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16. Abstract

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The following conclusions were reached:

1. All of the curing methods considered (involving tht use of some curing compound) proved to be effective.
2. In these tests the water soluble linseed oil curing compound (WSLO) was as effective as the white pigmented compound (WPC) in retaining moisture in the concrete.
3. Consistently, both WPC and WSLO tended to retain moisture more effectively than monomolecular film followed by white pigmented curing compound (MMF + WPC).
4. Applying MMF in two small applications instead of one large single application retained moisture more effectively except at low relative humidities.

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6. The results of this research program indicate that the use of monomolecular film during construction could be valuable in gaining time before final finishing of the surface.

# EFFECTS OF TEMPERATURE, WIND AND HUMIDITY ON SELECTED CURING MEDIA

by

Larry D. Groth

A. H. Meyer, P.E.

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Research Report 141-3

Quality of Portland Cement Concrete Pavement
as Related to Environmental Factors and
Handling Practices During Construction

Research Study 2-6-70-141

Sponsored by

The Texas Highway Department

In Cooperation with the

U. S. Department of Transportation
Federal Highway Administration

August, 1974

TEXAS TRANSPORTATION INSTITUTE
Texas A&M University
College Station, Texas

# FOREWORD

The information contained herein was developed on Research Study 2-6-70-141 titled "Quality of Portland Cement Concrete Pavement as Related to Environmental Factors and Handling Practices During Construction," in a cooperative research program with the Texas Highway Department and the Federal Highway Administration. The primary purpose of this study is to develop methods whereby the handling of portland cement concrete paving mixtures during construction can be improved.

This is the third report to be issued on this study. The others are:

Research Report 141-1, "Laboratory Study of Effects of Environment and Construction Procedures on Concrete Pavement Surfaces," November 1972.

Research Report 141-2, "First Progress Report on Concrete Experimental Test Sections in Brazos County, Texas," August 1973.

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The authors wish to acknowledge the assistance by the advisory committee for this study. They provided valuable guidance in the formulation of the research plan. The members are: (a) Texas Highway Department personnel - Mr. Steve Salek, Study Contact Representative; Mr. W. E. Elmore, Materials and Test Division Representative; Mr. B. R. English, Bridge Division Representative; and Mr. T. R. Kennedy, Planning and Research Division Representative; and (b) Federal Highway Administration personnel - Mr. Lee Gibbons, Division Representative. The authors wish to acknowledge the assistance of the following personnel in gathering and summarizing data: Mr. Sidney Greer, Mr. Leonard Ingram, Mr. Walt Lehmann, Mr. Joe Haynes, and Mr. M. B. Robertson.

# ABSTRACT

A portland cement concrete pavement should possess various qualities to be considered effective. Most important to the driving public is a smooth ride. But the pavement should also be durable and structurally sound, and should maintain surface qualities required for traffic safety with respect to skid resistance. Proper consolidation, finishing, and curing are of particular importance in the production of high quality concrete. This research study summarizes the results of two laboratory studies and one field study conducted to investigate the curing component in producing high quality concrete pavements.

The following conclusions were reached:

1. All of the curing methods considered (involving the use of some curing compound) proved to be effective.

2. In these tests the water soluble linseed oil curing compound (WSLO) was as effective as the white pigmented compound (WPC) in retaining moisture in the concrete.

3. Consistently, both WPC and WSLO tended to retain moisture more effectively than monomolecular film followed by white pigmented curing compound (MMF + WPC).

4. Applying MMF in two small applications instead of one large single application retained moisture more effectively except at low relative humidities.

5. Evaporation rates measured experimentally do not give the same trends indicated by the Portland Cement Association (PCA) chart.

6. The results of this research program indicate that the use of

monomolecular film during construction could be valuable in gaining time before final finishing of the surface.

Key Words: Concrete, Concrete Pavements, Concrete Construction, Concrete Finishing, Concrete Curing, Temperature, Wind, Humidity, Evaporation, Curing Compound.

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# 1. INTRODUCTION AND SUMMARY

## 1.1 General Remarks

Improvement should be the objective of any practiced art. The construction procedures for Continuously Reinforced Concrete Pavements (CRCP) have continued to change due to the results obtained from field experience and laboratory research. However, more information is still required if the desired improvement of such pavements is to continue. A concrete pavement must be durable when subjected to natural weathering, chemical or mechanical means used for ice and snow control, and repeated traffic loadings. It must maintain surface qualities required for traffic safety with respect to skid resistance.

Proper consolidation, proper finishing, proper curing are of particular importance in the production of high quality concrete pavements. This research study is concerned with the curing component in producing this high quality concrete. This report summarizes the results of two laboratory studies and one field study conducted to investigate curing methods.

## 1.2 Purpose of the Investigation

This study was initiated to develop methods to improve the quality of portland cement concrete pavements through laboratory examination of construction practices related to the curing of the concrete pavement.

## 1.3 Scope

The scope of this investigation included the determination of the combined effects of wind velocity, air temperature and relative humidity, type of curing compound, and method of applying the curing compound on evaporation of water from the surface of the concrete pavement.

## 1.4 Conclusions

The following conclusions were reached after laboratory and field evaluations were made on high quality, low slump concrete.

1. All of the curing methods considered (involving the use of some curing compound) proved to be significantly more effective than using no cure.

2. In these tests the water soluble linseed oil curing compound (WSLO) was as effective as the white pigmented curing compound (WPC) in retaining moisture in the concrete.

3. Consistently both WPC and WSLO tended to retain moisture more effectively than monomolecular film followed by WPC (MMF + WPC).

4. Applying MMF in two small applications instead of one large single application retained moisture more effectively with the exception of low relative humidities.

5. Evaporation rates measured experimentally do not give the same trends indicated by the Portland Cement Association (PCA) chart.

6. The results of this research program indicate that the use of monomolecular film during construction could be valuable in gaining time before final finishing of the surface.

## 1.5 Recommendations for Implementation

Based on the findings of this study the following recommendations for implementation are made:

1. Based on the tests made in this study it is recommended that the monomolecular film continue to be used under emergency conditions in order to gain time.

2. Recommend consideration by given to experimentally permitting the use of WSLO as a curing medium for portland cement concrete pavements to provide field evaluation of this product.

These recommendations for implementation are made jointly by the authors and the study Contact Representative.

## 2. BACKGROUND

### 2.1 Curing

The effectiveness of curing has been found to influence the durability and wear resistance of a concrete pavement surface.[1*] If the cure is not applied properly, much of its effectiveness is lost, and the durability and wear resistance of the pavement are affected adversely. Therefore, proper use of curing methods is essential in order to develop high quality portland cement concrete pavement.

The surface properties of portland cement concrete are greatly affected by the combined effects of wind velocity, air temperature and relative humidity, concrete temperature, and type of curing compound.

Properties of concrete such as resistance to freezing and thawing, strength, water tightness, wear resistance, and volume stability improve with age as long as conditions are favorable for continued hydration of the cement. These favorable conditions include the presence of moisture and a proper temperature.[2] Hydration virtually ceases when concrete dries below a relative vapor pressure (relative humidity) of about 0.80.[3] At this pressure the water-filled capillaries begin to empty. Since hydration occurs in these water-filled spaces, the effective curing time is limited to that period during which the relative humidity in the concrete is above 80 percent. When the concrete is placed in an environment with a vapor pressure less than that of saturated air, the concrete will lose water by evaporation. Excessive loss of water by evaporation removes the moisture necessary for full hydration and improved concrete quality.

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[*] Superscript Arabic numbers refer to corresponding items in the list of references (Sec. 5.5).

Therefore, it is necessary to retard the evaporation in some manner. Concrete sealed against evaporation must initially contain more than about 0.5 gm of water per gm of cement to insure full hydration, since self-desiccation progressively reduces the space available for hydration products.[3] Membrane cure used as a sealant will not assure full hydration, but may provide adequate moisture for most of the hydration to occur.

Because of increased labor costs and rapid construction pace, an increasing number of portland cement concrete pavements are being cured with membrane-forming curing compounds. Although it is recognized that moist-curing methods (ponding, sprinkling, wet coverings) best insure continued cement hydration, membrane-cured concretes have given creditable performance.[4]

The object of membrane curing is to seal the exposed surface with an impervious membrane in order to prevent the evaporation of the water which is necessary for the hydration of the cement. In addition, the membrane may have a white or light color so that it will reflect a considerable amount of heat from the sun. This helps maintain a more favorable curing temperature.

Field and laboratory tests have been conducted to evaluate several combinations of curing and protective treatments for concrete. A study conducted by the Virginia Highway Research Council evaluated concrete panels cured with white pigmented liquid membrane (WPC) and white polyethylene, both with and without subsequent treatments using linseed oil.[5] On some panels a monomolecular film (MMF) was used to reduce evaporation prior to regular curing. Results showed that a film of linseed oil (in mineral spirits) continued to be the most satisfactory of the several alternatives practically available for improved quality. Monomolecular film was used on days where a high evaporation potential existed, or when there was a delay in applying the curing compound.

Researchers with the Pennsylvania Department of Highways and Kansas State University, in their evaluation of concrete protective sealants and curing compounds, reported that linseed oil (in mineral spirits) proved superior.[6,7] Linseed oil appears to act as a perma-selective membrane in that it permits the penetration of water into hardened cement paste at a reduced rate, but prevents the penetration of salts and other chemicals.

Field and laboratory tests conducted at Utah State University have demonstrated that a monomolecular film will serve as a suitable evaporation retarder on the surface of the concrete. A typical material which will serve as a suitable evaporation retarder is composed of molecules having a long hydrocarbon chain, which is hydrophobic, attached to a hydrophillic alcohol terminal group. The long hydrophobic chain orients itself vertically on the surface of the bleed water as illustrated in Figure 2-1.[8] If sufficient molecules are present, they form a tightly compressed, effective film. Water molecules may not possess sufficient energy to escape through this long chain film and evaporation is significantly retarded.

## 2.2 Plastic Shrinkage Cracking

A problem that is affected by surface properties of the concrete involves plastic shrinkage. Plastic shrinkage cracking is usually associated with hot weather concreting and may develop whenever the rate of evaporation is greater than the rate at which water rises to the surface

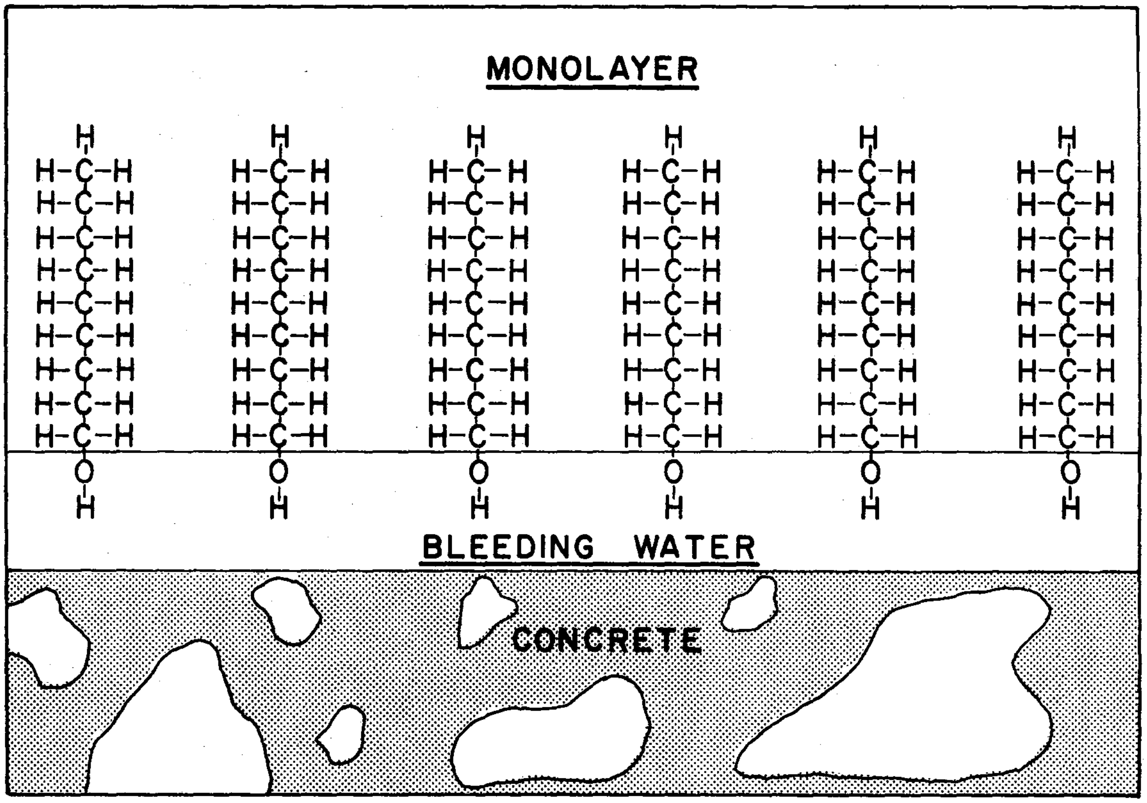
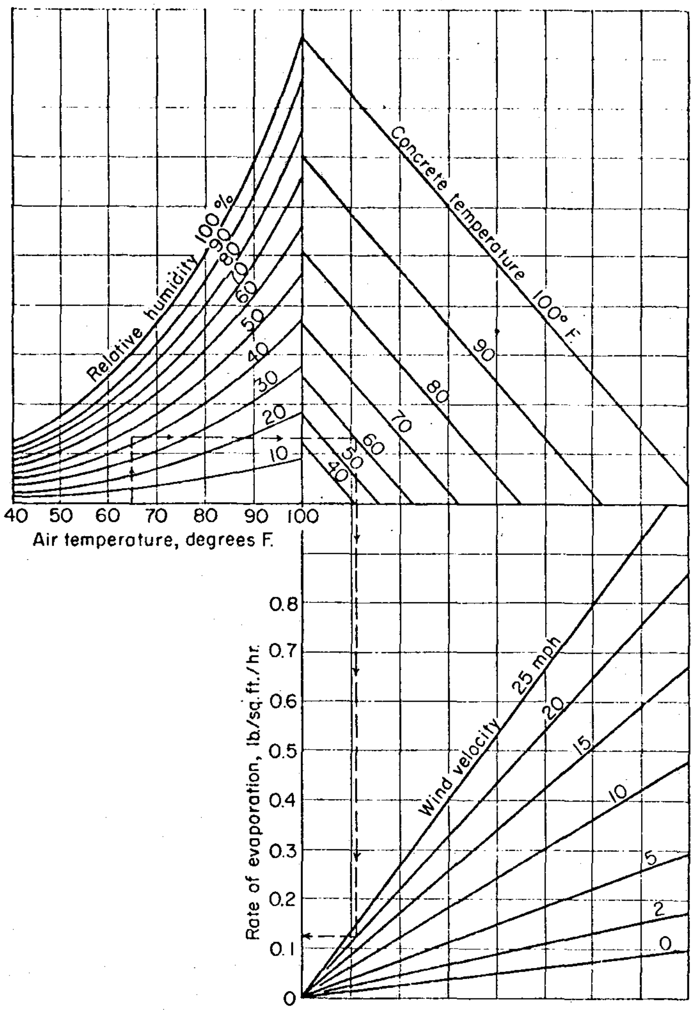


Fig. 2-1. Film Forming Molecules Properly Oriented on the Surface of Bleeding Water (Cordon and Thorpe Ref. 8).

of the fresh concrete. Plastic shrinkage also occurs in spring and fall when there are higher winds and lower humidities.[9] Evaporation causes the concrete to shrink creating tensile stresses at the drying surface. Liquid-membrane curing compounds are utilized to retard or prevent evaporation of moisture from the concrete. Without the application of these curing compounds, stresses will develop before the concrete has attained adequate strength, resulting in surface cracking.[2,8,10] Plastic shrinkage cracks vary in length from 2 to 3 inches to about 3 to 7 feet.[11] They have depths up to 4 inches.[10] Unless cracks are quite shallow and narrow, they can weaken the pavement, permit penetration of moisture and render the reinforcement vulnerable to corrosion.[12] Therefore, it is very important that a method of curing which retards evaporation to preventing plastic shrinkage cracks be used.

Field investigations have shown that the characteristics of the concrete do not have a major influence on plastic shrinkage.[10] This has led to the preparation, by the Portland Cement Association (PCA), of a chart indicating the interrelationship between air temperature, relative humidity, concrete temperature, wind velocity, and rate of evaporation of surface moisture.[2] This chart, Figure 2-2, is based on data obtained by Menzel.[10] PCA states that evaporation rates above about 0.2 lbs/sq ft/hr may increase the possibility of plastic shrinkage cracking and that at rates below 0.1 plastic shrinkage cracking will probably not occur.[2]



TO USE THIS CHART:

1. ENTER WITH AIR TEMPERATURE, MOVE UP TO RELATIVE HUMIDITY.
2. MOVE RIGHT TO CONCRETE TEMPERATURE.
3. MOVE DOWN TO WIND VELOCITY.
4. MOVE LEFT; READ APPROX. RATE OF EVAPORATION.

Fig. 2-2. Effect of Concrete and Air Temperatures, Relative Humidity, and Wind Velocity on the Rate of Evaporation of Surface Moisture from Concrete (PCA Ref. 2)

# 3. EXPERIMENTAL METHODS AND PROCEDURES

## 3.1 General

The results given in this report are obtained from data collected during three investigations. The first was a laboratory study conducted during the summer, 1971. Three variables included in the evaporation rate test of this study were: (1) wind, (2) curing environment, and (3) curing method. The second investigation was again a laboratory study conducted during January, 1973. Curing environment and curing method constituted the variables used during this study. Both of these laboratory studies were conducted at McNew Laboratory at Texas A&M University. The third set of evaporation data was obtained during a field investigation near Van Horn, Texas along Interstate Highway 10 in September, 1973. Five curing methods were tested under the existing natural environmental conditions. Table 3-1 gives the various variables used in the tests with code designations. Table 5-1 gives a complete description of the curing methods.

