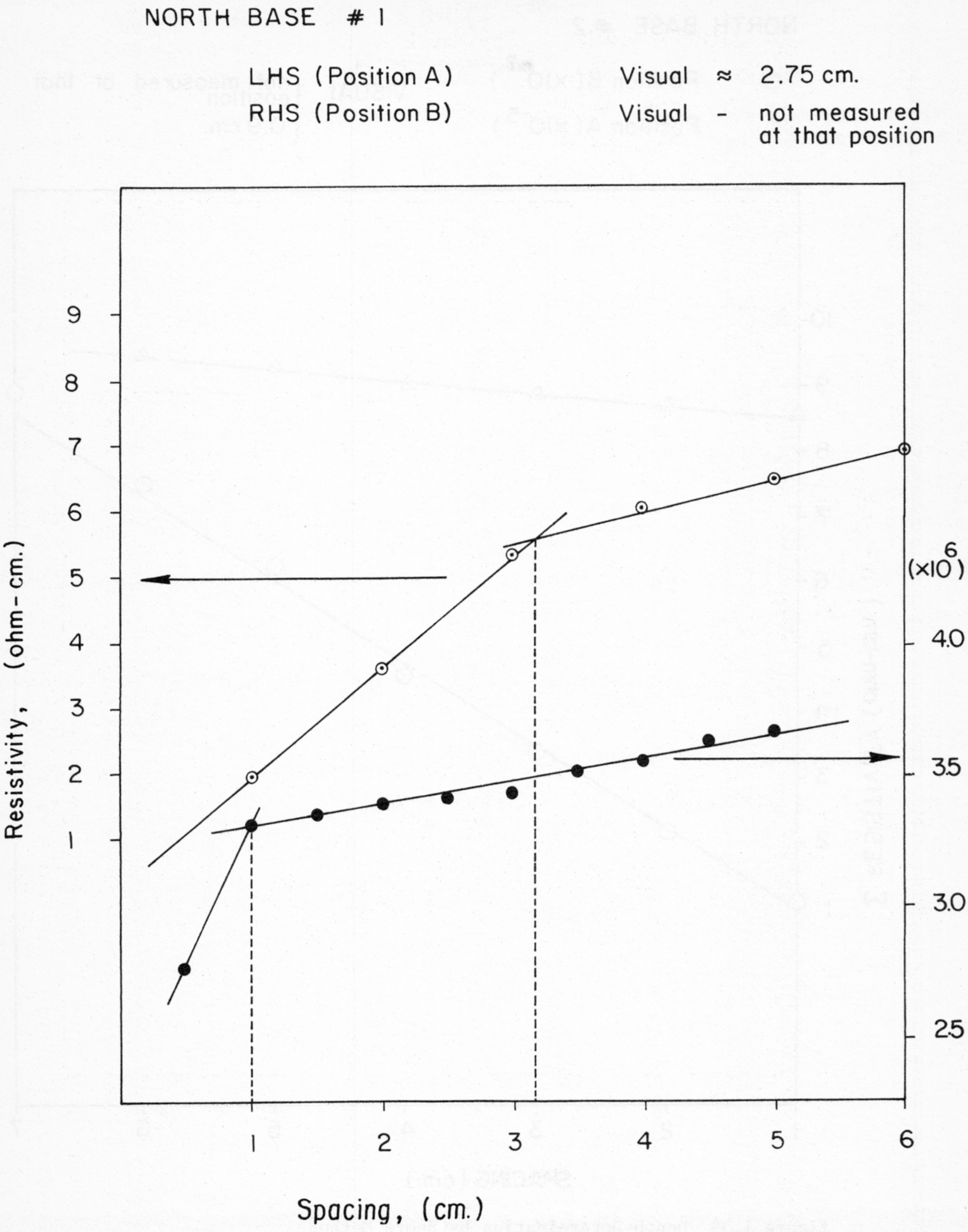


Figure 1.38 Depth Determination by Moore Method

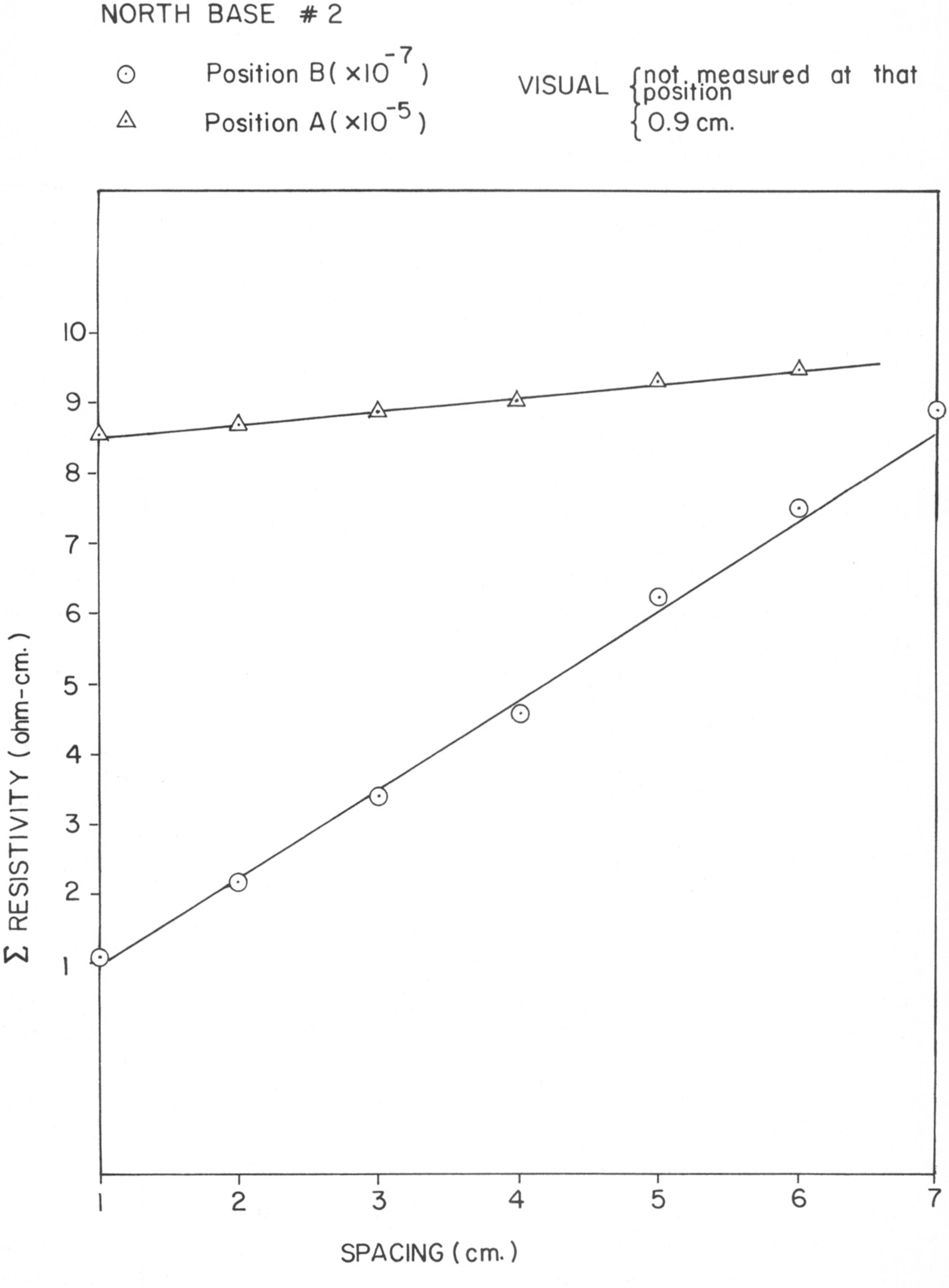


Figure 1.39 Depth Determination by Moore Method

E. Discussion

The resistivity measurements of polymer impregnated concretes were very useful in analyzing the penetration depth of polymers. Though the resistivity technique was applied to determine the thickness of concrete pavements and to explore subsurface structure of the earth, no work has been conducted previously by other investigators to apply it as a method of measuring the penetration depth of PIC. The resistivity behavior of some of the concrete slabs containing different moisture content will also be described in one of the sections.

Moore Cumulative Curve Method of Depth Determination

Laboratory Test

The general downtrend in the resistivity curves shown in Figures 1.23-1.28, for the electrode spacing 2-4 cm resulted, because at the electrode spacing the unimpregnated concrete was measured.

For example, in Figure 1.24, the resistivity curve drops sharply for electrode spacings in the range of 2 to 3 cm. The measurement at these electrode spacings includes the unimpregnated, lower resistivity drops.

In this study, there is only one intersection from the straight lines of the cumulative curve for each resistivity measurement of impregnated concrete. It means that there is a very uniform quality throughout the slab.

The penetration depths obtained by resistivity method were comparable to the visual depth. The average deviation from the visual depth was less than 0.2 cm for an average visual depth of 2.5 cm (Table 1.18).

Outdoor Test

In order to evaluate the feasibility of applying the resistivity technique to the determination of impregnation depth of PIC pavement, it is more important to know whether this technique can detect the impregnation depth of these outdoor slabs. The resistivity data obtained from the large slabs seemed to give reasonable indication of the impregnations depths. The penetration depth at location A on Slab No. 1 was found to be 3.15 cm by resistivity method, while the visual depth was 2.75 cm. (Fig. 1.38). At location B, the resistivities showed a drastic drop between 1 cm and 1.5 cm spacings, and the penetration depth obtained by Moore method seemed to be close to 1 cm. However, the accuracy of this value was somewhat lower as the straight line representing the higher resistivity portion was determined with only two data points. Since the smallest spacing that could be achieved was 0.5 cm, this type of uncertainty would exist if the impregnation depth was small ($\leq$ 1 cm). The visual depth at that position was not measured, but, according to the data in Table 1-16, it seemed that the visual depth might be between 1 and 0.4 cm.

