AN ASSESSMENT OF CONCRETE BRIDGE DECK EVAPORATION RATES AND CURING REQUIREMENT CATEGORIES FOR ALABAMA

HRC Research Project
2-13746
Final Report

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Highway Research Center

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ABSTRACT

Early cracking due to plastic shrinkage, drying shrinkage, and thermal shrinkage in concrete bridge decks can result in lower durability and, eventually, reduced structural integrity. This research investigated the effect of weather parameters in the state of Alabama on shrinkage and identifies curing requirement categories for bridge deck concrete based on evaporation rates calculate using the evaporation nomograph from ACI Committee 305. Also presented are relationships between concrete and ambient temperature, and results of an evaporation rate parameter sensitivity analysis.

Curing categories are presented for different times of the year and describe the methods needed to ensure proper curing. The state was considered as one region and two distinct seasonal categories were developed. From the research performed it was determined that evaporation rates are generally not severe in Alabama if proper precautions are undertaken, but adverse conditions can occur, particularly during summer months and/or windy periods. The results of this research should be helpful in preforming testing of actual bridge decks, or in developing accurate models to properly determine the effects of weather parameters on shrinkage cracking and, therefore, identify proper curing methods for concrete bridge decks in Alabama.

ACKNOWLEDGMENTS

The authors would like to thank the Highway Research Center for funding of this project. Great appreciation is also extended to the Alabama Department of Transportation, Southeast Regional Climate Center, National Climate Data Center, and Blue Circle Cement Company for the information provided by each, which was instrumental in executing the research and preparing this report.

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1. INTRODUCTION

1.1 Statement of Problem

The durability/longevity of concrete bridge decks is closely related to the quality of the top 1" or 2" of deck concrete. The quality of curing greatly affects the properties of this top layer of deck concrete and, therefore, has a definite impact on durability of the deck. The proper procedures required for concrete deck curing are affected by many parameters with two dominant factors being (1) weather exposure conditions at the time of and immediately after placement, and (2) the type of cement, cement replacement materials, and admixtures used in the concrete. The Alabama Department of Transportation (ALDOT) requires that a standard mixture design be used for all concrete bridge decks. It is not clear what curing procedures should be required for different conditions throughout the year, and for different regions across the state.

The American Concrete Institute (ACI) has published a water evaporation chart which aids in deciding if weather conditions will cause plastic shrinkage at the time of concrete placement. The chart could be used in conjunction with relative humidity, temperature, and wind velocity data for different times during a day, times of the year, and locations in Alabama to provide a more sophisticated and improved guideline for indicating appropriate weather related pseudo evaporation rates and, in turn, curing requirements for bridge decks in Alabama. A study of this potential improvement in recognition of weather and its effects on curing is the purpose of this research.

1.2 Objectives

The primary objective of this research is to develop a design/construction tool to reduce early cracking in concrete bridge decks and, hence, improve durability of concrete bridge decks in Alabama. In order to fulfill this objective, the following three sub-objectives were established:

- Use weather data from regional weather data collection centers to generate temperature, relative humidity, and wind curves which are appropriate for specifying curing requirement categories for bridge decks in Alabama.
- Perform analysis of parameters pertaining to evaporation rate, strength gain, shrinkage characteristics, and temperature variations to determine the effect of each on plastic and early drying and thermal shrinkage cracking in ALDOT bridge decks.
- Using the results from the two previous sub-objectives, develop weather exposure condition categories, and related curing requirement categories for bridge deck placements in Alabama.

1.3 Work Plan

A brief summary of the work plan used to achieve the research objective/sub-objectives cited above is as follows:

1. Secure weather data for Alabama from the Southeast Regional Climate Center in Columbia, SC, and the National Climate Data Center in Asheville, NC. Data will include such information as median temperatures (T), relative humidities (RH), and surface winds (W) for each month of the year for South, Central, and North Alabama. Typical 24-hour cycles for T, RH, and W will also be acquired.
2. Analyze weather data to identify breakdowns in Alabama for locations, for time of year, and for times of day with similar expected evaporation rates and curing requirements. It is anticipated that the breakdown of data will allow combining months into

- cold weather conditions
- moderate weather conditions
- hot weather conditions.

It is also a goal to combine location within the state into regions, e.g.,

- northern region
- central region
- coastal region.