## 3.2 Evaporation Rate Data

All three investigations employed the same methods to determine evaporation rate. Slabs were made using steel forms (72 x 26 x 8 in.) with two wooden dividers to separate the concrete into three equal smaller slabs. These three slabs were, in turn, each subjected into two different curing treatments on each half. In each of these halves, as illustrated in Figure 3-1, there was a smaller metal box (6 x 4 x 4 in.) which was inside a wooden box. These smaller metal boxes were designed to be lifted out and weighed periodically on a 10,000 gm capacity balance (sensitivity 0.29 gm), obtaining the loss of weight due to the evaporation of water.

TABLE 3-1. Variable Code Designations

| Variable | | Code Symbol |
|---|---|---|
| Study Site and Date | McNew Laboratory, Summer 1971 | $S_1$ |
| | McNew Laboratory, January 1973 | $S_2$ |
| | Van Horn, Texas, September 1973 | $S_3$ |
| Wind | 0 mph | $W_1$ |
| | 8-10 mph | $W_2$ |
| | 18-20 mph | $W_3$ |
| | 0-10 mph (Van Horn) | $W_4$ |
| Curing Environment | 51°F - 23% R.H. | $E_1$ |
| | 57°F - 50% R.H. | $E_2$ |
| | 73°F - 25% R.H. | $E_3$ |
| | 100°F - 30% R.H. | $E_4$ |
| | 140°F - 25% R.H. | $E_5$ |
| | 80-95°F - 10-25% R.H. (Van Horn) | $E_6$ |
| Curing Method | White Pigmented Curing Compound-Resin Based (WPC) | 1 |
| | Monomolecular Film (one application) Plus White Pigmented Curing Compound (MMF(1) + WPC) | 2 |
| | Monomolecular Film (two applications) Plus White Pigmented Curing Compound (MMF(2) + WPC) | 3 |
| | Water Soluble Linseed Oil (WSLO) | 4 |
| | No Curing Compound | 5 |

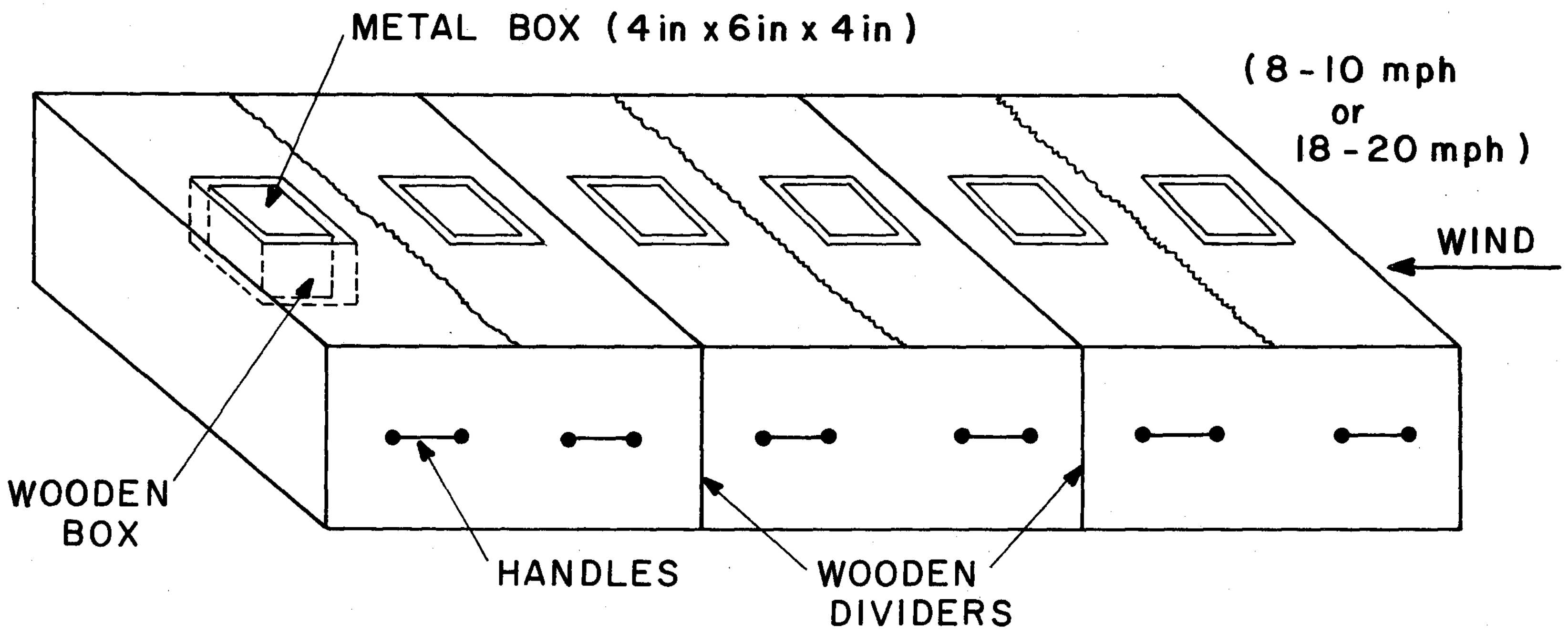


Fig. 3-1. Concrete Slab Setup.

Concrete was placed in the forms in three layers, vibrated in place, finished with a burlap drag, and the proper cure applied to the surface. To simulate outdoor conditions in the laboratory investigations, the slabs were cast in controlled environmental rooms at Texas A&M University. Wind was generated over the surface of the slabs by use of a squirrel-cage blower at the end of the slabs. In order to insure uniform air-flow, two-foot high walls were placed along each side of the slabs to channel the air. Wind velocity measurements indicated the velocity varied within ± one mph throughout the slab surfaces. Locations of each specific curing treatment were randomized in the various environments and wind conditions. Further details are given in Sec. 5.1.

# 4. RESULTS AND DISCUSSION

## 4.1 General

The data and results which follow are from the following sources: Texas A&M in summer of 1971, Texas A&M in summer of 1973, and Van Horn, Texas in September, 1973. Testing procedures were normalized so that correlations could be determined between the study sites and variables tested. The data and figures represented are generally the average values of two test specimens produced during each investigation. It should be remembered that only high quality concrete with no discernible bleeding was used in this research (slump 1 in. ± 1/2 in.). The major results are summarized in the following sections with respect to each study site. All of the figures were obtained from the data in Table 5-2.

## 4.2 Laboratory Summer 1971

As discussed in Section 3.2, measurements of water loss from the surface of the test slabs were recorded until the loss became negligible. Four types of curing methods were considered -- monomolecular film followed by white pigmented curing compound[MMF(1) + WPC], water soluble linseed oil curing compound (WSLO), white pigmented curing compound (WPC), and no cure (Table 5-1). The following wind velocities were employed: 0, 8-10, 18-20 mph. Three curing conditions were considered: (1) 73°F - 25% RH, (2) 100°F - 30% RH, and (3) 140°F - 25% RH.

Figures 4-1 through 4-6 show results from this study with water loss being plotted against time. The figures are representative of the effectiveness of each curing compound's ability to retain water when exposed to various environmental conditions. By simple comparison it can be clearly

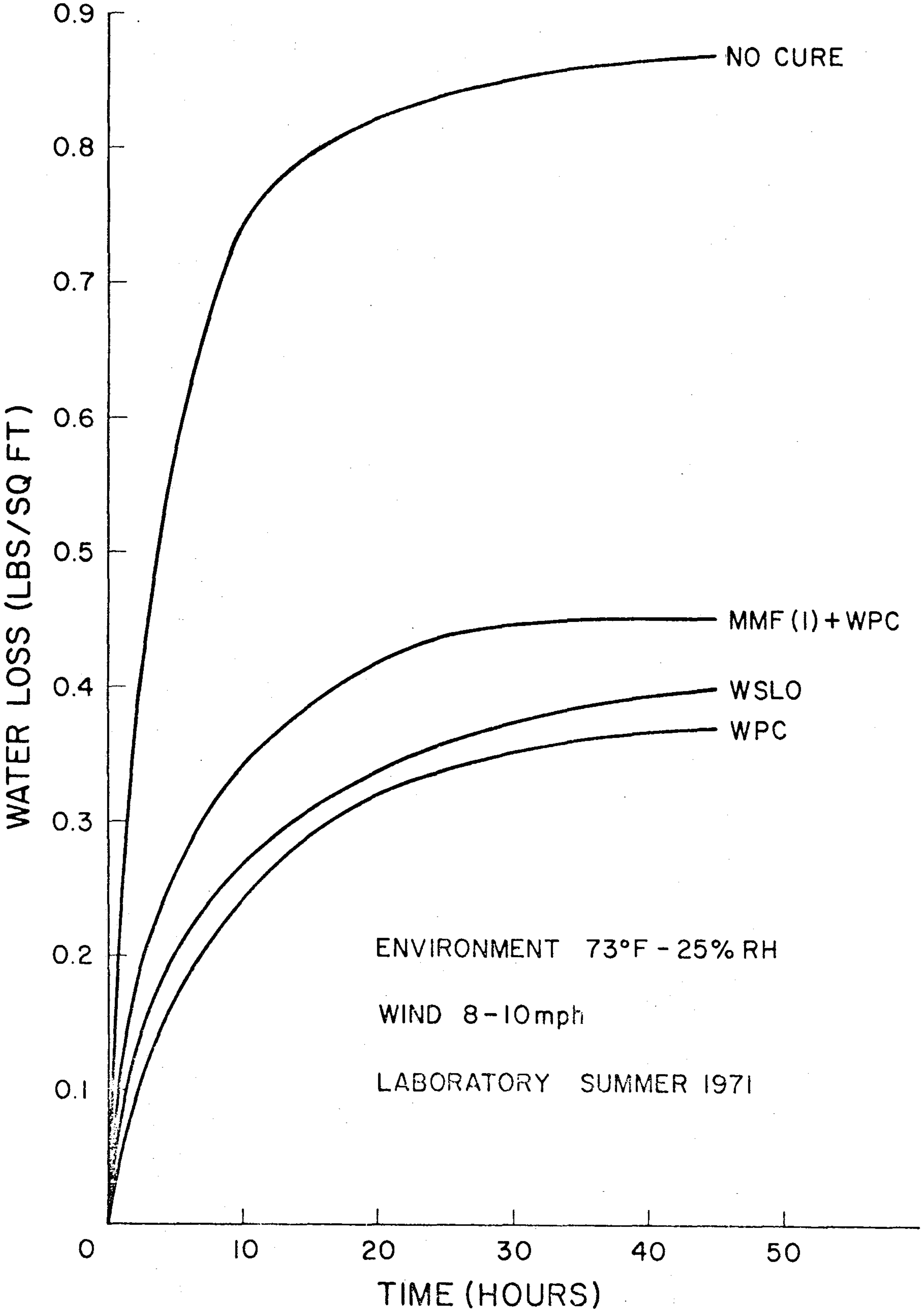


Fig. 4-1. Effect of Curing Method on the Evaporation of Water from the Surface of the Concrete Slabs at a Curing Temperature of 73°F, Relative Humidity of 25%, and Wind Velocity of 8-10 mph.

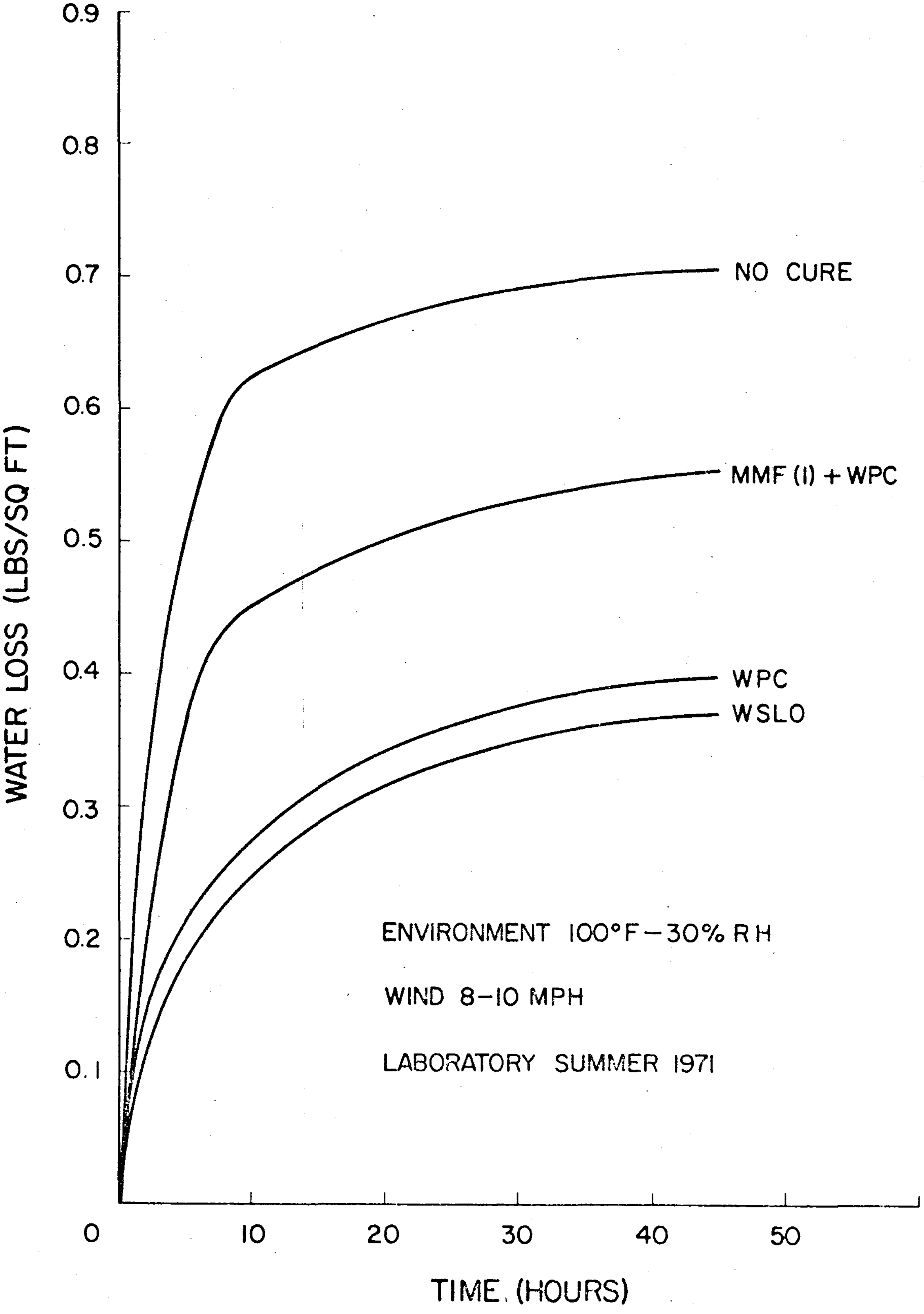


Fig. 4-2. Effect of Curing Method on the Evaporation of Water from the Surface of the Concrete Slabs at a Curing Temperature of 100°F, Relative Humidity of 30%, and Wind Velocity of 8-10 mph.

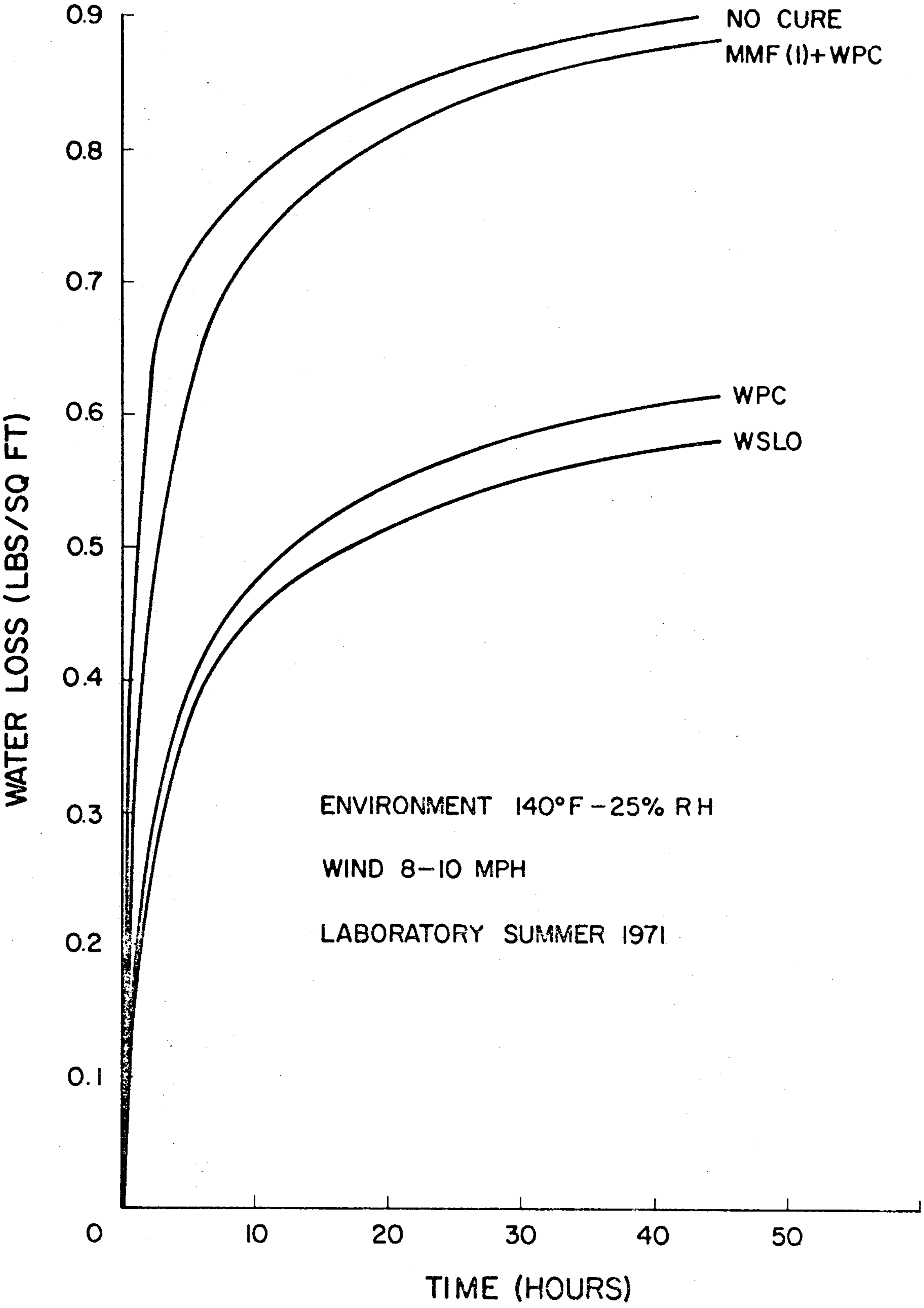


Fig. 4-3. Effect of Curing Method on the Evaporation of Water from the Surface of the Concrete Slabs at a Curing Temperature of 140°F, Relative Humidity of 25%, and Wind Velocity of 8-10 mph.