The values of visual depth of Slab No. 2 were found to be low (Table 1.16). The visual depth was found to be 0.9 cm at location A, but visual depth was not measured at location B. The data listed in Table 1.16 seems to indicate that the penetration depth is higher at locations close to the central portion of slab. Thus, it was probable that the penetration depth at location B of Slab No. 2 was lower than that of location 2 (1.0 cm).

The results from both laboratory test and outdoor test indicate it will be possible to determine the depth of impregnation by a relatively simple surface resistivity measurement. In fact, it may be that the resistivity determined depths will be the most accurate method since there is some uncertainty in the visual measurement on the cut surface. However, it should be emphasized that some experience in the use of the test and the method of analyzing the test data may be required for the best results.

The Analysis of Resistivities on Cut Surface

It was mentioned earlier that there certainly are uncertainties in the visual method of depth determination. It was difficult many time to see the slight color difference between the impregnated material and the unimpregnated portland cement concrete. Since the resistivity varies with the component and moisture content in each layer, the analysis of resistivities on cut surface might help to mark the boundary between layers.

Figure 1.29 and 1.30 show the resistivities versus distance from the impregnated surface. In Figure 1.30, there is a sharp drop in resistivity near the region close to the surface. The resistivity at the rear part of the curves are 10^6 to 10^7 ohm-cm, which is the range of resistivity for unimpregnated concrete slab in laboratory condition. Therefore, as Figure 1.30, it is possible to predict the boundary should be in the range between 2 to 5 centimeters from the impregnated surface.

If the moisture content is known in the concrete slab and the relation is fully developed between the moisture content and resistivity, then the cut surface scan resistivity measurements may be the most fruitful method of measurement as a comparison method.

The Influence of Moisture on Resistivity

Figure 1.31 shows the resistivity is up to 10^{10} ohm-cm for the unimpregnated concrete slab after 24 hours drying in the oven. Figure 1.32 is the plot of resistivity versus electrode spacing of the unimpregnated concrete slab after soaking in water for 14 days. The moisture content in this condition is 6.1%. The results show that the resistivity at such high moisture is about 10^4 ohm-cm, this is within the range of semi-conductors. Table 1.19 shows the comparison between literature and experiment data.

TABLE 1.19

Comparison between Experimental and Literature Data for Resistivity of Portland Cement Concrete

Condition	Resistivity, ohm-cm (4), (6) Literature	Experimental
Oven Dried	10^{11}	10^9 — 10^{10}
Lab Humidity	10^5	10^6
Water Soaked	10^3	10^3 — 10^4

The average moisture content of the slabs stored in the laboratory at room temperature is about 1.1%. The resistivity of these slabs was 10^6 to 10^7 ohm-cm.

This value is lower than the resistivity of the unimpregnated concrete slab after drying in the oven for 24 hours (10^{10} ohm-cm). It means that some moisture exists in the unimpregnated region of the partially impregnated concrete.

Both the straight lines by Moore Cumulative Curve Methods in Figures 1.31 and 1.32 show no intersections. It means that there is a uniform quality in the concrete slabs. The variation in resistivity with the electrode spacing might be explained in terms of moisture migration. The oven-dryed slab might have been absorbing moisture from the atmosphere during the resistivity measurement, which resulted in a moisture profile in the slab. If so, the inner portion of the slab should be dryer than the portion close to the surface and the resistivity measured at a large spacing should be higher than that measured at a smaller spacing, as was observed (Fig. 1.31). The observed resistivity data of the soaked slab (Fig. 1.32) could be interpreted with the same approach except that the soaking slab was losing moisture to the atmosphere and had lower moisture content at the surface.

The Influence of Moisture Content on Penetration Depth Determination

It was mentioned earlier that the resistivity of the unimpregnated portion increased to a magnitude of 10^8 ohm-cm after the slabs had been stored in the laboratory for six months, and the Moore Cumulative Method did not give any clear interception which could indicate the penetration depth. The reason for this observation might be that the resistivity of the impregnated portion became so high that there was no significant difference between the resistivities of the impregnated and unimpregnated protions. Therefore, no intercept appeared on cumulative resistivity diagrams. The higher resistivity observed in the aged slabs might be due to subsequent drying under the laboratory conditions during the aging period.

This interpretation was supported by another experimental result. As shown in Fig. 1.35, the resistivity of unimpregnated portion of an aged slab dropped substantially after the slab had been soaked in water for eleven days, and an interception at a spacing of 2.1 cm was obtained from the cumulative resistivity diagram. It was noticed that this penetration depth was nearly the same as that obtained before aging (2.2 cm). These results suggest that it was the moisture content which primarily affected the resistivity and the depth determination. However, it seems that the depth determined by resistivity technique will not change with the moisture content in the slab, as long as the moisture content is high enough to cause significantly different resistivities in impregnated and unimpregnated concrete.