3. Secure field data of ambient and concrete temperatures in order to establish a correlation between concrete temperature (T_c) and ambient temperature (T_a).
4. Perform parameter sensitivity analyses and develop evaporation rate (E_r) curves based on Alabama weather data and the ACI 305 Surface Evaporation Chart. Refine the weather data breakdowns based on the results of these analyses.
5. Based on steps 2-4 above, identify curing requirement categories for concrete bridge deck placement in Alabama.
6. Use results of 1-5 above to develop weather and evaporation maps for Alabama, and guidelines on weather related curing requirements for concrete bridge decks in Alabama for various seasons of the year.

1.4 Scope

This study identifies typical temperature, relative humidity, and wind weather exposure conditions in Alabama for various months/seasons of the year and times of day; and evaluates, via the ACI 305 Surface Evaporation Chart, concrete surface evaporation rates for these typical Alabama weather exposure conditions. Based on these data and results of parameter analyses, bridge deck curing requirement categories appropriate for Alabama are identified.

It is anticipated that the results from this study will determine the necessity of actual testing of green concrete exposed to different weather conditions. If the findings of this study reflect significant effects of weather conditions on cracking of decks , then, a more detailed study involving testing of actual ALDOT bridge decks in the field or testing of simulated laboratory specimens should be undertaken. This follow-up study should refine and quantify the effects of the weather parameters and move the results on to in-field implementation.

2. LITERATURE REVIEW

2.1 General

An abundance of research has been performed concerning early cracking of concrete bridge decks. Early cracking can be defined as cracking of the concrete while it is still in the plastic state or the "green" hardened state in which the concrete has not developed adequate strength to resist shrinkage stresses. The cracking occurs due to stresses which develop from shrinkage of the cement paste due to loss of mixing water or contraction of the concrete due to temperature changes. Water leaves the concrete due to bleeding and subsequent evaporation of the bleedwater. Weather conditions and concrete temperature affect the evaporation rate and, therefore, the rate of water loss from the concrete. The information in this chapter provides the necessary background to understand what causes plastic and early drying shrinkage cracking, the factors relating to evaporation rate which may cause shrinkage, and construction and curing methods which can mitigate shrinkage cracking.

2.2 Plastic Shrinkage Cracking

According to Lerch [25], plastic shrinkage is the shrinkage that occurs in the surface of fresh concrete within the first few hours after placement, while the concrete is still plastic and before it has attained any significant strength. He states that plastic shrinkage cracks do not appear to have a definite pattern but an occasional crow foot pattern has been observed. When cracking starts, it proceeds rapidly. The cracks are not usually progressive and do not immediately affect the structural performance of pavements or structures. Powers [31] states that the pattern of plastic shrinkage cracks is determined by the nature of restraint against contraction. If the concrete contains fixed objects such as a rectangular grid of reinforcement, the restraint of the movement by the steel bars may be reflected in the crack pattern. The pattern of cracking may also be influenced by the flaws developed during settlement. Raina [32] writes that plastic shrinkage cracking can occur in a variety of patterns: at 45° to the edges of the slab with the cracks 0.7-6.6 ft apart; normal to the wind direction since shrinkage would manifest in the direction of the wind, and following the pattern of reinforcement. These cracks usually pass through the full depth of the slab except in minor cases. Plastic shrinkage cracks which follow the pattern of reinforcing steel can be distinguished from plastic settlement cracks because the shrinkage cracks pass through the full depth of the slab and settlement cracks do not. However, it is important to note that other sources do not agree that plastic shrinkage cracks always pass through the entire depth of the slab.

The consensus thought is that plastic shrinkage cracking is caused by excessive evaporation of water from the concrete surface. Shaeles and Hover [37] point out that the study of plastic shrinkage cracking is complicated because the material properties which determine whether such cracks will form are time dependent and change rapidly during the first few hours in the life of the concrete. Such properties include: rate at which water is lost from the concrete in response to evaporative conditions; the degree to which the loss of water results in volume reduction; the consistency or stiffness of the mixture; and the development of tensile stresses and strain capacity of the material.

In 1957, William Lerch [25] published findings from an extensive study of plastic shrinkage cracking of concrete. Field investigations presented in his study indicated that evaporation rate is the principle cause of plastic shrinkage cracking. With the same mixture and construction methods, plastic shrinkage cracks can occur at different times due to changes in weather conditions which increase the evaporation rate. At the time when evaporation rate exceeds bleeding rate, cracks can propagate due to characteristics of the concrete. At this stage, the concrete has attained some rigidity and cannot accommodate the rapid volume change due to the plastic shrinkage by plastic flow. The concrete has not developed sufficient strength to withstand the tensile stresses which accompany the situation, therefore, plastic shrinkage cracks may develop. Very high rates of evaporation which occur on some projects greatly exceed the bleeding rate providing further evidence that bleeding characteristics cannot reduce the effect of weather parameters on plastic shrinkage cracking.