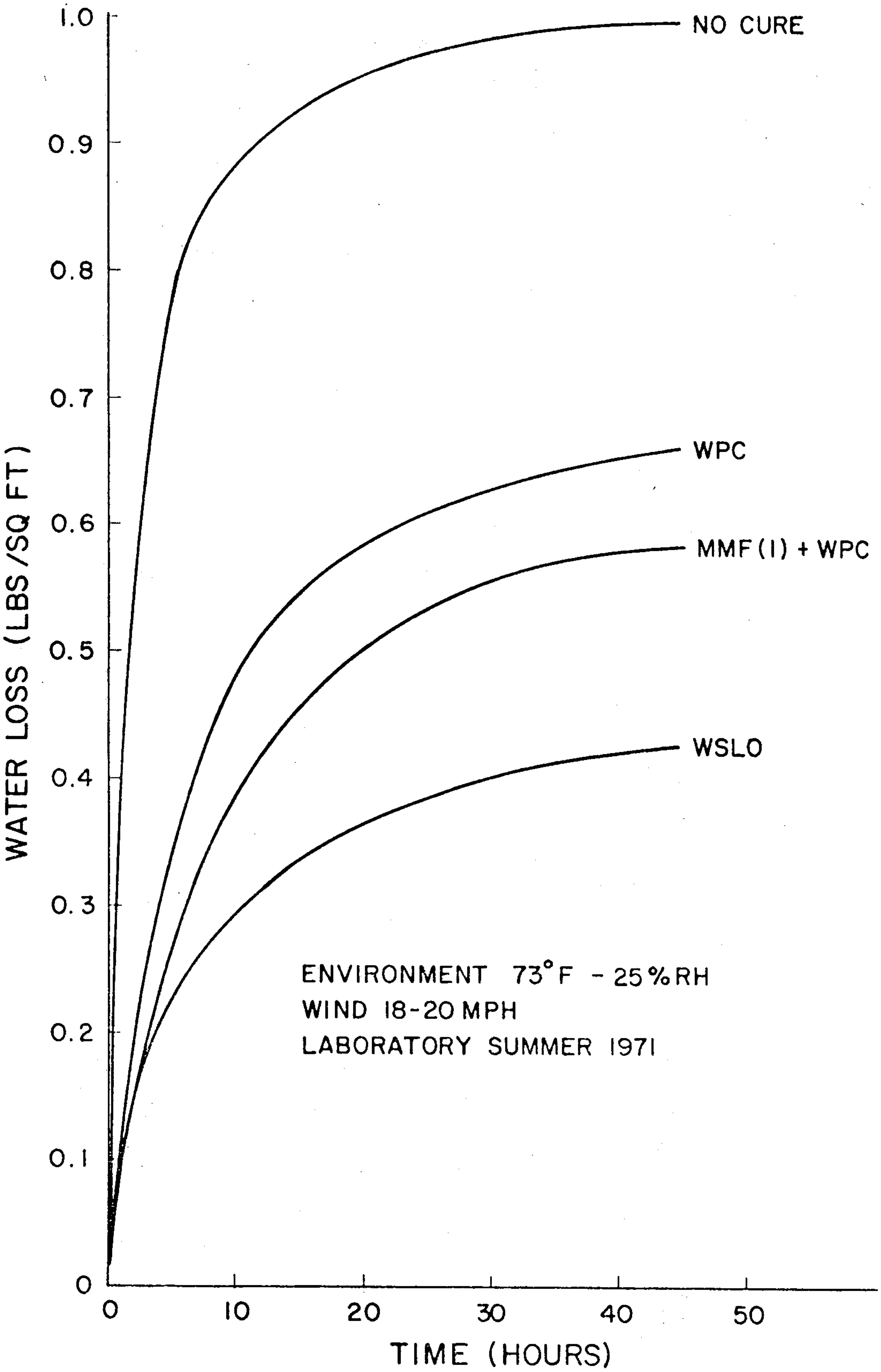


Fig. 4-4. Effect of Curing Method of the Evaporation of Water from the Surface of the Concrete Slabs at a Curing Temperature of 73°F, Relative Humidity of 25%, and Wind Velocity of 18-20 mph.

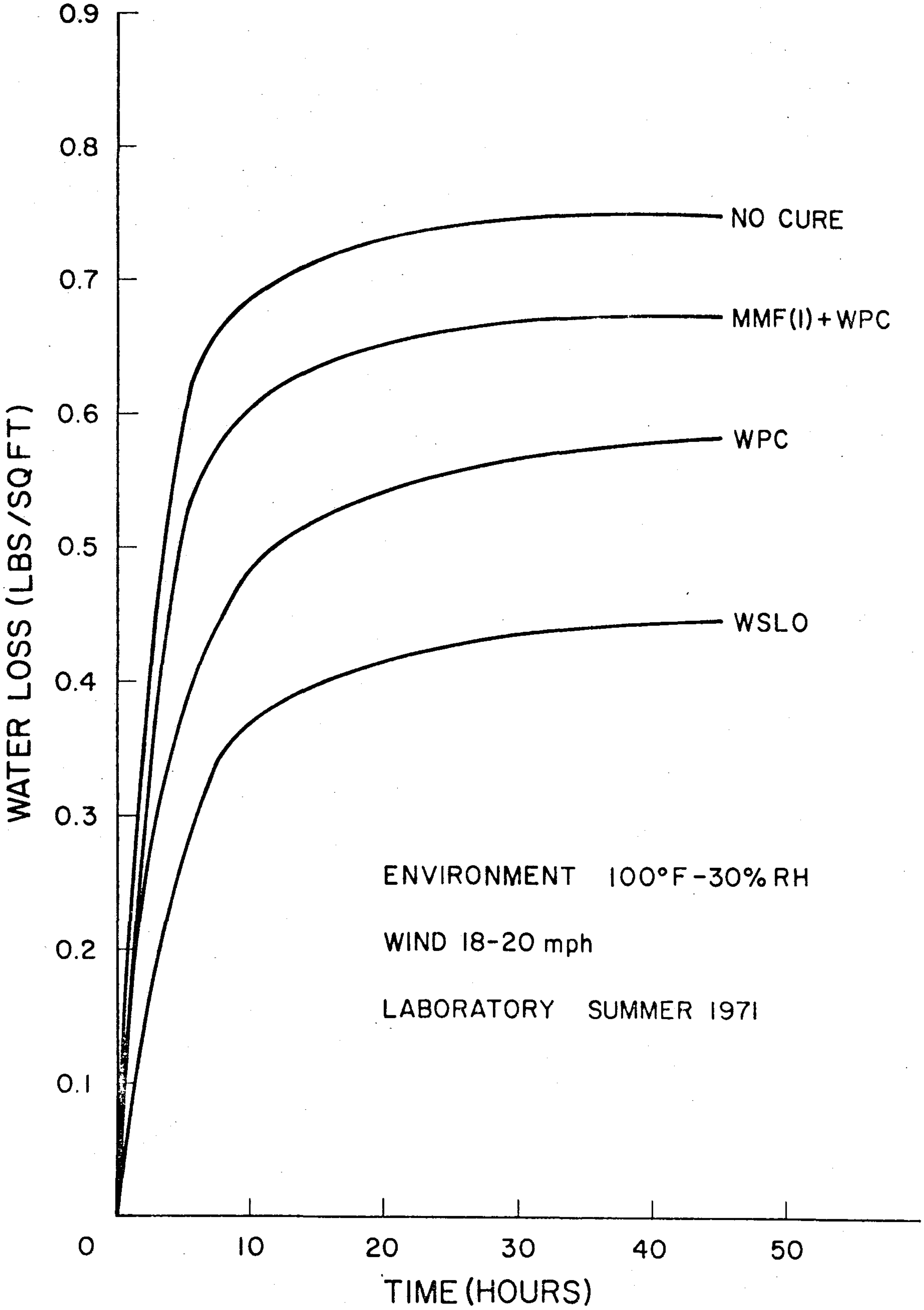


Fig. 4-5. Effect of Curing Method on the Evaporation of Water from the Surface of the Concrete Slabs at a Curing Temperature of 100°F, Relative Humidity of 30%, and Wind Velocity of 18-20 mph.

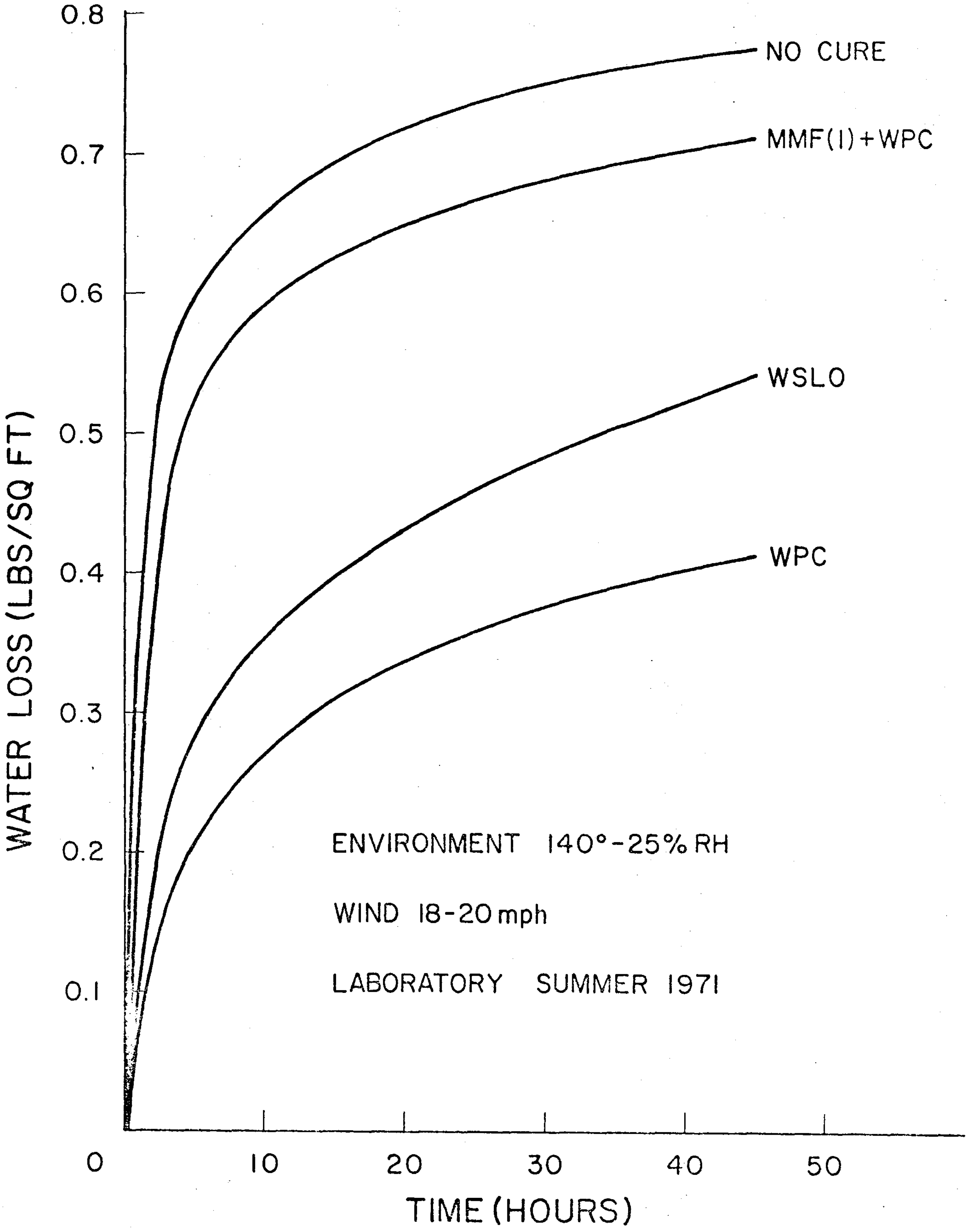


Fig. 4-6. Effect of Curing Method on the Evaporation of Water from the Surface of the Concrete Slabs at a Curing Temperature of 140°F, Relative Humidity of 25%, and Wind Velocity of 18-20 mph.

seen that the slabs without any curing compound (no cure) exhibited considerably higher water loss than any of those with a curing compound. Further examination of these six figures shows that no significant benefits were obtained by adding a monomolecular film prior to the application of white pigmented curing compound. It should be noted that a single application of monomolecular film was used, at the highest rate recommended by the manufacturer. For every environmental condition, except 73°F - 25% RH and wind 18-20 mph, the water soluble linseed oil (WSLO) and the white pigmented curing compound (WPC) retarded the rate of evaporation better than MMF (1) + WPC. In fact, at least a 15 percent reduction in water loss was noted with use of WSLO and WPC as opposed to MMF (1) + WPC at 73°F and 8-10 mph (Figure 4-1), and there was a reduction of 30 percent at 140°F and 8-10 mph (Figure 4-3).

### 4.3 Laboratory January 1973

Three curing methods were considered in this phase of the study -- monomolecular film (single application) followed by white pigmented curing compound (MMF (1) + WPC), white pigmented curing compound (WPC), and monomolecular film (two applications) followed by white pigmented curing compound (MMF (2) + WPC) (see Tables 5-1 in details). In using this third curing method, it was thought that perhaps two smaller applications of MMF would be more effective than one large single application. The wind conditions were held constant at 8-10 mph. Four curing conditions were employed: (1) 51°F - 23% RH, (2) 57°F - 50% RH, (3) 100°F - 30% RH and (4) 140°F - 25% RH. In the 51°F - 23% RH environmental condition a no-cure specimen was included.

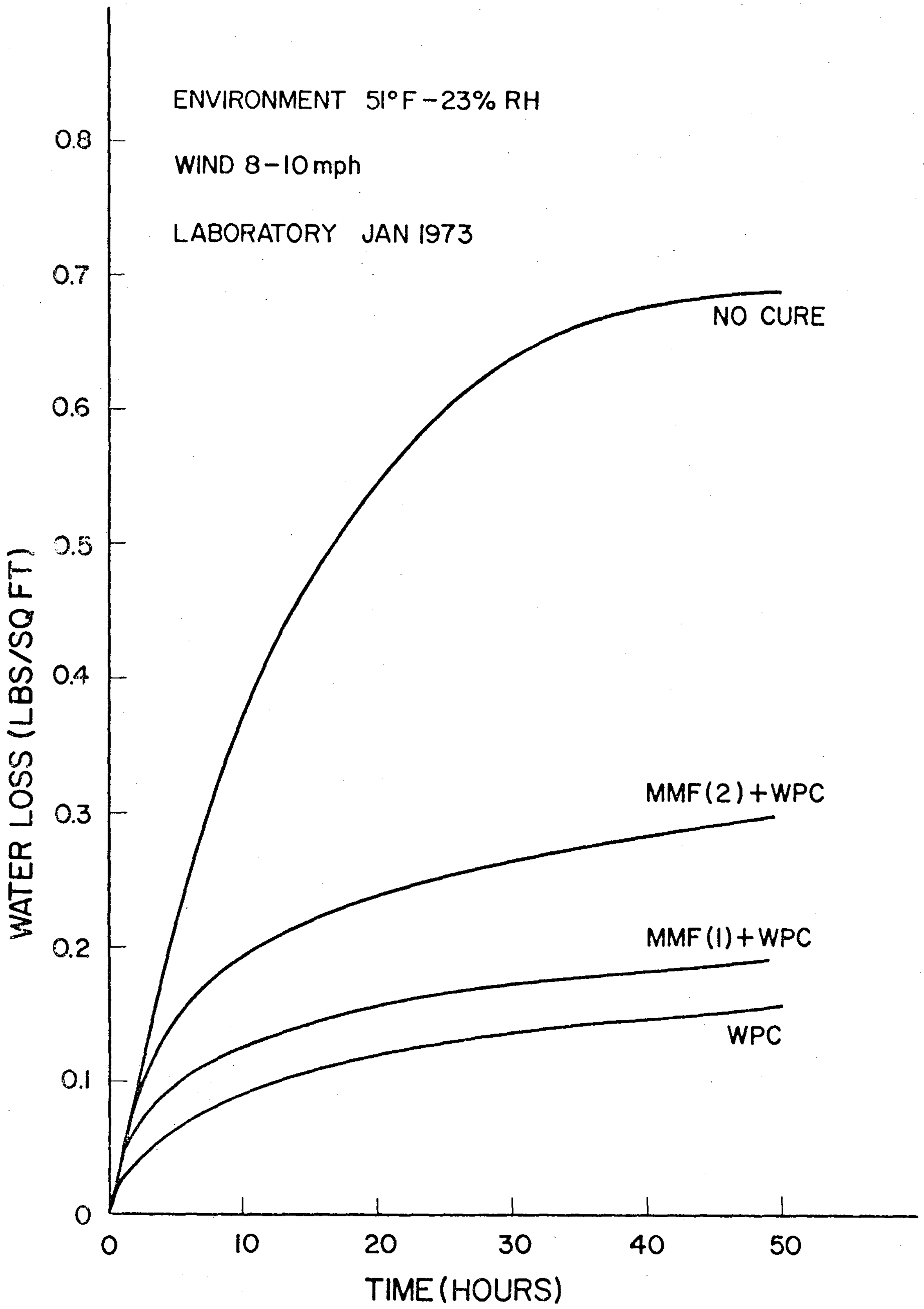


Fig. 4-7. Effect of Curing Method on the Evaporation of Water from the Surface of the Concrete Slabs at a Curing Temperature of 51°F, Relative Humidity of 23%, and Wind Velocity of 8-10 mph.