Maximum Resistivity and Polymer Loading

Figure 1.33 is a plot of maximum resistivity versus polymer loading. Four slabs at monomer loading of 0.7 and 0.8 lb/ft^2 have resistivities in the range of 10^8 to 10^9 ohm-cm. Two of these slabs were impregnated with a slightly different technique. The 0.7 and 0.8 lb/ft^2 of monomer loading were poured on the sand and additional monomer was added to keep the sand wet. Obviously they have higher monomer loading than shown and therefore higher resistivities. The reason the other two points have resistivity values in 10^8 - 10^9 ohm-cm. is unknown. In general, although there is some scatter, the maximum resistivity did in fact increase with an increase in loading. It may be possible to determine the quality of the impregnated layer using this technique. Indications are that the resistivity may be as much as an order of magnitude higher when the polymer loading are higher. This is probably due to the polymer more completely filling the portland cement concrete void spaces. Possibly specifications for contract work could be written with a given level of resistivity as the criterion for an acceptable impregnation job.

Penetration Depth and Polymer Loading

In this experiment, the average porosity of concrete slab is 6.74%, based on the amount of air entrainment. The paste pores and aggregate pores are not included in this value. For a 12" x 12" x 7" concrete slab, the volume of air voids is 0.00056 ft^3 for one inch depth impregnation on this basis. If a 0.6 lb/ft^2 monomer loading is assumed (commonly used on bridge decks) and one inch penetration is obtained, the volume of PMMA resulting would be 0.0102 ft^3 impregnated in the concrete.

The difference between void volume and PPMA volume can be attributed to:

1) Monomer evaporation during soaking period.

2) Porosity of concrete is greater than the air entrained- due to the paste porosity, and the porosity of aggregate.

3) Some monomer may be retained in the sand layer.

The standard error of estimate (SE) is 0.103 cm. It means that Moore method is an effective way to determine the depth of polymer in PIC.

Experimental Techniques

Up to present, there are still some technical problems in the resistivity measurement. These problems, which might be responsible for the possible experimental error are described below.

1) It was not easy to control the flow rate of $Cu/CuSO_4$ solution out of the electrodes. When the solution flows out too fast, the area wetted by the solution will largely increase and sometimes will contact with the wetted area of other electrodes.

2) In order to ensure accurate prediction of the penetration depth, the electrodes should be such that they could be spaced 0.5 cm.

3) The electrode reading tend to shift after the electrodes contacted with the concrete surface. The readings had to be taken at the same time after the circuit had been completed, and this introduced some error to the resistivity data. The shifting seems to be mainly due to the diffusion of the solution on the concrete surface as the readings generally were observed to shift faster when the solution diffused faster. However, it is also possible that the use of DC power source might have caused some polarization which initiated the shifting.

Modification of the experimental techniques will be necessary before this technique can serve as a standard test method for determination of penetration depth.

F. Conclusions and Recommendations

Conclusions

1) It is possible to determine the depth of polymer penetration in partial depth impregnation of portland cement concrete by using a resistivity measurement technique. The measurement is made from the surface and is a rapid nondestructive testing method.

2) It would seem that the maximum resistivity of PIC is proportional to the polymer loading, so it may be possible to use the resistivity values as a method of evaluating the quality of the impregnation layer.

3) Resistivity is sensitive to the moisture content in the concrete slab. So it may be feasible to determine the moisture content of portland cement concrete after the drying step prior to polymer impregnation. This would be helpful in controlling the drying step.

Recommendations

1) It is necessary to develop a smaller size electrode, since for more accurate analysis, the electrode spacing should be less than one centimeter.

2) It is necessary to get better control of the electrolyte flow rate. This may be achieved by either modifying the sponge in the electrode, or by increasing the viscosity of the electrolyte solution.

3) Further study is needed to correlate the resistivity with moisture content in PIC.

4) Moore Cumulative Curve Method for depth determination may be used to tell the rebar location in PIC.

5) An easier, portable equipment for resistivity measurement is needed to operate in the field.

6) The possibility of using alternating current (AC) should be investigated.

POLYMER CONCRETE OVERLAYS

INTRODUCTION

Polymer concrete is a concrete mix in which the aggregate is bound together with a polymer. It has been demonstrated that such a mix provides an impermeable, highstrength, quick setting material for overlays on bridge decks. Concrete overlays improve the durability of bridge decks by sealing the concrete against corrosion of reinforcing steel. The quick setting of the polymer concrete eliminates extended closure of highways which could lead to intolerable congestion of traffic.

At the moment there are three known procedures for placing polymer concrete overlays that have been tried. The first two of these, known as "Polymer Concrete Overlays" Method A and Method B, were developed and tested by the Oregon State Highway Division and Brookhaven National Laboratory, respectively for the Federal Highway Administration. The third procedure was developed by the Center for Highway Research, the University of Texas at Austin for the Texas State Department of Highways and Public Transportation. All three procedures have been tested on bridge decks and found satisfactory. The subject of this report is to look into these procedures, make recommendations as to which is most feasible and prepare a work plan for the construction activities in regard to the materials. The investigation includes curing time study, laboratory and small scale field demonstrations for each procedure. These are described below, preceeded by brief discussions of the three procedures.