Mindess and Young [26] conclude that the loss of water from the fresh concrete, if not prevented, can cause cracking. The most common situation is surface cracking due to evaporation of water from the concrete surface. When water is removed from the paste by exterior influences, such as evaporation at the surface, a complex series of menisci are formed. These, in turn, generate negative capillary pressures which will cause the volume of the paste to contract. Shrinkage occurs in the paste and is mitigated by aggregate as shown in Fig. 2. 1. Plastic shrinkage cracking is most common on horizontal surface pavements and slabs where rapid evaporation is possible and its occurrence will destroy the integrity of the surface and reduce its durability.

Lerch developed a nomograph, Fig. 2.2, to predict evaporation rate on the exposed concrete surface. The nomograph requires input of air temperature, relative humidity, concrete temperature, and wind velocity. Increase in temperature differential, concrete vs. ambient, decrease in relative humidity, and increase in wind velocity increase the evaporation rates. ACI 305 [7] specifies the nomograph developed by Lerch as the method to predict evaporation rate for placement of concrete. This nomograph will, hereafter, be referred to as the ACI 305 Surface Evaporation Chart. Kosmatka and Panarese [22] provide the following statements which summarize typical effects of weather conditions on concrete evaporation rates during and after finishing: a) If air temperature and humidity remain the same and wind speed increases from 5 to 20 mph, evaporation rate will increase by 300 percent; b) If humidity and wind remain the same and the air temperature changes from 60 to 90°F, evaporation rate will increase by 300 percent; c) If air temperature and wind remain the same and the humidity decreases from 90 to 70 percent, evaporation rate will increase by 300 percent; d) If all of the previous increases occur, the evaporation rate will increase by 900 percent.

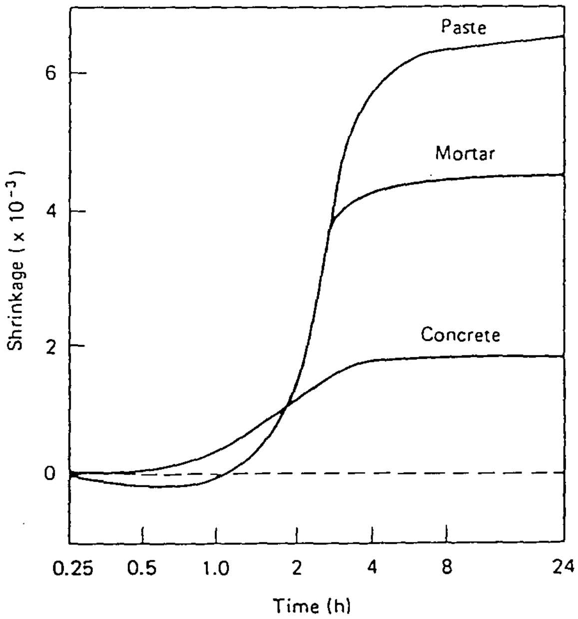
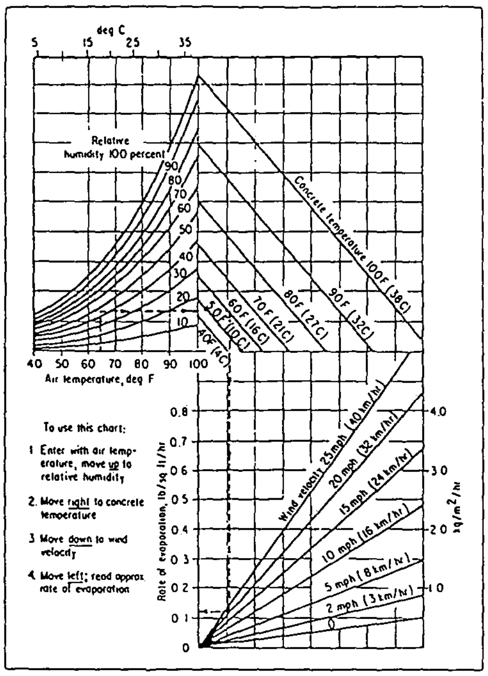


Fig. 2.1. Effect of Aggregate on Plastic Shrinkage [26]



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. ACI 305 Surface Evaporation Chart [7,25]

The Federal Highway Administration (FHWA) [18] provides an equation in Sl units to calculate evaporation rate in accordance with the ACI 305 Surface Evaporation Chart:

$$E_r = \frac{1+0.2374W}{2906} *[(C^2-4.762C+220.8-RH(\frac{T^3+127.8^2+665.6T+34283}{20415})] \tag{2.1}$$

E_r = Evaporation Rate (kg/m^2/hr); C = Concrete Temperature (°C);
RH = Relative Humidity (%); *T* = Ambient Temperature (°C)
W = Wind Speed (km/hr).