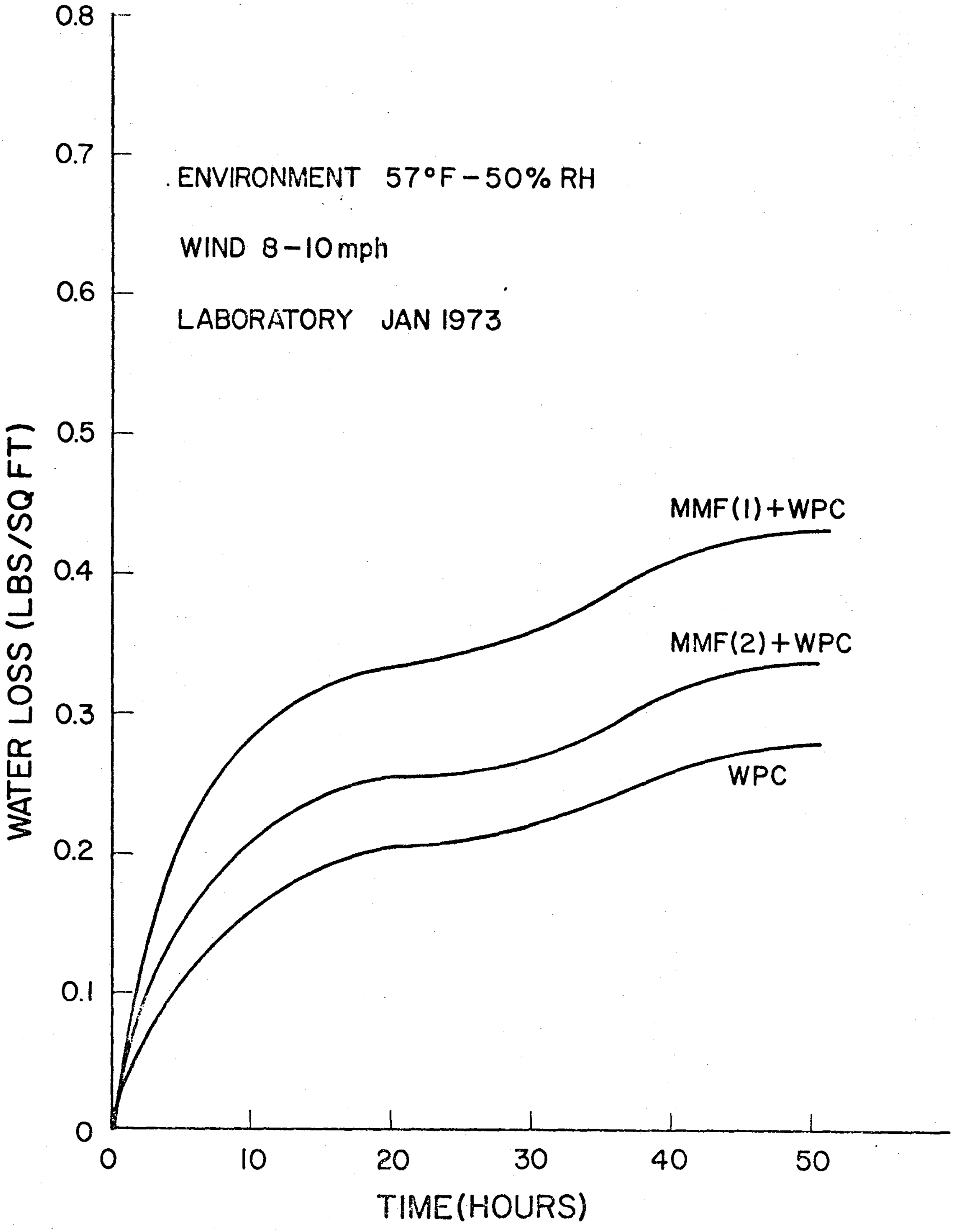


Fig. 4-8. Effect of Curing Method on the Evaporation of Water from the Surface of the Concrete Slabs at a Curing Temperature of 57°F, Relative Humidity of 50%, and Wind Velocity of 8-10 mph.

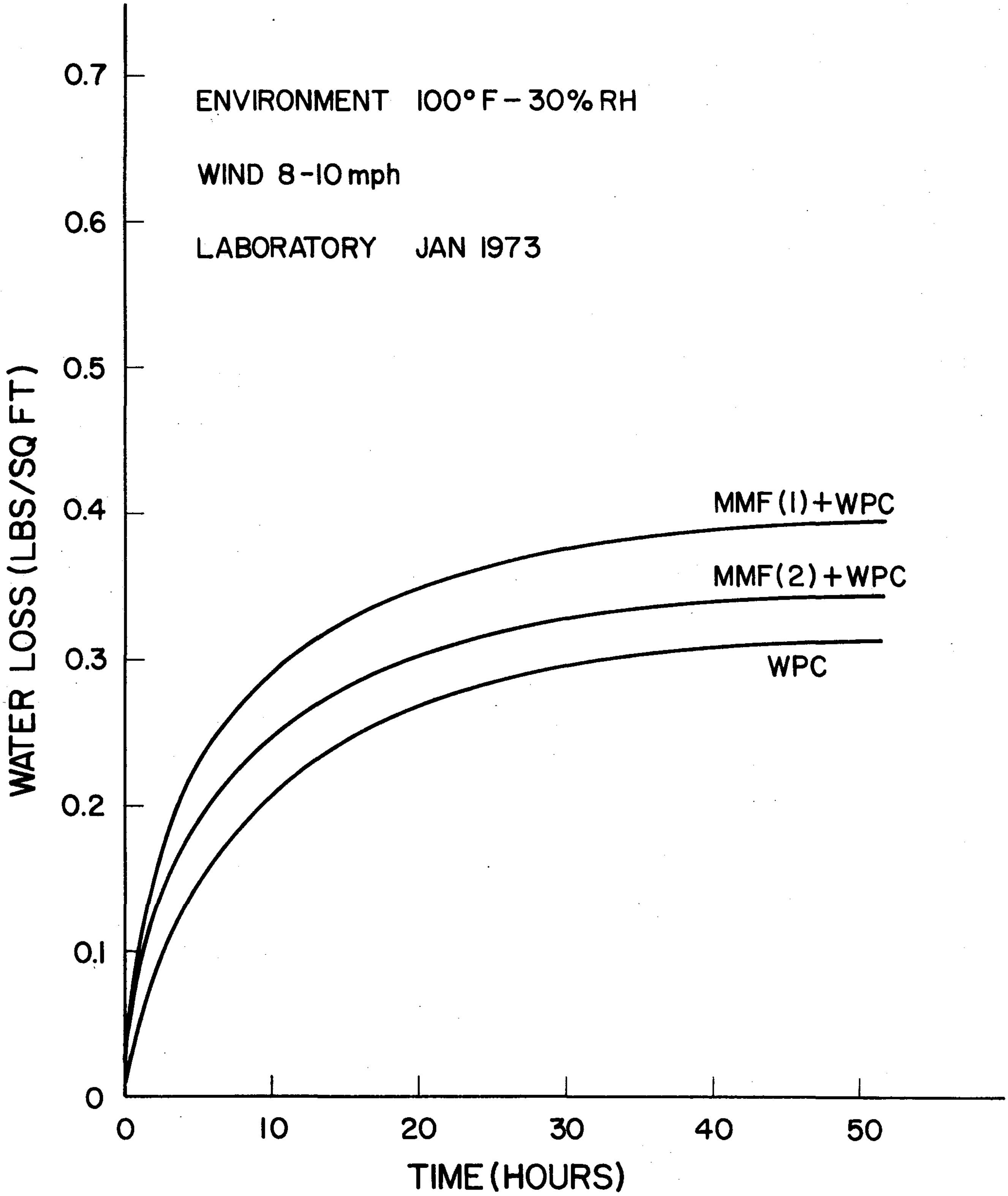


Fig. 4-9. Effect of Curing Method on the Evaporation of Water from the Surface of the Concrete Slabs at a Curing Temperature of 100°F, Relative Humidity of 30%, and Wind Velocity of 8-10 mph.

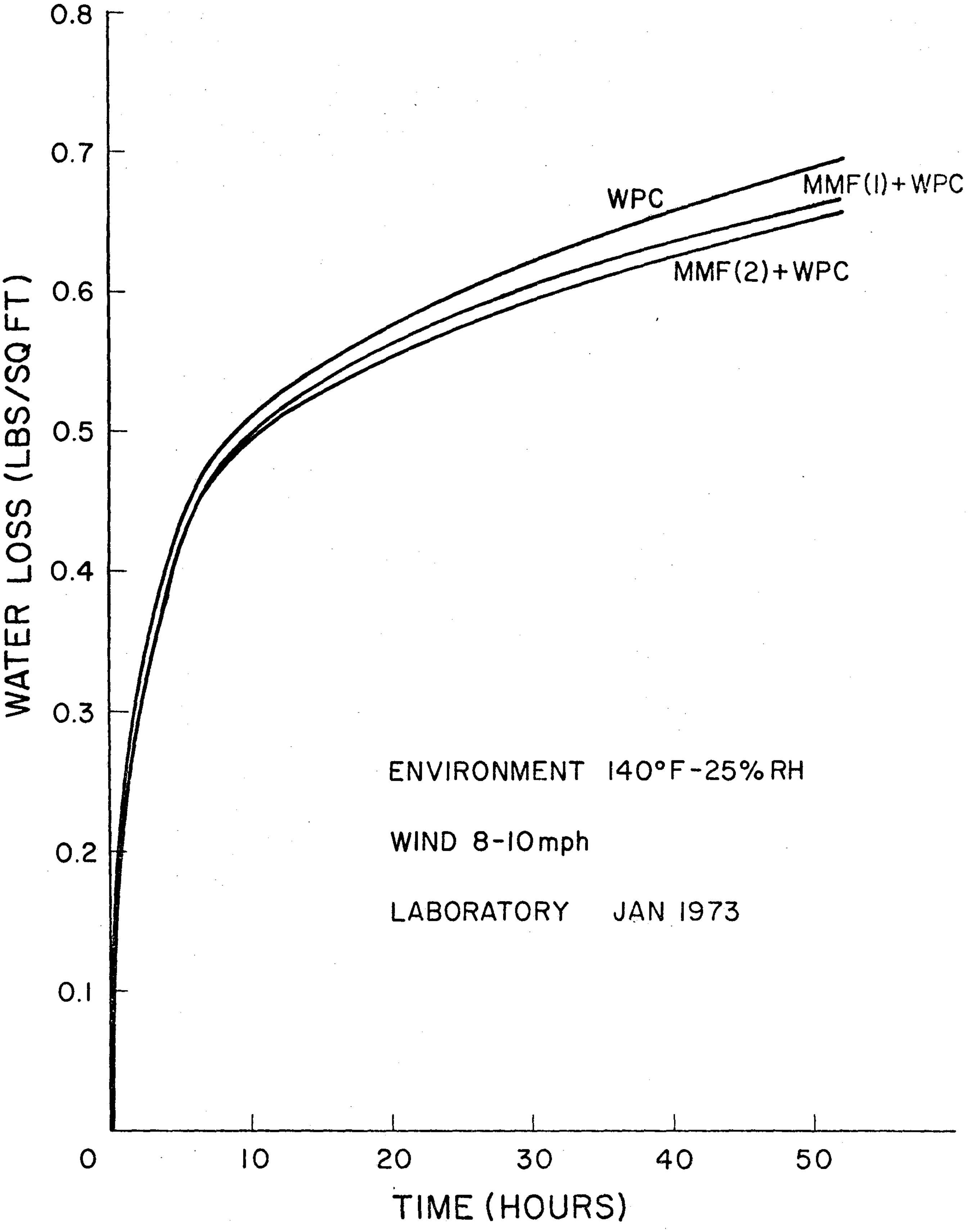


Fig. 4-10. Effect of Curing Method on the Evaporation of Water from the Surface of the Concrete Slabs at a Curing Temperature of 140°F, Relative Humidity of 25%, and Wind Velocity of 8-10 mph.

Figures 4-7 through 4-10 represent the data obtained from this investigation. In all cases, except 140°F - 25% RH, the white pigmented curing compound was found to be the most effective evaporation retarder. Applying MMF in two applications generally improved its effectiveness (except in 51°F - 23% RH). Again there was a significant difference between using any of the three curing methods and no cure (Figure 4-7). As in the previous section, it can be stated again that there was no significant benefit gained by applying monomolecular film before finishing. Applying it in two applications instead of one, however, did improve its effectiveness.

### 4.4 Field Study - Van Horn, September 1973

Five curing methods were tested in this phase of the study: MMF (1) + WPC, MMF (2) + WPC, WPC, WSLO, and no cure. Because this test was conducted outside in a natural environment, the conditions varied somewhat. The air temperature ranged from 80° - 95°F during the day and decreased to as low as 60°F at night. The relative humidity ranged from 10 to 25 percent. The wind conditions varied from 0 to 10 mph.

Figure 4-11 contains the results of this series of tests. All four curing compounds greatly reduced the evaporation loss compared to the no-cure method. The material with two applications of MMF lost more water than did that with only one application, as was the case in the 51°F - 25% RH condition (Figure 4-7). As the difference between MMF (1) + WPC and MMF (2) + WPC at 140°F = 25% RH was insignificant (Figure 4-10), it is hypothesized that single applications of MMF are more effective at low relative humidities than two smaller applications. Figure 4-11 shows that WSLO, WPC, and MMF (1) + WPC all proved to be effective cures with little difference in results between any of the three.

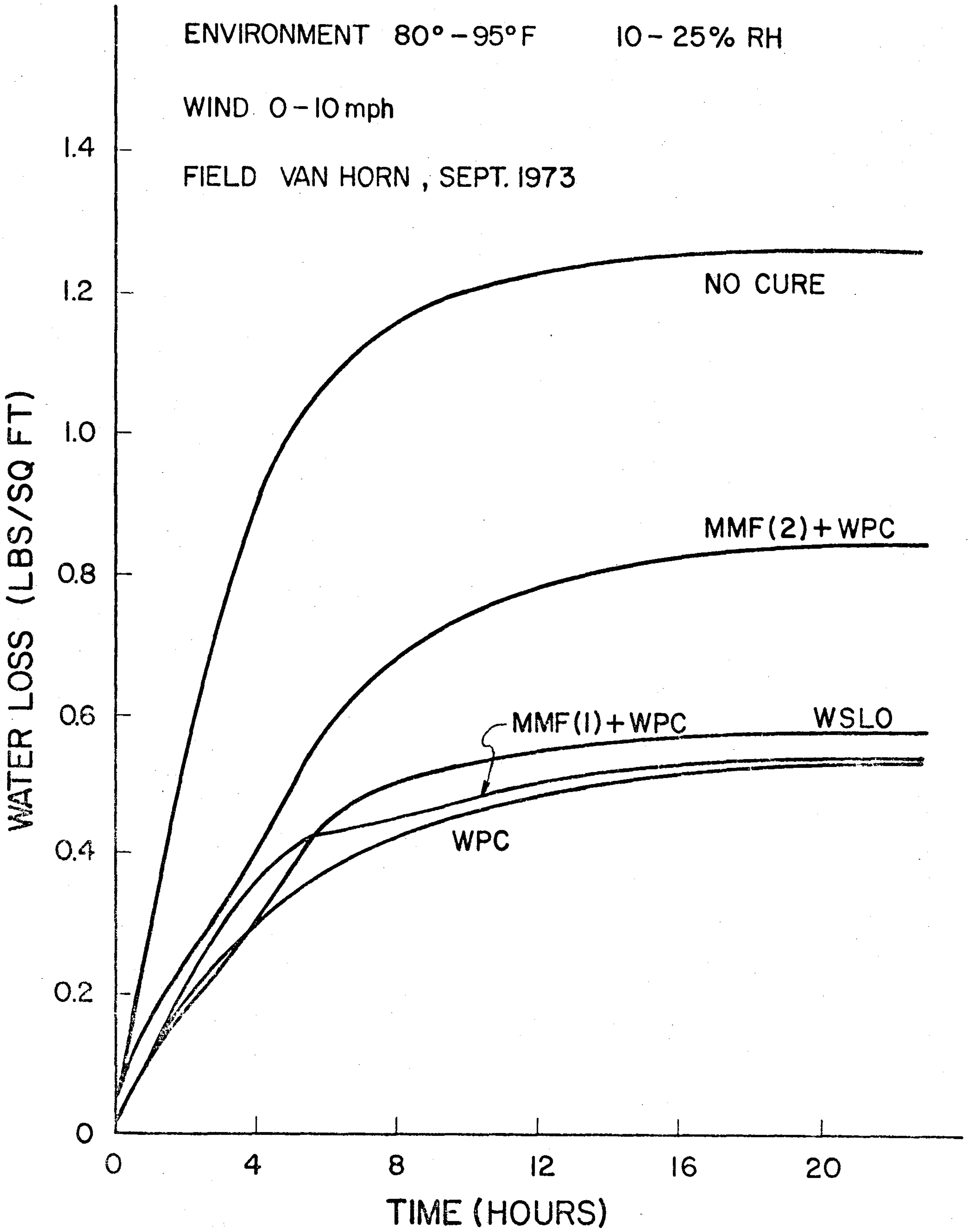


Fig. 4-11. Effect of Curing Method on the Evaporation of Water from the Surface of the Concrete Slabs at a Curing Temperature of 80-95°F, Relative Humidity of 10-25%, and Wind Velocity of 0-10 mph.