METHOD A

Brief Description of Procedure:

The top 1/4-inch of the concrete bridge deck is removed by scarification. All loose and unsound concrete must be removed and the deck area to be treated should be air blasted.

The material consists of polyester styrene resin (the binder), methyl ethyl ketone peroxide, (the initiator), cobalt naphthnate or cobalt octoate, dimethylaniline (the promoters) and tert-butyl hydroquinone (the inhibator). Thirteen pounds per square foot of the resin is used for 1-1/2 inch thick overlay. The other components of the material are calculated as percentages of the resin, depending on the working temperature. A tack coat consisting of all of the above chemicals, including an organic-silane ester is applied to the surface of the bridge deck to be treated just before the polymer concrete mix is placed down. This acts as a coupling agent between the resin and the silica in the aggregate.

130 lbs/ft^3 of high quality aggregate is recommended for 1-1/2 inch thick overlay. The material and aggregate are mixed together either in a conventional rotating drum or a paddle type mortar mixer.

Screed rails are placed on the deck after it has been cleaned. The tack coat is applied to the area to be treated and the polymer concrete mix is quickly placed and spread evenly to give 1 1/2 inch thick overlay. It is compacted with either a light two pound roller or by a vibrating plate asphalt compactor. The deck can be opened for traffic 2 1/2 hours after the final concrete batch has been placed and finished. The equipment and tools require cleaning every 45 minutes. It is estimated that a 1 inch overlay will cost $30 per square yard.

Cure Time Study:

Resin formulations recommended to give a minimum work time of 30 minutes for this procedure were tried and verified to be correct. No additional cure time study has been done.

Laboratory Demonstration:

An inch thick overlay was placed on a 1 ft^2 concrete slab at room temperature (78°F) in the laboratory. The surface of the slab was brushed but no scarifiction was done. The material and aggregate were mixed by hand using a large bowl. No inhibition was added because the resin already had some and besides the material and aggregate were small enough to be handled quickly and easily. The polymer concrete mix set within 40 minutes. No problem was encountered. The calculation of the proportions of the material components is as follows:

Temperature: 78°F

Area to be treated: 1 ft^2

Overlay thickness: 0.5 inches

Amount of Aggregate: 2460 g

Polyester Styrene (Resin): 246 g = 227.7 cc

Promoters: 12% con = 0.25% of 246 g = 0.607 cc

Dimelthyl Aniline = 0.2% of 246 g = 0.515 cc

Initiator: 50% MEKP = 1.5% of 246 g = 3.300 cc

Tack coat formulation:

Resin = $(0.00125\ ft^3/ft^2)(1\ ft^2)$ = 35.4 cc = 38.25 g

Promoters: 12% con = 0.25% of 38.25 g = 0.094 cc

Dimethyl Aniline (DMA) = .2% of 38.25 g = 0.080 cc

Initiator: MEKP = 1.2% of 38.25 g = 0.410 cc

Silane = 0.02% of 38.25 g = 0.800 cc

Small Scale Field Demonstration:

This was done on a 6'x3.5' section of a 12'x7' concrete slab at the North Base of the University of Oklahoma. The overlay was 1 1/2 inch thick. The surface of the slab was cleaned and brushed but there was no scarification. An 1 1/2 inch screed rails were placed around the section of the slab to be treated. The material and aggregate were mixed in three batches by hand using a wheelbarrow and a shovel. An inhibitor was not used here too. Unintentionally less material than the one recommended was used for the first batch and more was used for the third batch. It was found that the overlay done with the first batch was too dry and the one done with the third batch was too wet. Another 6'x3.5' section of the slab was treated. There was an obvious improvement in the appearance of the overlay. The polymer concrete mix set within 35 minutes. The calculation of the proportions of the material components follows:

Temperature range: 80-90°F

Area to be treated: 21 ft^2

Overlay thickness: 1.5 inches

Amount of aggregate: 7377.5 g/ft^2

Material Mix Per 1 ft^2:

Resin = 737.75g = 683 cc

Promoter: 12% con = 0.25% of 737.75g = 1.82 cc

DMA = 0.2% of 737.75g = 1.54 cc

Inhibitor: Tert-butyl Hydroquinone = $737.75 \times \frac{100}{10^6}$ g = 0.074g

Inhibitor: 50% MEKP = 1.2% of 737.75g = 8.90 cc

Tack Coat:

Resin = 35.4 cc = 38.2 g

Promoters: 12% con = 0.25% (38.2g) = -.094 cc

DMA = 0.2% (38.2g) = 0.080 cc

Silane = 2% (38.2g) = 0.865 g

Tert-butyl Hydroquinone = $\frac{200}{10^6}$ x 38.2 g = 0.0076 g

Initiator: MEKP = 0.96% (38.2g) = 0.33 cc

METHOD B

Brief Description of Procedure:

The bridge deck to be treated must be sound with its surface cleaned preferably by sandblasting. The deck is air dried for a minimum of two consecutive days without rain or heaters can be used to dry the deck. Either an unsaturated polyester resin such as W.R. Grace polyester resin LB183-13 or a vinylester resin such as Dow Chemical Company vinylester Derakane 470 may be used as the main binder. In addition, the material contains methylethylketone peroxide (the initiator), cobalt naphltenate and dimethyl aniline (the promotors). Screed rails are placed around the seciton of the deck to be treated. The material mix is applied to the surface of the deck and immediately, aggregate shall be broadcast to excess over the monomer and compacted into the monomer. The aggregate shall consist of clean, dry, round grained silica sand. After the monomer has polymerized, any unbounded aggregate is removed by brooming. The procedure is repeated four times to give four layers of about 0.5 to 0.63 inch thick overlay. A cure time of 1 to 3 hours is required between each layer. About 11.25 lb/sq yd to 23.85 lb/sq. yd of resin is recommended for the four layers. 18.0 to]7.0 lb/sq. yd of aggregate should be broadcast for each layer although only about 9.0 to 13.5 lb/sq. yd. of this will be bonded.

Cure Time Study:

Resin formulations recommended to give certain work times depending on the ambient temperature were tried and found to be wrong. The proportions of the initiator and promoters were so small that the monomer mix did not set even after two hours. Some cure time studies done by this laboratory using polyester resin were used.

Laboratory Demonstration:

Attempts were made in the laboratory to place a polymer concrete overlay on a 1 ft^2 concrete slab using this method without much success. The overlay failed repeatedly to bond to the surface of the slab and never set completely. However, it was suspected that this might have been caused by the method used to broadcast the aggregate into the monomer mix. Also the aggregate used was too fine to allow the aggregate to properly set in the monomer mix (the recommended grade of aggregate could not be obtained). No field demonstration was attempted with this method because of the problems encountered in the laboratory demonstration.

TEXAS METHOD

Brief Description of Procedure:

The surface of the bridge deck to be treated is cleaned and air dried for seven consecutive days without rain or it can be dried for 30 minutes using heaters. Arrange 1/2" wood strips around the perimeter of the area to be treated, using latex caulking to hold the strips in place. The wood strips serve to confine the monomer mix. 2 psf of clean, dry sand is spread evenly to a 1/4" to 1/8" thickness over the area to be treated. This is followed by 1.8 psf of crushed aggregate to produce a total thickness of 3/8" to 1/2" overlay. The aggregate is rolled and compacted into the sand.

Two monomer mixes are applied to the aggregate and sand. The first monomer mix consists of 95% methyl methacrylate (MMA) and 4% Trimethylolpropane trimeltacrylate (TMPTMA). It is applied and let soak for 30 minutes. The second monomer mix consists of 48% MMA, 32% MMA syrup, 17 1/2% Butyl acreylate (BA) and 2 1/2% TMPTMA. It is applied 30 minutes after the first monomer mix was applied. Either Benzoyl peroxide (BP) or Lauroyl peroxide could be used as the initiator for the two monomer mixes. Dimethyl-P-toluidine (DMPT) is used as the accelerator for the monomer mixes. The proportions of the initiator and accelerator used depend on the ambient temperature and the cure time desired. The cure time is the period between the time the initiator is added to the monomer mix and the time the polymer concrete begins to set. In an actual field work done in Texas, 0.72 psf and 0.25 psf monomer mix loadings were used for the first and second monomer mix applications, respectfully. These loadings were more than twice the amount expected to be used because of losses due to evaporation. The produce is estimated to cost about $8.4 per square yard, depending on the amount of material losses from evaporation.

Cure Time Study:

A cure time of about 45 minutes or more is required to provide enough time for mixing the monomer mix components and applying it to the sand and aggregate. The second monomer mixtures cures faster than the first one for the same proportion of initiator and accelerator because of the syrup added to the second monomer mix. The cure time studies were done for the second monomer mix (containing the syrup) using LP as the initiator and DMPT as the accelerator (Figure 1.40). Work time as shown in the figure is the time it takes the monomer mix to jell after the initiator was added.

Laboratory Demonstration:

Polymer concrete overlays were done on three 1 ft^2 concrete slabs using this procedure in the laboratory at an ambient temperature of 78°F. The first slab was just cleaned and brushed and the overlay was done on it, using the recommended monomer mix loadings. The other two slabs were dried in an oven at 240°F for 24 hours and left for another 24 hours to cool down to room temperature (78°F). The