What should be the limiting value for evaporation rate for concrete bridge deck placement is in dispute. ACI 305 [7] stipulates that when the evaporation rate exceeds 0.2 lbs/ft^2/hr, "precautions to inhibit plastic shrinkage cracking by reducing evaporation rate are necessary." FHWA [18] specifies "when placing concrete in bridge decks or other exposed slabs, limit expected evaporation rate to less than 0.5 kg/m^2/hr (0. 1 lbs/ft^2 /hr)." PCA sets the limit at 0.25 lbs/ft^2 /hr. Mindess and Young [26] caution that if evaporation rate exceeds 0. 1 lbs/ft^2/hr, loss of moisture from the concrete may exceed the rate at which bleedwater reaches the surface, creating the negative capillary pressures which cause plastic shrinkage. Precautionary measures should always be used if the evaporation rate exceeds 0.2 lbs/ft^2 /hr. Chapter 5 covers in more detail how variations in the four input parameters for the ACI 305 Surface Evaporation Chart affect evaporation rate.

Many studies have been conducted to determine at what time plastic shrinkage cracks will develop with respect to the time of placement and to the evaporation rate. Laboratory research cited by ACI 305 [7] shows the highest rate of water loss due to evaporation occurred in the first 4 hours for concretes with low water content, but more water was lost from concretes with high water content over a 24 hour period. Raina [32] says plastic shrinkage cracks develop within about one hour of placing concrete (longer with addition of retarders) but may not be noticed until much later. In field experiments conducted by Ravina and Shalon [33], plastic shrinkage cracks were observed a few hours after casting, following the disappearance of bleedwater. Plastic settlement cracks developed within one-half hour or so after casting while the concrete was still covered with bleedwater. These cracks tended to close unless exposed to rapid drying. In a lab study, cracks appeared 0.5-2 hours after evaporation of all visible water from the surface. No correlation between bleeding and cracking was found. Fig. 2.3 plots shrinkage of the test mixtures vs. time. Each mixture is identified according to its environmental exposure conditions. The subscript of each mixture identifier represents the wind speed in km/hr. The superscript represents the air temperature in °C. Mixtures with the "rad" were exposed to infrared irradiation. Each mixture was exposed to relative humidity of 35% except for E_{20}^{20} which was exposed to 45% relative humidity. One can see that most of the shrinkage occurs in the first few hours after placement. A plot of water loss due to evaporation over time is given in Fig. 2.4. It can be seen that following initial evaporation of the bleedwater, the rate remained constant for 2.5 to 4 hours and subsequently slowed down. In this study, the effect of mixture proportions was found to be practically negligible on the evaporation rate. It can be observed from Figs. 2.4 and 2.5 that more shrinkage and evaporation occurred in mixtures subjected to lower relative humidity, higher temperature, and irradiation. The appearance of the first plastic shrinkage crack was observed to coincide consistently with the transition from rapid shrinkage to the slow rate of shrinkage, approaching the order of magnitude of length change characteristic for hardened mortar. Shaeles and Hover [37] found that plastic shrinkage cracking generally began 45 to 100 minutes after fans simulating wind were started. The fans were started 8 minutes after leveling the concrete and 30 minutes after mixing. The cracks continued to develop for up to 2.5 hours.

Samman et al. [35] subjected concrete test panels of four compressive strengths to indoor (ID) conditions (25°C (77°F), 55% RH), outdoor (OD) conditions (natural variation of temperature and humidity) with wind barriers and outdoor conditions with 15 km/h (9.32 mph) wind (ODW). A 23 MPa (3336 psi) mixture showed no signs of cracking in the OD conditions with a 40 MPa (5802 psi) cracking under the same conditions. The cracks appeared about 90 minutes after placement. In the ODW

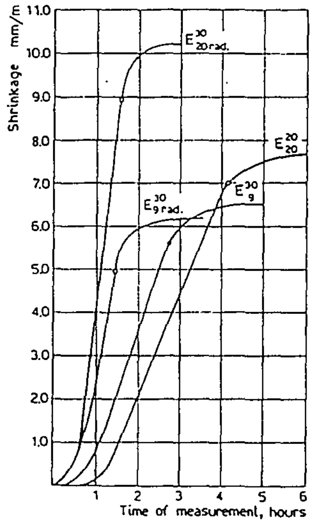


Fig. 2.3. Shrinkage -Time Relationship [33]