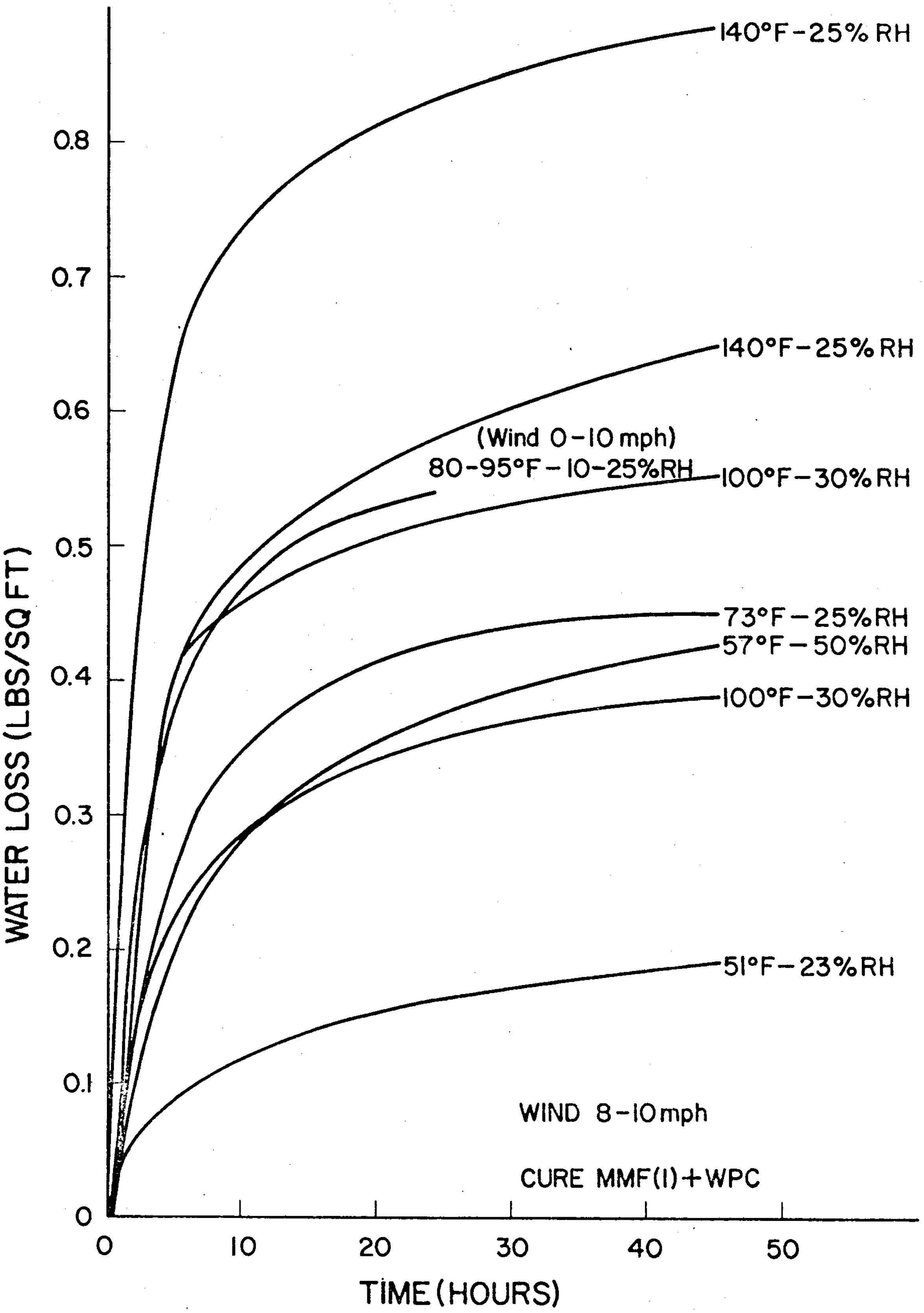


Fig. 4-12. Effect of Temperature on the Evaporation of Water from the Surface of the Concrete Slabs Maintaining Constant Curing Method (MMF(1) + WPC) and Wind Conditions of 8-10 mph.

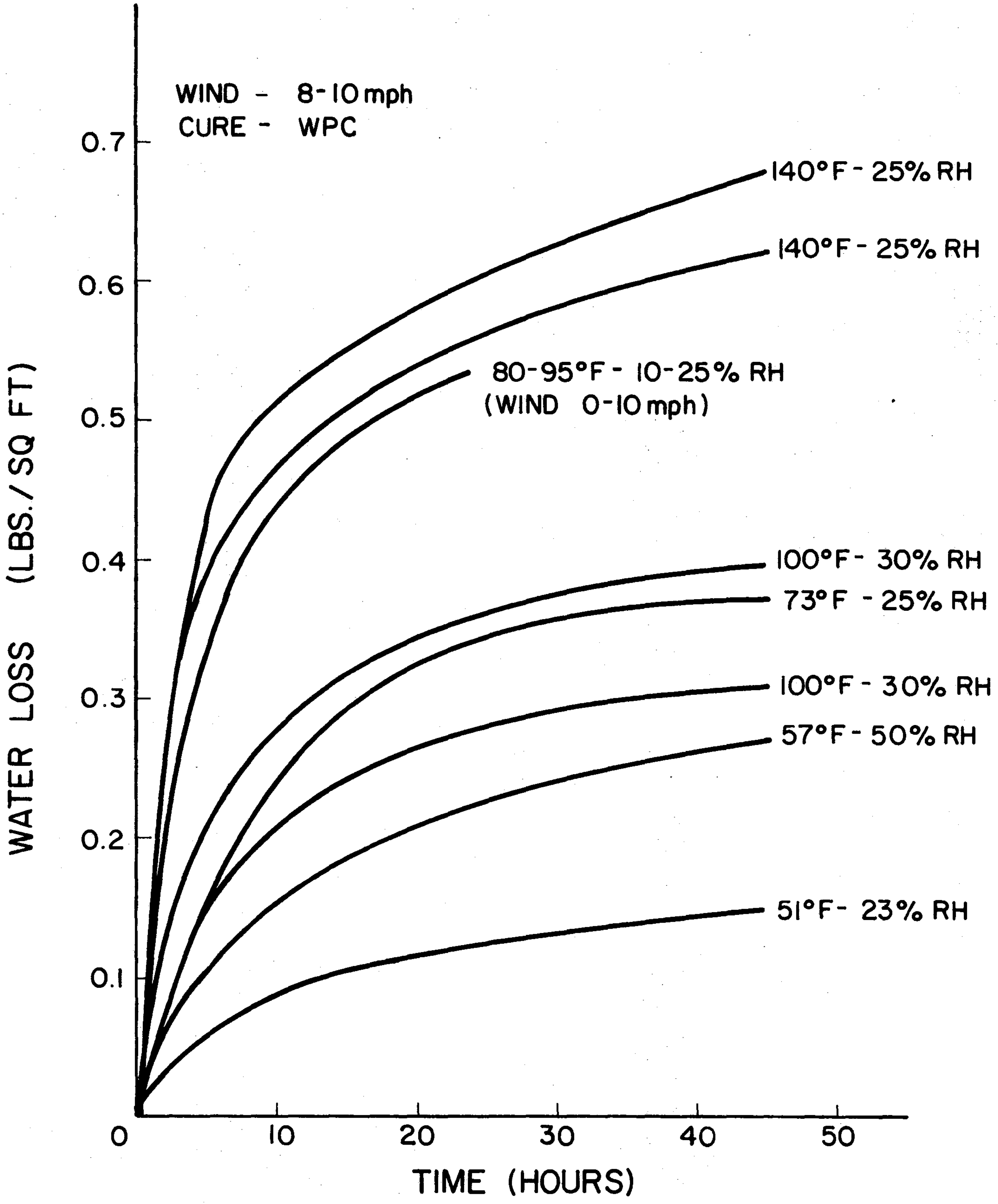


Fig. 4-13. Effect of Temperature on the Evaporation of Water from the Surface of the Concrete Slabs Maintaining Constant Curing Method (WPC) and Wind Conditions (8-10 mph).

### 4.5 Comparison of Evaporation Rates

As early evaporation plays an important role in the development of plastic shrinkage cracks, evaporation rates (lbs/sq ft/hr) were determined for all conditions investigated (see Figures 5-1 through 5-11 in the Appendix) and are summarized in Table 4-1. Evaporation rates are significantly reduced through the application of any curing compound, with the WPC and the WSLO compounds generally allowing less evaporation than either the MMF (1) + WPC or MMF (2) + WPC.

As a matter of interest a comparison was made between the results obtained experimentally and evaporation rates predicted by the Portland Cement Association (PCA) evaporation chart (Figure 2-2).[2] Table 4-2 shows several comparative rates for various temperatures, humidities, and wind velocities. Some of these values compared quite well while others did not. Figures 4-12 and 4-13 indicate the relationships obtained in this study between temperature and evaporation for the data obtained in this research. It can be seen that there is a general trend for the evaporation to increase with increasing temperature. This is in disagreement with the published PCA chart.

### 4.6 Construction Time Consideration

Although the application of monomolecular films does not appear to reduce total evaporation, it does have some advantages. By applying a MMF cure after placing the concrete, time can be gained before having to finish the pavement. In this research program the monomolecular film was sprayed on the surface after placement. Then, as soon as the water sheen disappeared, the surface finishing was performed and the white pigmented curing compound (WPC) applied. Disappearance of the water

TABLE 4-1. Evaporation Rates

| Code Designation[a] | Evaporation Rates (lbs/sq ft/hr) |
|---|---|
| $S_1$ $W_2$ $E_3$ 1 | .031 |
| $S_1$ $W_2$ $E_3$ 2 | .058 |
| $S_1$ $W_2$ $E_3$ 4 | .044 |
| $S_1$ $W_2$ $E_3$ 5 | .158 |
| $S_1$ $W_2$ $E_4$ 1 | .065 |
| $S_1$ $W_2$ $E_4$ 2 | .085 |
| $S_1$ $W_2$ $E_4$ 4 | .045 |
| $S_1$ $W_2$ $E_4$ 5 | .136 |
| $S_1$ $W_2$ $E_5$ 1 | .099 |
| $S_1$ $W_2$ $E_5$ 2 | .198 |
| $S_1$ $W_2$ $E_5$ 4 | .085 |
| $S_1$ $W_2$ $E_5$ 5 | .206 |
| $S_1$ $W_3$ $E_3$ 1 | .058 |
| $S_1$ $W_3$ $E_3$ 2 | .062 |
| $S_1$ $W_3$ $E_3$ 4 | .029 |
| $S_1$ $W_3$ $E_3$ 5 | .186 |
| $S_1$ $W_3$ $E_4$ 1 | .107 |
| $S_1$ $W_3$ $E_4$ 2 | .111 |
| $S_1$ $W_3$ $E_4$ 4 | .056 |
| $S_1$ $W_3$ $E_4$ 5 | .182 |
| $S_1$ $W_3$ $E_5$ 1 | .031 |
| $S_1$ $W_3$ $E_5$ 2 | .128 |
| $S_1$ $W_3$ $E_5$ 4 | .047 |
| $S_1$ $W_3$ $E_5$ 5 | .235 |

TABLE 4-1. (Cont'd.)

| Code Designation[a] | Evaporation Rates (lbs/sq ft/hr) |
|---|---|
| $S_2$ $W_2$ $E_1$ 1 | .011 |
| $S_2$ $W_2$ $E_1$ 2 | .013 |
| $S_2$ $W_2$ $E_1$ 3 | .025 |
| $S_2$ $W_2$ $E_1$ 5 | .047 |
| $S_2$ $W_2$ $E_2$ 1 | .015 |
| $S_2$ $W_2$ $E_2$ 2 | .032 |
| $S_2$ $W_2$ $E_2$ 3 | .044 |
| $S_2$ $W_2$ $E_4$ 1 | .029 |
| $S_2$ $W_2$ $E_4$ 2 | .036 |
| $S_2$ $W_2$ $E_4$ 3 | .033 |
| $S_2$ $W_2$ $E_5$ 1 | .068 |
| $S_2$ $W_2$ $E_5$ 2 | .088 |
| $S_2$ $W_2$ $E_5$ 3 | .090 |
| $S_3$ $W_4$ $E_6$ 1 | .050 |
| $S_3$ $W_4$ $E_6$ 2 | .067 |
| $S_3$ $W_4$ $E_6$ 3 | .084 |
| $S_3$ $W_4$ $E_6$ 4 | .063 |
| $S_3$ $W_4$ $E_6$ 5 | .225 |

[a] See Table 3-1 for explanation of code.

TABLE 4-2. Comparison of Evaporation Rates

| Temperature (°F) | Relative Humidity (%) | Wind (mph) | Evaporation Rates (lbs/sq ft/hr) | |
|---|---|---|---|---|
| | | | Experimental[a] | PCA[b] |
| 51 | 23 | 10 | .047 | .23 |
| 73 | 25 | 0 | .047 | .04 |
| 73 | 25 | 10 | .158 | .22 |
| 73 | 25 | 20 | .186 | .38 |
| 90 | 20 | 10 | .225 | .20 |
| 100 | 30 | 0 | .037 | .03 |
| 100 | 30 | 10 | .136 | .14 |
| 100 | 30 | 20 | .182 | .24 |

[a] Values obtained from specimens with no cure.

[b] From Figure 2-2 using an average concrete temperature of 80°F.

sheen is the controlling factor before finishing is performed. Table 4-3 shows the various delay times under different environmental conditions, and three cures: (WPC, MMF (1) + WPC, and MMF (2) + WPC. Note that the application of MMF (1) increases the standard delay from 10 to 100 percent and the application of MMF (2) increases it a remarkable 20 to 300 percent. These results indicate monomolecular film could prove to be very valuable in case of delays during construction.

TABLE 4-3. Delay Time Before Applying White Pigmented Curing Compound

| Code Designation[a] | Delay Time, Min. |
|---|---|
| $S_2$ $W_2$ $E_1$ 1 | 25 |
| $S_2$ $W_2$ $E_1$ 2 | 40 |
| $S_2$ $W_2$ $E_1$ 3 | 180 |
| $S_2$ $W_2$ $E_2$ 1 | 48 |
| $S_2$ $W_2$ $E_2$ 2 | 135 |
| $S_2$ $W_2$ $E_2$ 3 | 165 |
| $S_2$ $W_2$ $E_4$ 1 | 50 |
| $S_2$ $W_2$ $E_4$ 2 | 55 |
| $S_2$ $W_2$ $E_4$ 3 | 80 |
| $S_2$ $W_2$ $E_5$ 1 | 30 |
| $S_2$ $W_2$ $E_5$ 2 | 35 |
| $S_2$ $W_2$ $E_5$ 3 | 45 |
| $S_3$ $W_4$ $E_6$ 1 | 38 |
| $S_3$ $W_4$ $E_6$ 2 | 53 |
| $S_3$ $W_4$ $E_6$ 3 | 48 |

[a] See Table 3-1 for explanation of code.

# 5. APPENDIX

## 5.1 Discussion of Variables

Curing Method. After placing the concrete slabs, one of the five curing methods was begun. These five curing methods are described in Table 5-1. Where curing compounds were used the manufacturers recommendations for application were followed as nearly as practical.

Curing Environment. For the first two study sites the environmental rooms utilized were located in the McNew Laboratory at Texas A&M University. The third study site employed natural field conditions at Van Horn, Texas. The slabs were cured in one of six environments as prescribed in Table 3-1. The specified conditions (in laboratory tests) were accurately maintained and monitored during the testing periods.

Wind. In the first two study sites, to simulate outdoor conditions, the slabs were subjected to produce steady conditions, 0 mph ($W_1$), and wind velocities of 8-10 mph ($W_2$) and 18-20 mph ($W_3$) in order to simulate outdoor conditions. The wind was generated through the use of a fan run by an electric motor and it was checked periodically with an anemometer. This generated wind was tunneled through duct work to the required wind velocity ± one mph. In the Van Horn study the existing wind conditions ranged from 0-10 mph ($W_4$).

Finishing. Finishing was accomplished by first screeding the surface and then applying two passes of a burlap drag.

Design Mixes. The mixes were designed using the absolute volume method with a specified cement factor and air entrainment admixture.[13] All batches were designed to produce similar strengths based on a cement factor

TABLE 5-1. Curing Methods

| Designation | Curing Type | Description |
|---|---|---|
| 1 | White Pigmented Curing Compound-Resin Based (WPC) | A white pigmented curing compound was sprayed on the test slabs after finishing and after the water sheen had disappeared from the surface (180 sq ft/gal.) |
| 2 | Monomolecular Film with White Pigmented Curing Compound (MMF(1) + WPC) | A monomolecular film was sprayed on the surface of the test slabs in one single application prior to finishing (200 sq ft/gal.). After finishing, as soon as the water sheen had disappeared from the surface, the same white pigmented curing compound as was used in curing method 1 was sprayed on the surface. |
| 3 | Monomolecular Film with White Pigmented Curing Compound (MMF(2) + WPC) | Same as curing method 2, except the monomolecular film was sprayed in two applications, 100 sq ft/gal. each. |
| 4 | Water Soluble Linseed Oil (WSLO) | A water soluble linseed oil was applied to the surface upon completion of the finishing operation (200 sq ft/gal.). |
| 5 | No Cure | The slab was allowed to cure without any type of curing compound application. |

of 5 sacks of cement per cubic yard of concrete, a coarse aggregate factor (CAF) of 0.78 with a maximum size of 1 1/2 in., a water-cement ratio (w/c) of 0.5, an air content of 3 percent (4 to 5 percent at Van Horn), and a slump of 1 in. ± 1/2 in. Due to the presence of free moisture in the aggregates used, the mixing water had to be altered slightly in some cases to maintain the desired slump. The time lapse between the introduction of cement to the mix and the final placement of the concrete into the forms was held as constant as practicable for all test slabs.