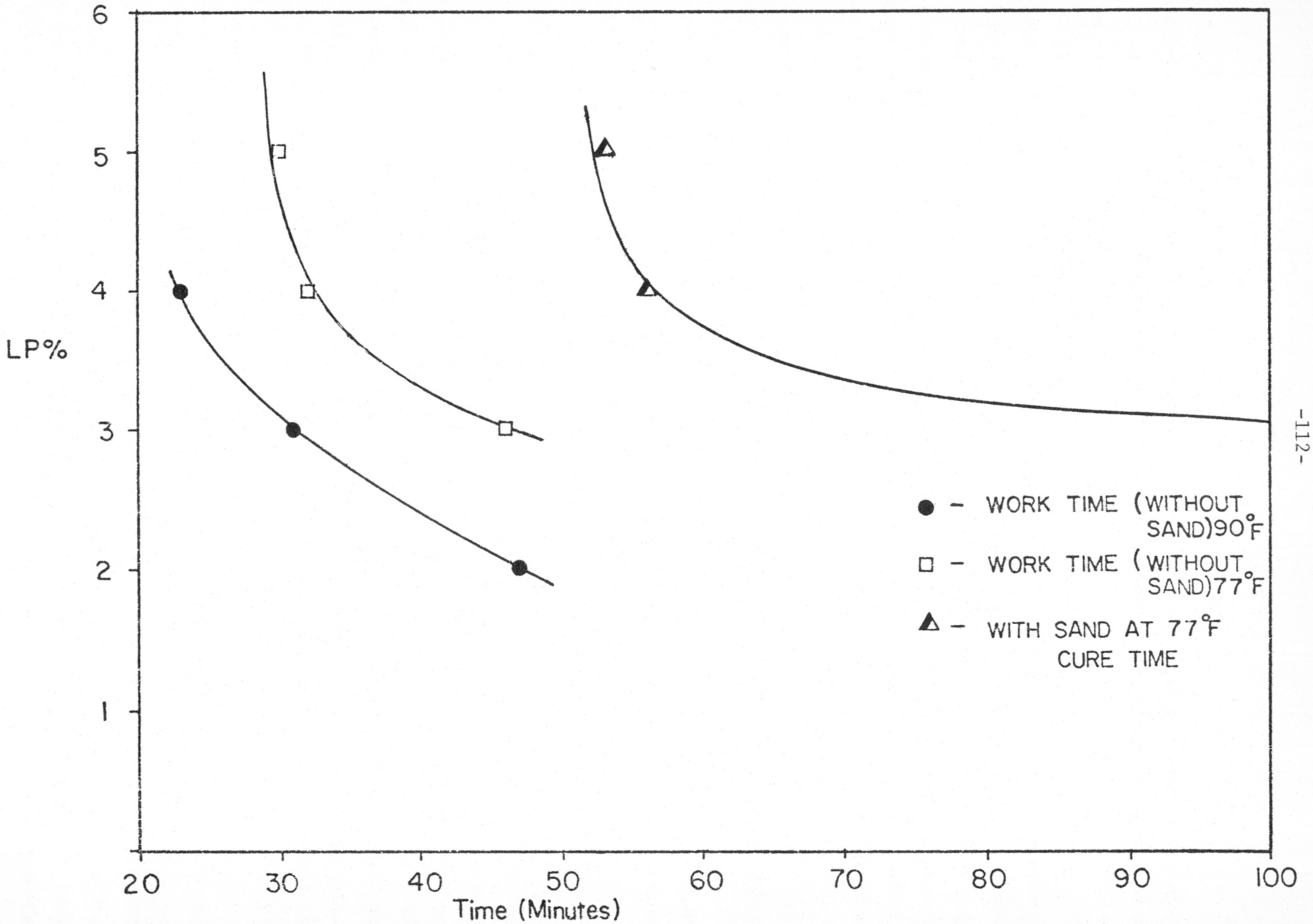


Figure 1.40 Work Time and Cure Time vs. Initiative Concentration

recommended monomer mix loadings were used on the second slab while the recommended monomer mix loadings were doubled for the third slab.

The overlay on the first slab appeared to have the best characteristics, good bonding of the aggregate to the surface of the slab and good surface appearance. The overlay on the other two slabs appeared too dry and were not well bonded to the slabs. However, the overlay on the third slab had a better appearance than the one on the second slab and seemed to be stronger too. This could be explained if we assumed that drying the slabs in the oven for 24 hours removed too much moisture from the slabs, leaving room for the monomer mix to penetrate into slab thus leaving the sand and aggregate too dry.

Small Scale Field Demonstration:

The procedure was used to place an overlay on a 6'x3.5' section of a 12'x7' concrete slab at the North base of the University of Oklahoma. The slab was cleaned and air dried for seven days. The recommended monomer mix loadings were used. The ambient temperature ranged from 75-80°F. No problem was encountered. The overlay had the desirable characteristics.

DISCUSSIONS AND RECOMMENDATIONS

Much remains to be done in the way of preparing a work plan for a large scale field application. More cure time studies are needed for the various ambient temperatures that could be encountered in large scale field application. Method A seems feasible but it requires frequent cleaning of the tools and equipment. A one and a half inch thick polymer concrete overlay does not seem justified. A one-half inch thick overlay will seal just as well the concrete bridge deck against water and deicing chlorides penetration. Such a reduction in thickness should serve to cut down the cost of the overlay and reduce the deck dead load. Maybe with the right grade of aggregate and better methods of broadcasting the aggregate on the monomer mix, Method B could be more feasible. It requires less equipment and tools than Method A and less cleaning. However, it requires a longer closure time of highways and could lead to intolerable congestion of traffic. The Texas method seems to be attractive cost-wise. Losses from evaporation could raise this cost considerably. During a recent application of this method to a bridge deck in North Texas the amount of material used was much greater than anticipated despite efforts to control evaporation.