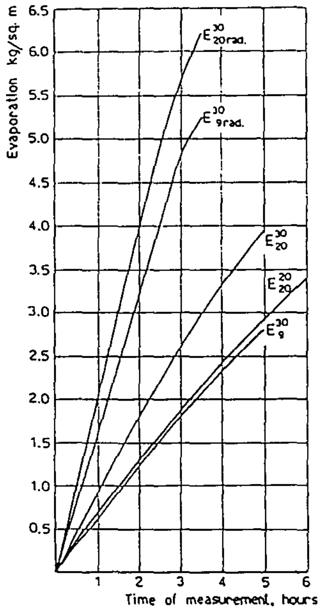


Fig. 2.4. Evaporation-Time Relationship for Different Climatic Conditions [33]

conditions, both mixtures exhibited cracking around 45 minutes after placement. More cracks were observed in the ODW conditions for the 40 MPa mixture than for OD conditions. No cracks were observed in either mixture in indoor conditions.

Although plastic shrinkage is most common in hot weather, it can occur in cold weather if temperature of the concrete is significantly higher than the ambient temperature. Gebler [20] indicates that evaporation can occur from concrete even when there is 100% humidity. If the concrete temperature is greater than the ambient temperature, vapor pressure in the concrete is greater than vapor pressure of the air so water moves out of the concrete towards equilibrium. Senbetta and Bury [36] performed a study on the effectiveness of a Freezing Weather Admixture (FWA) to mitigate plastic shrinkage cracking in cold weather. The results of the study revealed that an increase in the difference between ambient temperature and that of the concrete can result in a greater evaporation rate and increased plastic shrinkage cracking. Most of the cracks occurred within the first 4 to 5 hours after placing mortar specimens into forms. The test panels were placed in an environment of 30°F. Panels with a mixture temperature of 65°F showed a larger cracking area than panels with a mixture temperature of 40°F. Plastic shrinkage cracking in the 65°F panels most likely occurred because the rate of evaporation facilitated by the large temperature difference between the warm mortar and cool environment exceeded the bleeding rate. A subsequent experiment proved that mortar specimens at 65°F lost more moisture than specimens at 40°F. The results are plotted in Fig. 2.5. Data of the testing showed a strong correlation between total moisture loss and evaporation rates on the resulting test panels.

Sprinkel [38] writes about the effect of evaporation rate on plastic shrinkage cracking in Latex Modified Concrete (LMC) overlays placed on bridge decks in 1985 in Virginia. Table 2.1 shows weather data at the time of placement and the evaporation rate calculated from ACI 305. Plastic cracking for the June placements were so bad they had to be replaced in September and October. No cracking occurred in the other placements shown with the lower evaporation rates. His study recommends a limit of 0.1 lbs/ft^2

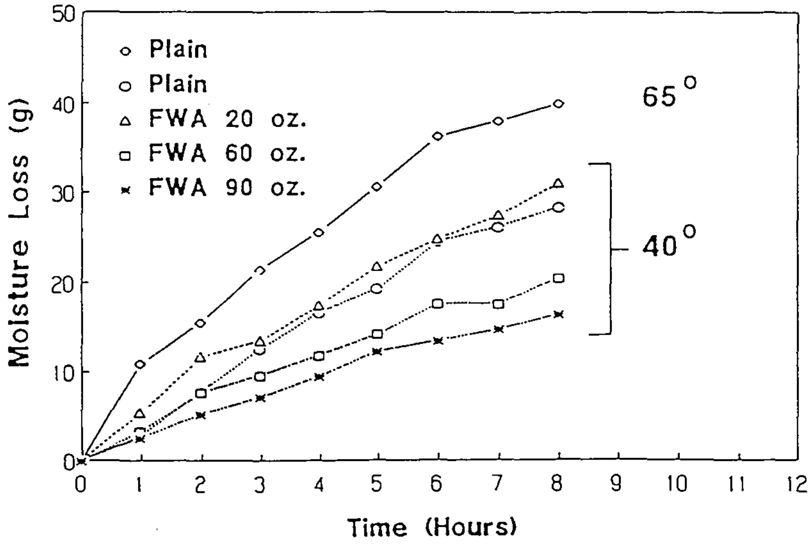


Fig. 2.5. Effect of FWA on Loss of Water on Test Specimens [36]