## 5.2 Laboratory Procedures

The concrete for all batches in the laboratory was mixed in a 6 cu ft portable rotary-drum mixer. Materials were stored inside the laboratory so as to maintain a constant batch temperature (approximately 80°F). Prior to batching, a small "butter batch" consisting of identical materials as the batch, was placed and mixed in the mixer. This compensated for the materials which would normally stick in the mixer. The coarse aggregate and part of the mixing water containing air entrainment admixture was added initially. After approximately one minute of mixing, the cement and fine aggregate were added. The mixing then continued for approximately five minutes.

After the mixing was completed, the slump test (ASTM C143-66), unit weight (ASTM C139-63), and air content (ASTM C231-68) were determined and recorded. At the completion of these control tests, the concrete was then taken to the appropriate environmental room and placed in three layers in the steel forms (Figure 3-1). As soon as the concrete was placed, it was vibrated and screeded. Next finishing and curing operations began as given in Table 5-1. After finishing the surface and applying the curing compounds, the water loss measurements were made in accordance with the procedure given in section 3-2.

## 5.3 Field Procedures

The concrete was batched in a large concrete mixing plant used in the construction of Interstate Highway 10 near Van Horn, Texas. Concrete for the evaporation study was taken from the haul trucks and placed in the steel forms (Figure 3-1), vibrated and screeded. Finishing and appropriate curing methods (Table 5-1) were applied and the water loss measurements were conducted in the same manner as in the laboratory.

## 5.4 Tabulated and Plotted Test Results

Table 5-2 contains the summarized results of this phase of research. Figures 5-1 through 5-11 present plots of the evaporation rates during the initial hours of the curing process. The data in Table 5-2 were corrected for the change in weight due to application of the curing compound. For complete curves see Figures 4-1 through 4-11.

TABLE 5-2. Evaporation Rates in Lbs Per Sq Ft

| Code Designation[a] | Time in Hours | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | 1/2 | 1 | 1 1/2 | 2 | 3 | 4 | 6 | 10 | 21 | 24 | 45 | 50 |
| $S_1$ $W_1$ $E_3$ 5 | .013 | .026 | .040 | .093 | .132 | .158 | .231 | .410 | - | .515 | .541 | - |
| $S_1$ $W_2$ $E_3$ 1 | - | .053 | .053 | .079 | .112 | .158 | .185 | .238 | - | .343 | .370 | - |
| $S_1$ $W_2$ $E_3$ 2 | .066 | .119 | .125 | .158 | .211 | .244 | .284 | .330 | - | .436 | .449 | - |
| $S_1$ $W_2$ $E_3$ 4 | - | .053 | .086 | .106 | .158 | .191 | .211 | .251 | - | .356 | .396 | - |
| $S_1$ $W_2$ $E_3$ 5 | .101 | .106 | .178 | .238 | .396 | .506 | .629 | .739 | - | .843 | .869 | - |
| $S_1$ $W_2$ $E_4$ 1 | - | .053 | .093 | .132 | .172 | .185 | .225 | .278 | - | .357 | .397 | - |
| $S_1$ $W_2$ $E_4$ 2 | .026 | .079 | .106 | .172 | .251 | .304 | .436 | .449 | - | .515 | .554 | - |
| $S_1$ $W_2$ $E_4$ 4 | - | .053 | .074 | .106 | .132 | .146 | .225 | .251 | - | .331 | .370 | - |
| $S_1$ $W_2$ $E_4$ 5 | .013 | .079 | .150 | .220 | .366 | .458 | .604 | .617 | - | .678 | .706 | - |
| $S_1$ $W_1$ $E_4$ 5 | .020 | .040 | - | - | .126 | .172 | .278 | .488 | - | .594 | .628 | - |
| $S_1$ $W_2$ $E_5$ 1 | - | .092 | .145 | .224 | .304 | .356 | .383 | .475 | - | .554 | .620 | - |
| $S_1$ $W_2$ $E_5$ 2 | .040 | .106 | .198 | .356 | .528 | .554 | .660 | .739 | - | .832 | .884 | - |
| $S_1$ $W_2$ $E_5$ 4 | - | .066 | .106 | .172 | .264 | .343 | .356 | .449 | - | .528 | .581 | - |
| $S_1$ $W_2$ $E_5$ 5 | - | .167 | .304 | .453 | .629 | .700 | .726 | .779 | - | .849 | .898 | - |
| $S_1$ $W_1$ $E_5$ 5 | .013 | .020 | .053 | .093 | .152 | .218 | .370 | .475 | - | .554 | .622 | - |
| $S_1$ $W_3$ $E_3$ 1 | - | .066 | .092 | .145 | .198 | .238 | .356 | .462 | - | .607 | .660 | - |
| $S_1$ $W_3$ $E_3$ 2 | - | .026 | .079 | .119 | .172 | .211 | .304 | .383 | - | .528 | .581 | - |
| $S_1$ $W_3$ $E_3$ 4 | - | - | .079 | .145 | .185 | .198 | .218 | .277 | - | .383 | .422 | - |

TABLE 5-2. (Cont'd.)

| Code Designation[a] | Time in Hours | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | 1/2 | 1 | 1 1/2 | 2 | 3 | 4 | 6 | 10 | 21 | 24 | 45 | 50 |
| $S_1$ $W_3$ $E_3$ 5 | - | .040 | .128 | .246 | .409 | .559 | .757 | .893 | - | .977 | .988 | - |
| $S_1$ $W_3$ $E_4$ 1 | - | .079 | .132 | .185 | .290 | .343 | .436 | .502 | - | .554 | .581 | - |
| $S_1$ $W_3$ $E_4$ 2 | .106 | .158 | .238 | .304 | .396 | .449 | .541 | .607 | - | .660 | .673 | - |
| $S_1$ $W_3$ $E_4$ 4 | - | .053 | .079 | .119 | .172 | .198 | .277 | .370 | - | .422 | .449 | - |
| $S_1$ $W_3$ $E_4$ 5 | .053 | .097 | .189 | .282 | .449 | .524 | .621 | .683 | - | .741 | .745 | - |
| $S_1$ $W_3$ $E_5$ 1 | - | .079 | .092 | .119 | .145 | .172 | .238 | .251 | - | .330 | .409 | - |
| $S_1$ $W_3$ $E_5$ 2 | .040 | .106 | .172 | .277 | .370 | .449 | .541 | .554 | - | .660 | .713 | - |
| $S_1$ $W_3$ $E_5$ 4 | - | - | .079 | .145 | .198 | .264 | .343 | .356 | - | .449 | .541 | - |
| $S_1$ $W_3$ $E_5$ 5 | .040 | .145 | .308 | .436 | .528 | .572 | .629 | .664 | - | .713 | .774 | - |
| $S_2$ $W_2$ $E_1$ 1 | - | .026 | .032 | .032 | .045 | .056 | .065 | .084 | .103 | .123 | - | .156 |
| $S_2$ $W_2$ $E_1$ 2 | .044 | - | .063 | .063 | .081 | .088 | .100 | .118 | .137 | .156 | - | .199 |
| $S_2$ $W_2$ $E_1$ 3 | - | .066 | .079 | .092 | .106 | .139 | .152 | .185 | .225 | .251 | - | .298 |
| $S_2$ $W_2$ $E_1$ 5 | .038 | .051 | .089 | .109 | .153 | .190 | .236 | .340 | .548 | .606 | - | .682 |
| $S_2$ $W_2$ $E_2$ 1 | .038 | .056 | .069 | - | .075 | .088 | .119 | .160 | .201 | .207 | .270 | .283 |
| $S_2$ $W_2$ $E_2$ 2 | .040 | .053 | .093 | .139 | .159 | .179 | .225 | .274 | .331 | .345 | .430 | .430 |
| $S_2$ $W_2$ $E_2$ 3 | .019 | .026 | .058 | - | .103 | .128 | .167 | .187 | .258 | .258 | .335 | .335 |
| $S_2$ $W_2$ $E_4$ 1 | .019 | .031 | .044 | .069 | .100 | .131 | .162 | .206 | .269 | - | .306 | .312 |
| $S_2$ $W_2$ $E_4$ 2 | .055 | .092 | .110 | .135 | .177 | .202 | .246 | .276 | .350 | - | .387 | .393 |

TABLE 5-2. (Cont'd.)

| Code Designation[a] | Time in Hours |  |  |  |  |  |  |  |  |  |  |  |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
|  | 1/2 | 1 | 1 1/2 | 2 | 3 | 4 | 6 | 10 | 21 | 24 | 45 | 50 |
| $S_2$ $W_2$ $E_4$ 3 | .045 | .089 | .102 | .134 | .159 | .185 | .205 | .237 | .288 | – | .334 | .346 |
| $S_2$ $W_2$ $E_5$ 1 | .149 | .164 | .184 | .239 | .316 | .365 | .461 | .506 | .582 | .582 | – | .683 |
| $S_2$ $W_2$ $E_5$ 2 | .076 | .113 | .170 | .232 | .314 | .370 | .427 | .489 | .571 | .578 | – | .661 |
| $S_2$ $W_2$ $E_5$ 3 | – | .126 | .164 | .226 | .296 | .365 | .448 | .486 | .561 | .561 | – | .649 |
| $S_3$ $W_4$ $E_6$ 1 | .114 | .186 | .192 | .216 | .255 | .302 | .356 | – | .533 | .533 | – | – |
| $S_3$ $W_4$ $E_6$ 2 | .066 | .159 | .159 | .186 | .269 | .335 | .422 | – | .539 | .539 | – | – |
| $S_3$ $W_4$ $E_6$ 3 | .110 | .186 | .198 | .225 | .323 | .410 | .560 | – | .839 | .839 | – | – |
| $S_3$ $W_4$ $E_6$ 4 | – | .116 | .138 | .165 | .237 | .284 | .455 | – | .572 | .572 | – | – |
| $S_3$ $W_4$ $E_6$ 5 | – | .198 | .290 | .437 | .650 | .916 | 1.048 | – | 1.246 | 1.251 | – | – |

[a] See Table 3-1 for explanation of code.

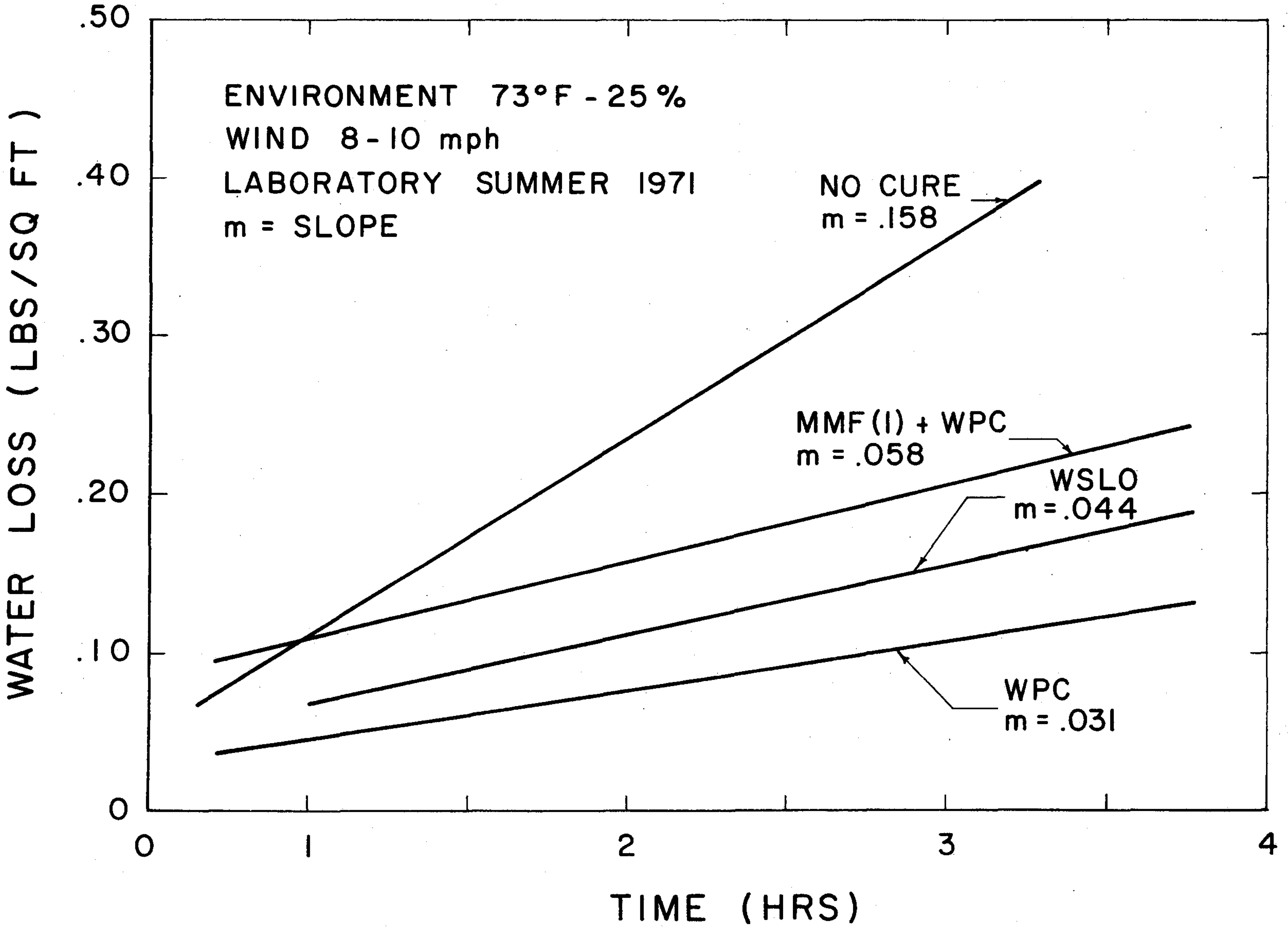


Fig. 5-1. Evaporation Rates at the Curing Temperature of 73°F, Relative Humidity of 25%, and Wind Conditions of 8-10 mph.

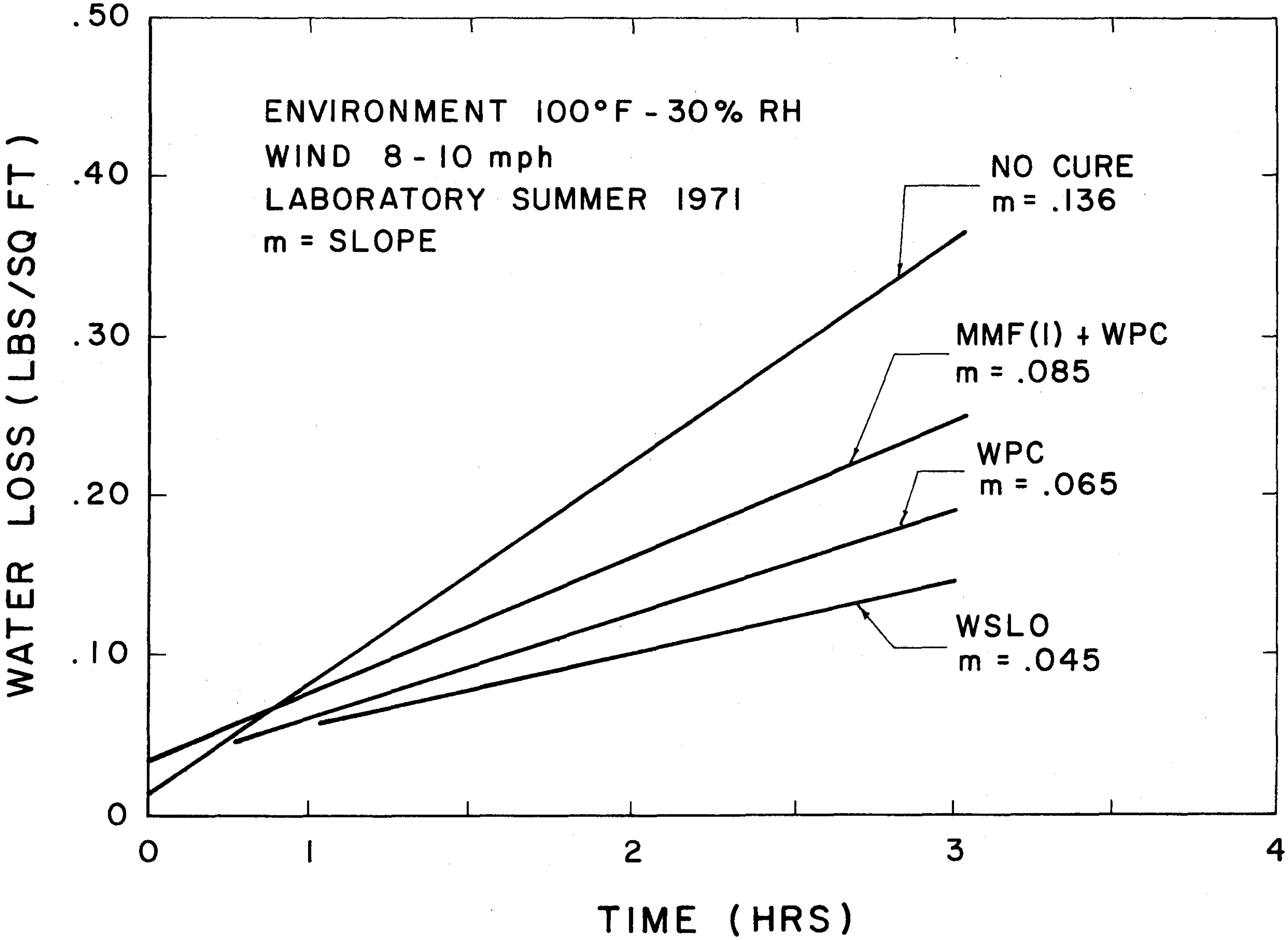


Fig. 5-2. Evaporation Rates at the Curing Temperature of 100°F, Relative Humidity of 30%, and Wind Condition of 8-10 mph.