REFERENCES

1. Report to The Congress of the United States: Solving Corrosion Problems of Bridge Surfaces could Save Billions. January 19, 1979.

2. Lipford, William A. The Nation's Bridges Problems and Progress Congressional Research Service.

3. Fowler, Paul D. and Houston, T. "Polymer-Impregnated Concrete for High-Way Applications," Research Report No. 114-1, Center for Highway Research, The University of Texas at Austin, February 1973.

4. Pita Himpraseit, Fowler, David W. and Paul, Donald R. Durability, Strength and Method of Application of Polymer Impregnated-Concrete for Slabs, January 1979.

5. Concrete Impregnated with Plastic, Lehigh University, Vol. 7, No. 1.

6. Temperature and Concrete, Publication SP-25, American Concrete Institute, Detroit, 1968.

7. Troxel, G.E., Davis, H.E., Kelly, J.W. <u>Composition and Properties of Concrete</u>, Second Edition, McGraw-Hill Book Company.

8. Fowler, D.W., Houston, J.T. and Paul, D.R. "Polymer-Impregnated of Surface Treatment for Highway Bridge Decks". Proceedings of a Symposium on Polymer in Concrete, Publication SP-40, American Concrete Institute, Detroit, 1973.

9. McNeil, Michael L, "An Investigation of the Durability Properties of Polymer-Impregnated Concrete Surface Treatments", The University of Texas at Austin, May 1973.

10. Steinberg, M., Kikeou, J.T., Kukacka, L.E., Backstrom, J.E., Colombo, P., Rubenstein, S., Kelsh, J.J. and Monowitz, B., "Concrete-Polymer Materials", First Topical Report BNL 50134 (T-509) and USBR General Report No-41, Dec. 1968.

11. Francis, J.E., Love, T.J., Calvert, F.O., Yao, L.P. and Zargar A.H. "Experimental Investigation of Solar Heating of Bridge Decks", Aerospace, Mechanics and Nuclear Engineering, University of Oklahoma.

12. Clear, Ken, "Internally Sealed Concrete For Bridge Decks," Federal Highway Administration, Washington, D.C.

13. Clear, K.C. and Hay, R.E. Time-to-Corrosion of Reinforcing Steel in Concrete Slabs, April, 1973.

14. Dikeou, J., Backstrom, K., Hickey, S., Rubenstein, C., Jones, M., Steinberg, L., KuKacka, P., Colombo, A., Auskein and Monowitz, B., Concrete-Polymer Materials, Second Topical Report BNL 50218 (T-560) and REC-OCE 70-1, 1969.

15. Manning, David J., Hope, Brian B. "The Effect of Porosity on the Compressive *Strength and Elastic Modulus of Polymer Impregnated Concrete," Cement and Concrete Research, Vol. 1, 1971.*

16. Depuy, G.W. and Dikeou, J.T., "Development of Polymer-Impregnated Concrete as a Construction Material for Engineering Projects", SP 40-3. Polymer in Concrete, American Concrete Institute, SP 40.

17. Kummer, H.W. and Meyer, W.E., "Tentative Skid-Resistance Requirements for Main Rural Highways," National Cooperative Highway Research Program, Report No. 37, 1967.

18. Hsu, H., Fowler, D., Miller, M., and Paul, D. "Polymer-Impregnated Concrete for Highway Applications," Research Report No. 114-7, Center for Highway Research, The University of Texas at Austin, March 1979.

19. Smoak, W.G., "Development and Field Evaluation of a Technique for Polymer Impregnation of New Concrete Bridge Deck Surfaces," Final Report, 1976.

20. Price, H. "Internal Structure and Load Response of Plastics, Structural Plastics Properties and POssibilities", Louisville, Kentucky,1969.

21. Meyer, Arthur Joseph, Rate Processes of Polymer Impregnation of Concrete Bridge Decks, The University of Texas, Austin, May, 1975.

22. Hammond, E. and Robson, T.D. "Comparison of Electrical Properties of Various Cements and Concretes", The Engineer (London). V.199, pp. 78-80, Jan. 1955.

23. Monfore, G.E. "The Electrical Resistivity of Concrete", Journal, PCA Research and Development Laboratories, V.10, No.2, pp. 35-48, May 1968.

24. Henry, Robert L. "Water Vapor Transmission and Electrical Resistivity of Concrete", Final Report. U.S. Naval Civil Engineering Laboratory, Technical Report R-314, June 1964.

25. Boenig, Herman V. Structure and Properties of Polymers, John Wiley & Sons, Inc., New York - Toronto, pp. 221, 1973.

26. Moore, R. Woodward, Highway Record, v. 218, pp. 221, 1973.

27. Neville, A.M. Properties of Concrete, John Wiley & Sons, Inc., New York, pp. 447-454, 1975.