Table 2.1 Weather Conditions and Evaporation Rates During LMC Overlay Placement [38]

Extent of Cracking	Relative Humidity (%)	Wind Speed (mph)	Air Temperature (°F)	Concrete Temp. (°F)	E_r (lb/ft^2/hr)
Bad Cracking (June Placement)	41	10	78	84	0.21
	59	10	64	76	0.15
	79	6	68	81	0.10
No Cracking (Aug. Placement)	56	9	80	76	0.08
	70	6	70	77	0.08
	80	9	75	79	0.08
	89	4	71	75	0.04
	79	8	76	80	0.08
Redone No Cracking (Sept.-Oct. Placement)	83	11	70	74	0.07
	56	8	75	75	0.08
	56	9	80	81	0.11
	81	11	69	71	0.08
	83	5	75	77	0.05

/hr on evaporation rate when placing LMC overlays. LMC concrete has a lower concrete bleeding rate than normal portland cement concrete making it more susceptible to plastic shrinkage cracking, but the results from such a study show the detrimental effects caused by excessive evaporation.

Powers [31] presented curves of bleeding rate shown in Fig. 2.6. From investigation of the curves, the initial bleeding rates are greater than the critical evaporation rate of 0.2 $lb/ft^2/hr$ set forth by ACI. The initial bleeding rates are given in comparable units to evaporation rate in Table 2.2. The initial bleeding rate continues for only 20-30 minutes before decreasing. At one hour the rate has slowed considerably and is most likely below the critical ACI evaporation rate of 0.2 lb/ft^2 /hr.

2.3 Drying Shrinkage Cracking

Another type of shrinkage that can lead to early cracking is drying shrinkage. The effects of drying shrinkage are graphically illustrated in Fig. 2.7. Raina [32] defines drying shrinkage as the reduction in volume of concrete caused by the chemical and physical loss of water from the concrete during the hardening process and exposure to unsaturated air. The drying shrinkage cracks result only in a restrained condition due to tensile stresses which develop from the drying shrinkage. Raina states that loss of water by evaporation is the primary cause of the drying shrinkage and, hence, the relative humidity of the air surrounding the concrete greatly influences drying shrinkage. Decrease of relative humidity and windy conditions increase evaporation rate and, therefore, increase drying shrinkage. As relative humidity increases, the mechanism of drying shrinkage is reduced until relative humidity equals 95% and moisture movement ceases.

Fig. 2.8 from Neville [28] shows the relationship between shrinkage and moisture loss, by plotting the shrinkage of the solid mixture of varying cement content against weight of water lost. It is quite apparent that shrinkage increases with the loss of water. Since relative humidity affects water loss, the effect of relative humidity on drying shrinkage is important. Fig. 2.9 provides such a plot. Although