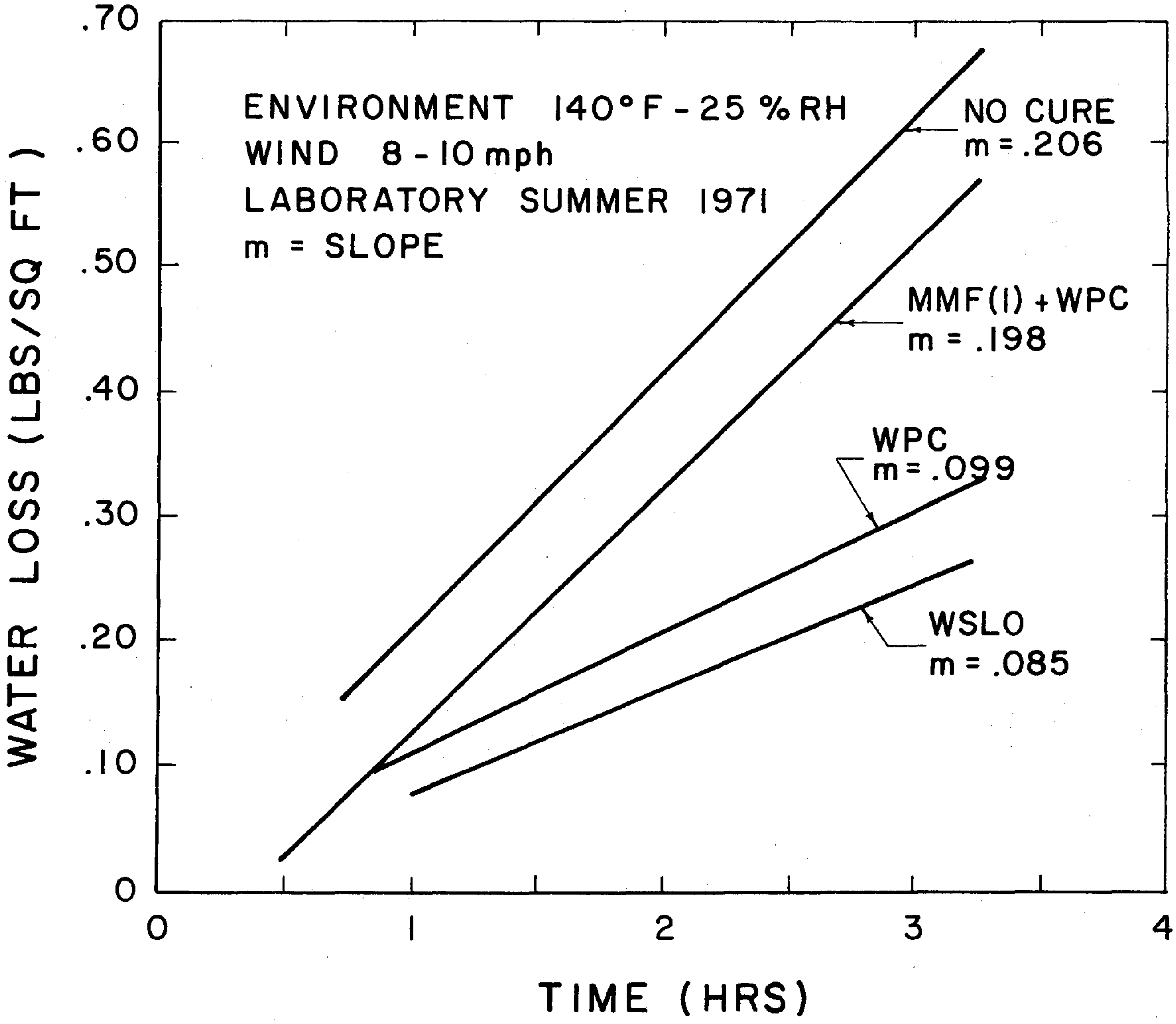


Fig. 5-3. Evaporation Rates at the Curing Temperature of 140°F, Relative Humidity of 25%, and Wind Conditions of 8-10 mph.

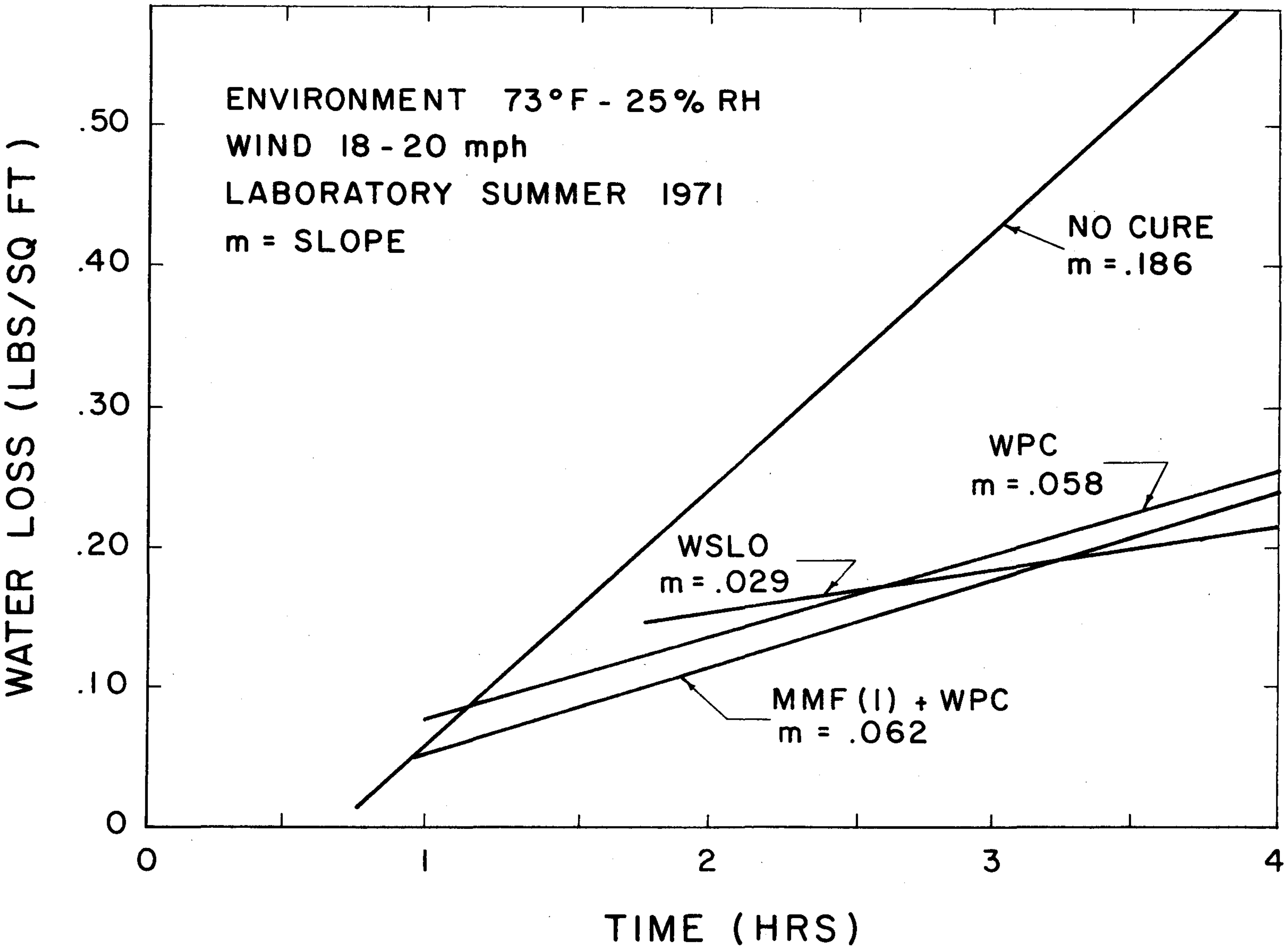


Fig. 5-4. Evaporation Rates at the Curing Temperature of 73°F, Relative Humidity of 25%, and Wind Conditions of 18-20 mph.

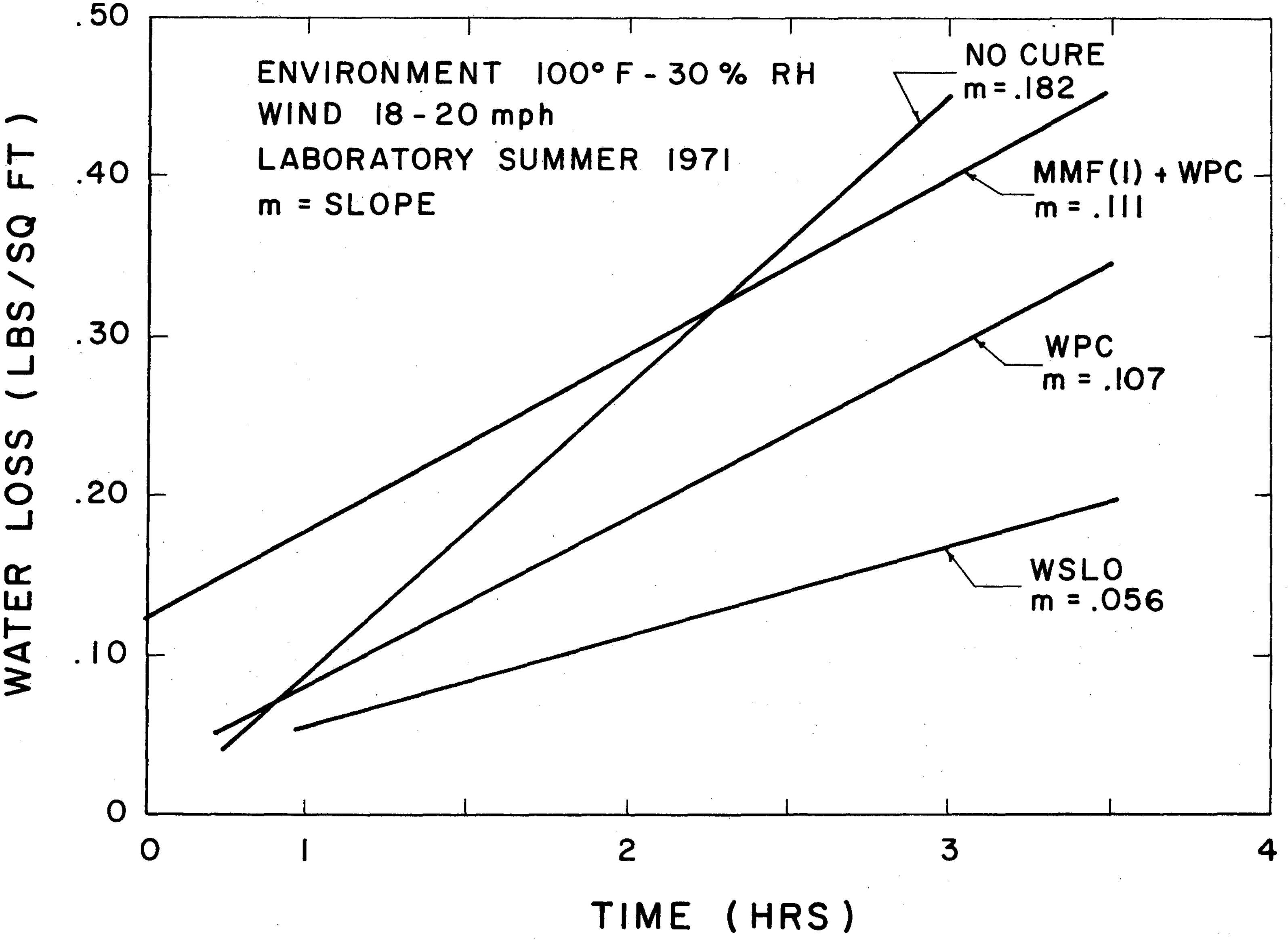


Fig. 5-5. Evaporation Rates at the Curing Temperature of 100°F, Relative Humidity of 30%, Wind Conditions of 18-20 mph.

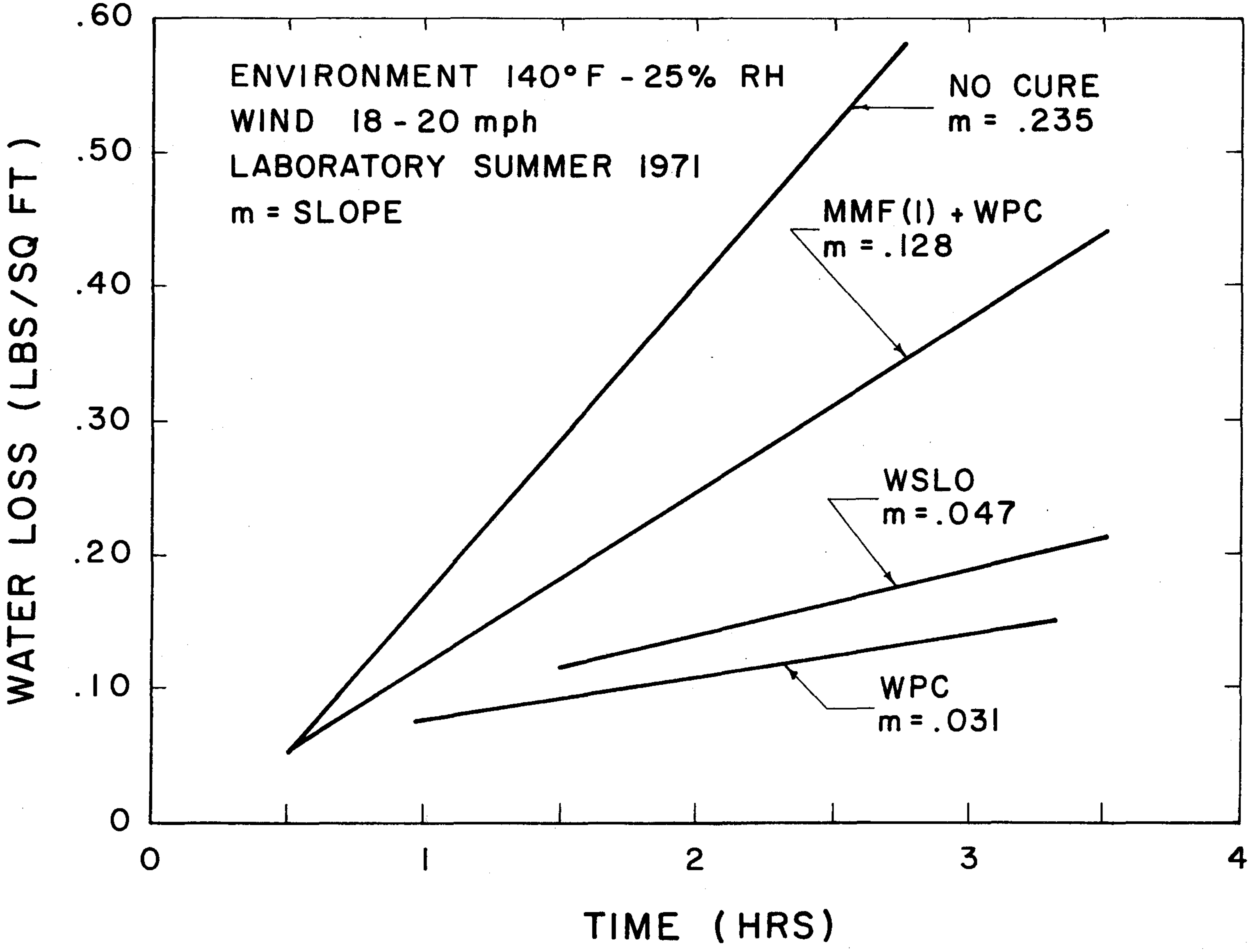


Fig. 5-6. Evaporation Rates at the Curing Temperature of 140°F, Relative Humidity of 25%, and Wind Conditions of 18-20 mph.