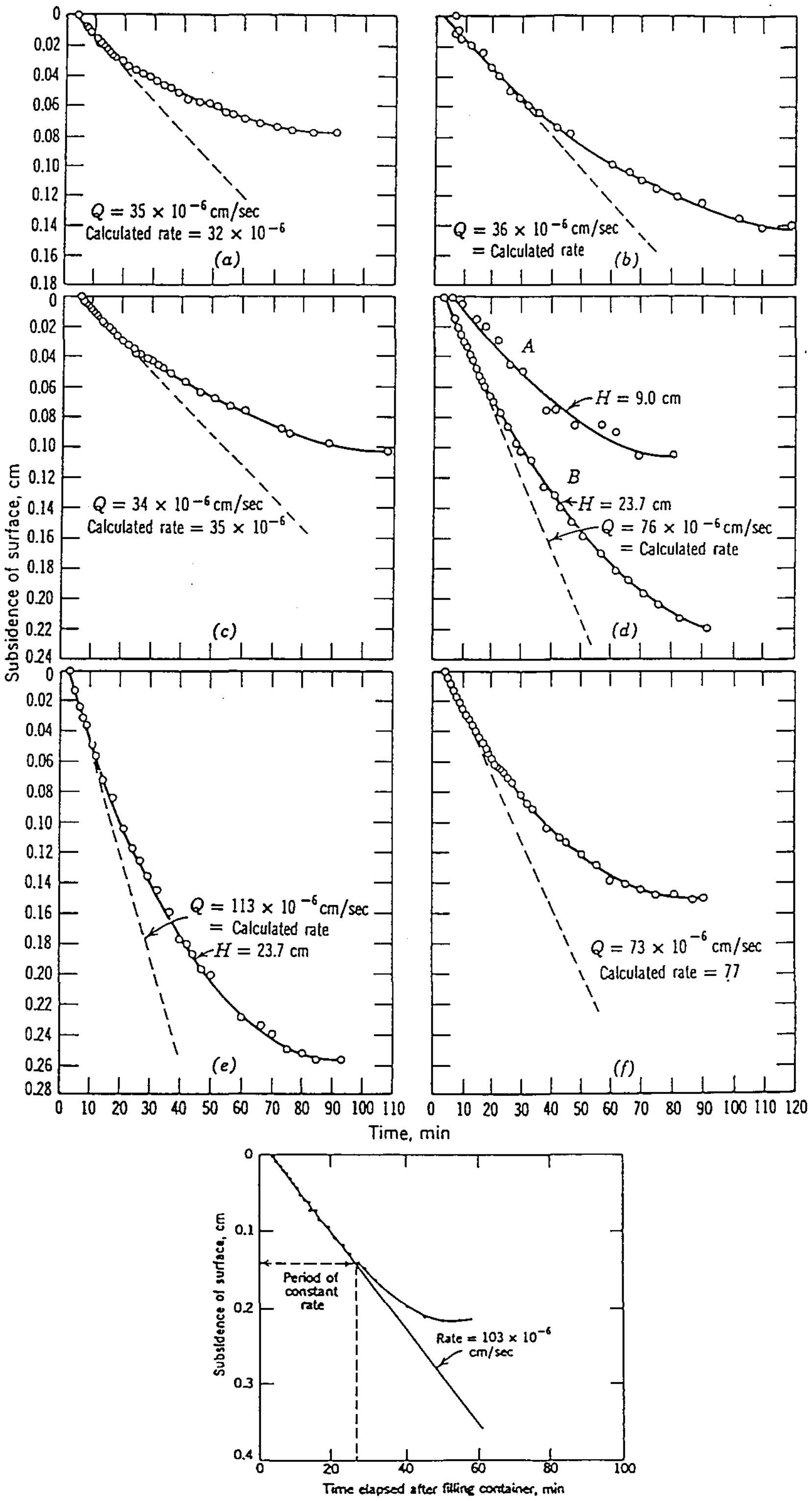


Fig. 2.6. Bleeding Rate Curves for Various Water-Cement Ratios [31]