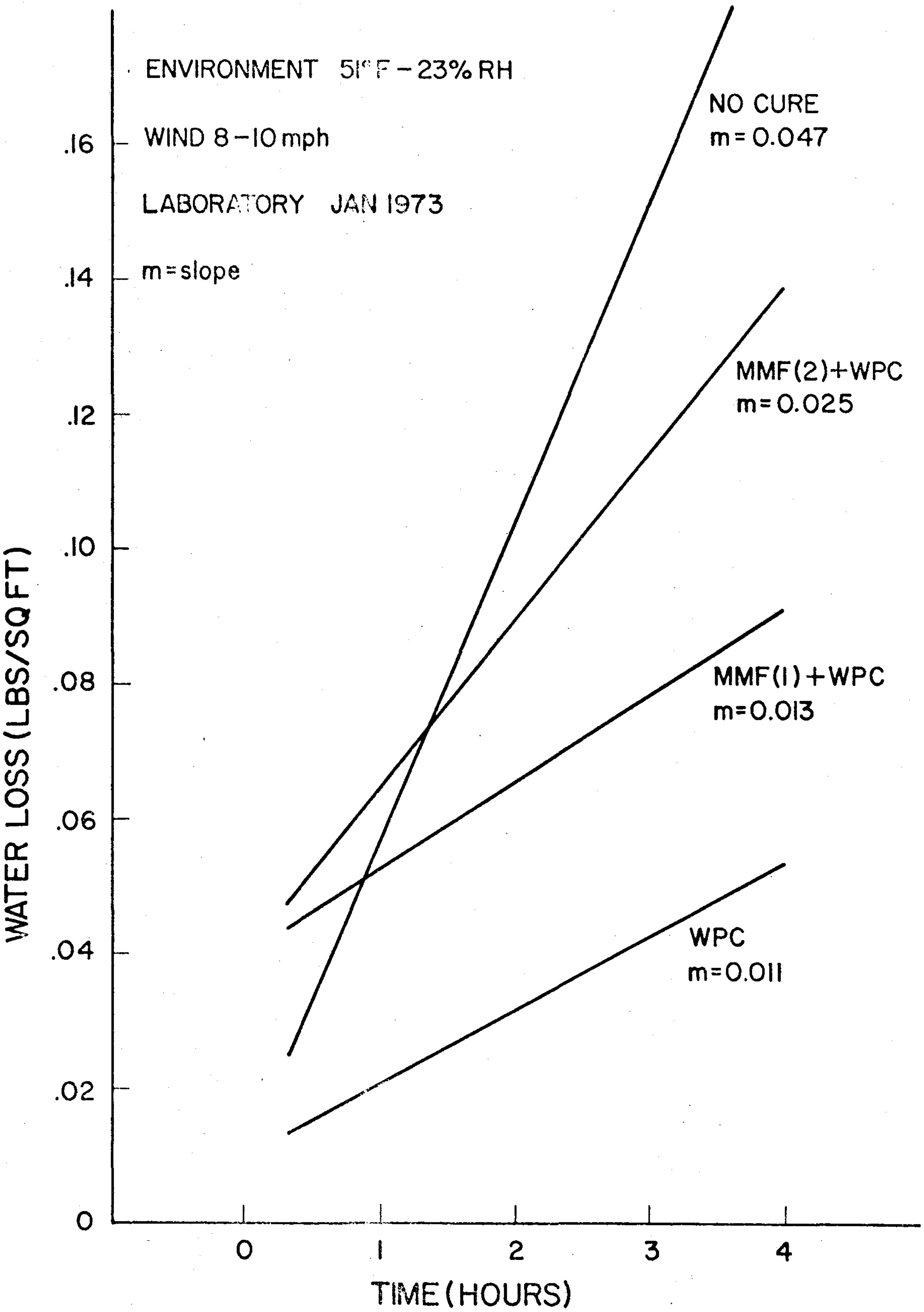


Fig. 5-7. Evaporation Rates at the Curing Temperature of 51°F, Relative Humidity of 23%, and Wind Conditions of 8-10 mph.

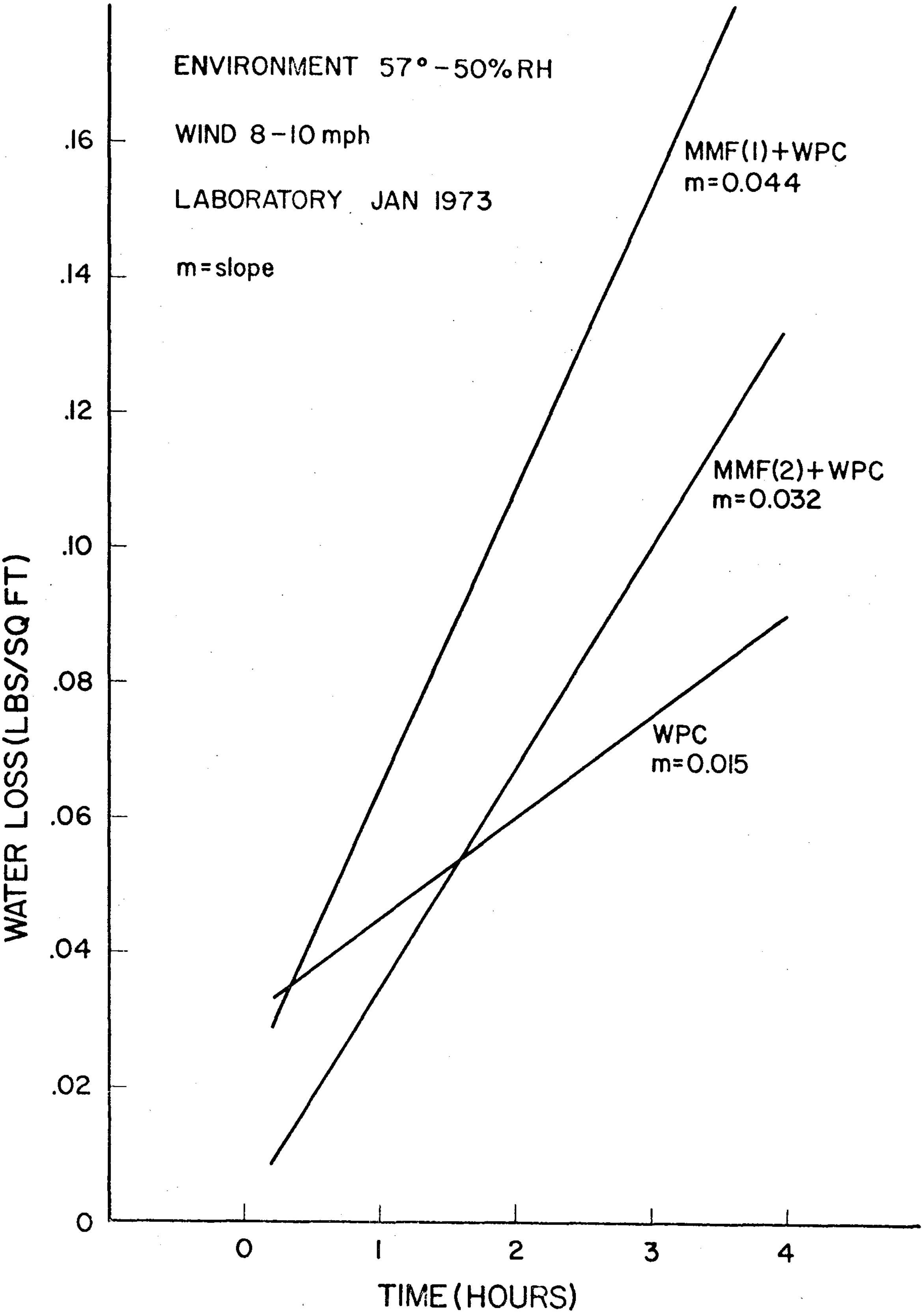


Fig. 5-8. Evaporation Rates at the Curing Temperature of 57°F, Relative Humidity of 50%, and Wind Conditions of 8-10 mph.

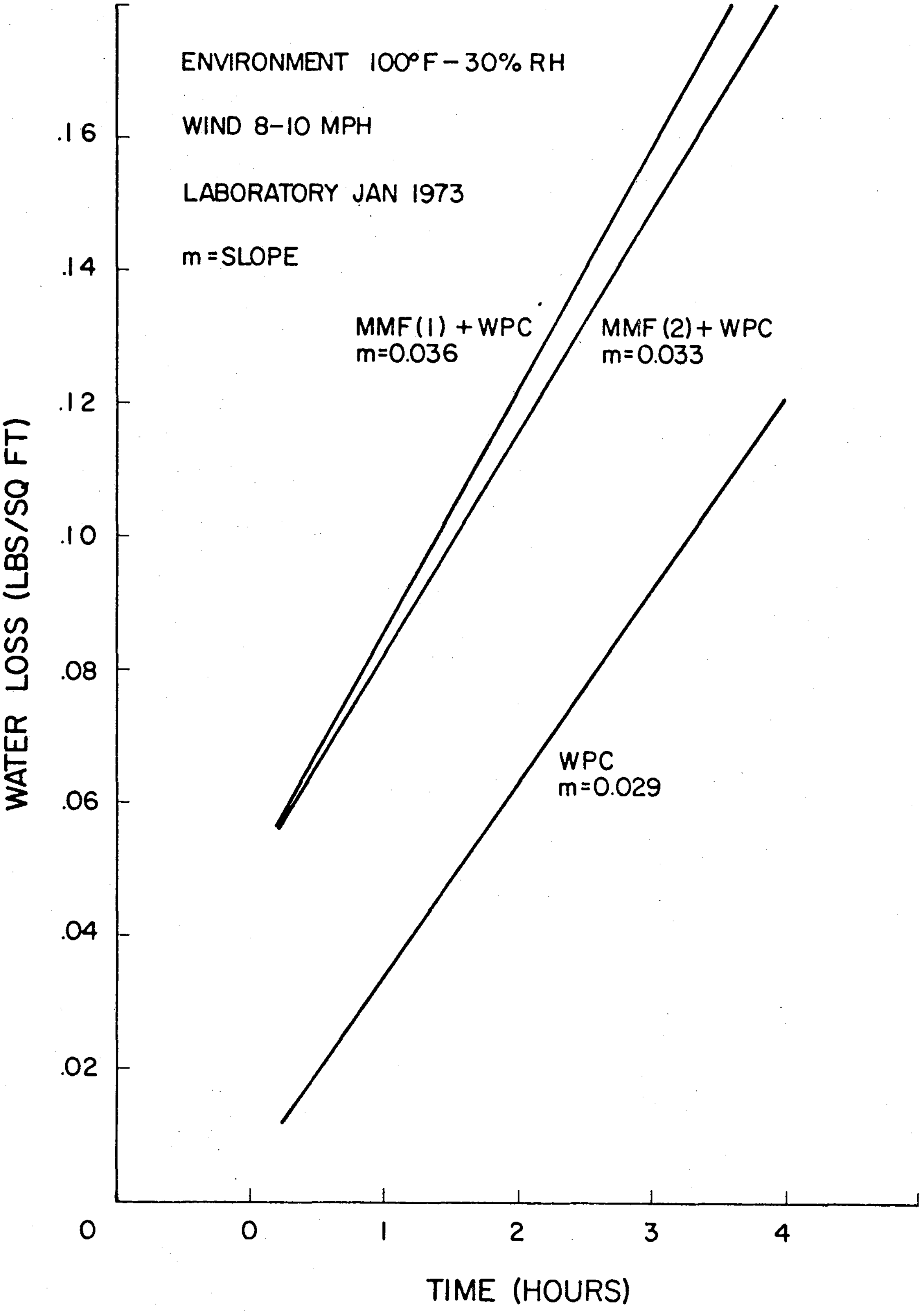


Fig. 5-9. Evaporation Rates at the Curing Temperature of 100°F, Relative Humidity of 30%, and Wind Conditions of 8-10 mph.

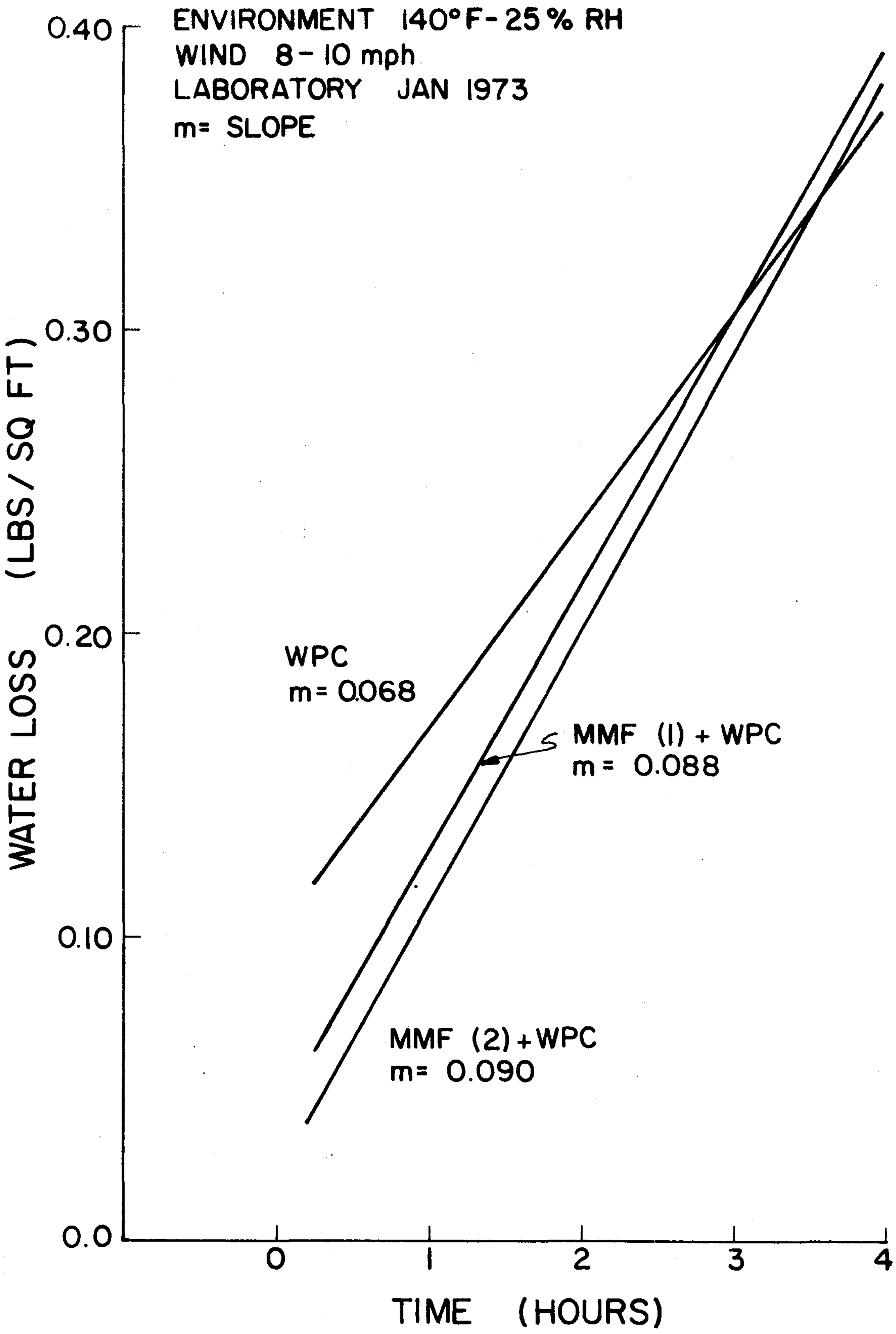


Fig. 5-10. Evaporation Rates at the Curing Temperature of 140°F, Relative Humidity of 25%, and Wind Conditions of 8-10 mph.

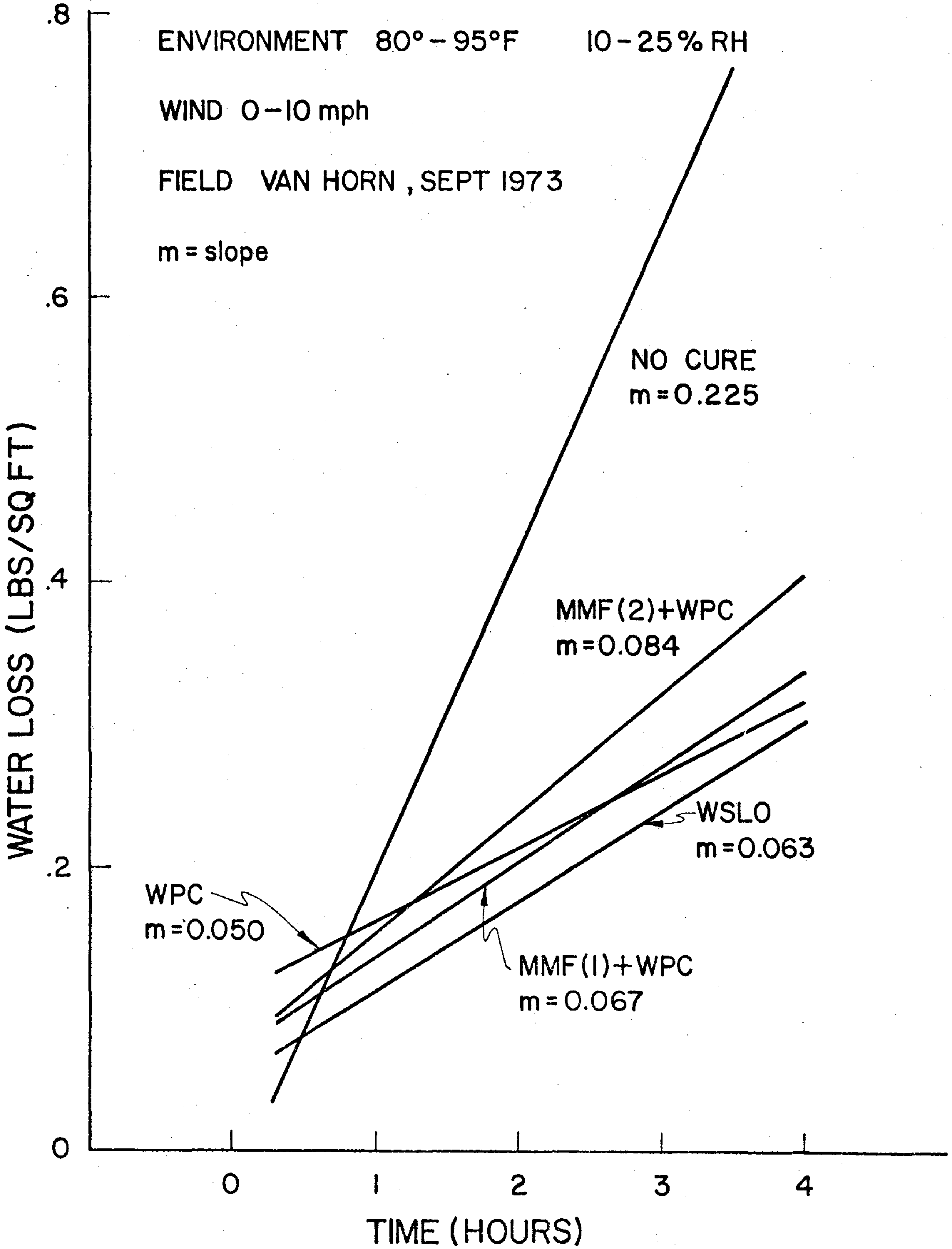


Fig. 5-11. Evaporation Rates at the Curing Temperature of 80-95°F, Relative Humidity of 10-25%, and Wind Conditions of 0-10 mph.

## 5.5 References

1. Paine, J. E., "Skid Resistance of Concrete Pavements," Concrete Construction, Vol. 14, No. 10, October 1969.

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