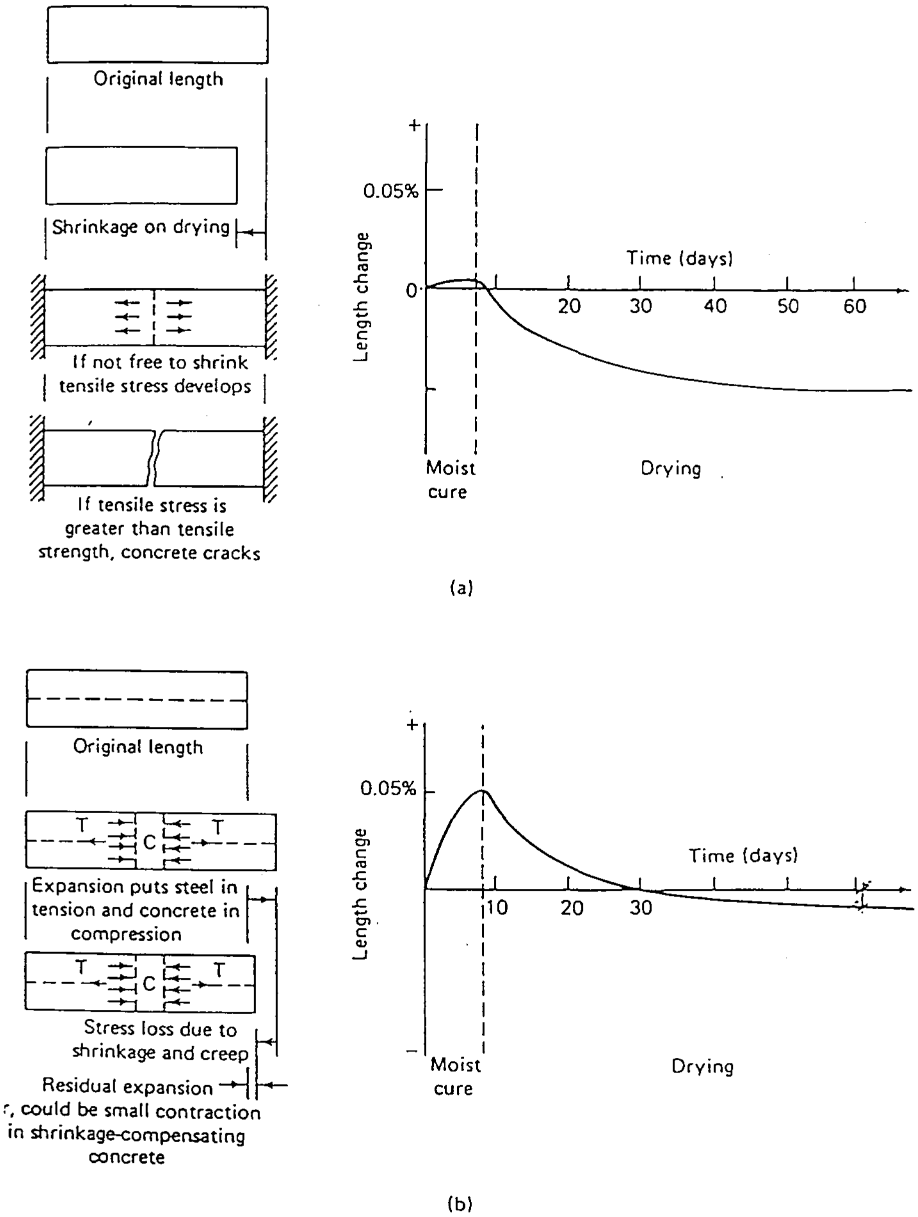


Fig. 2.7. Drying Shrinkage of Concretes Made with: a) Type I Portland Cement; b) Expansive Cement [26]

Table 2.2. Water-Cement Ratio and Concrete Bleeding Rates [31]

w/c	Bleeding Rate ($lb/ft^2/hr$)
0.40	0.245
0.41	0.742
0.49	0.547

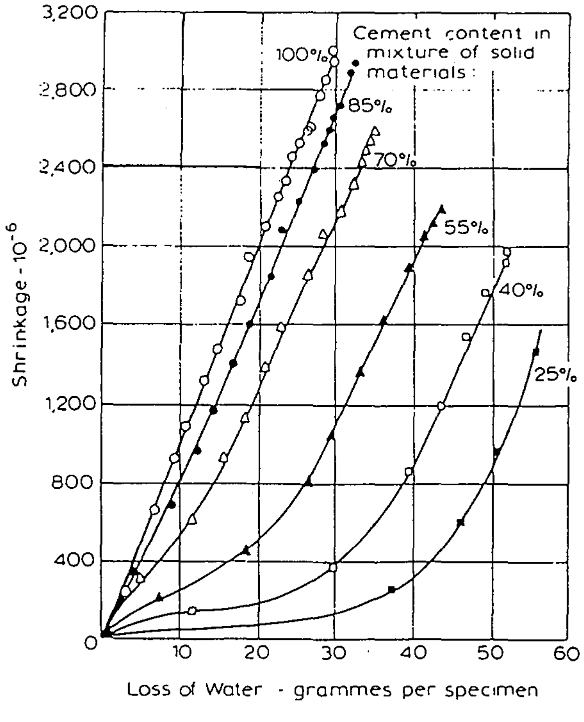


Fig. 2.8. Relation between Shrinkage and Loss of Water from Cement Specimens [28]

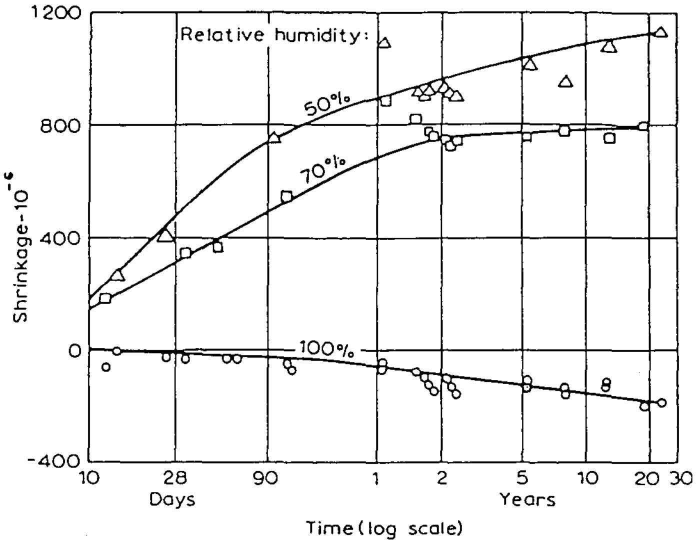


Fig. 2.9. Relation between Shrinkage and Time for Concretes at Different Relative Humidities [28]

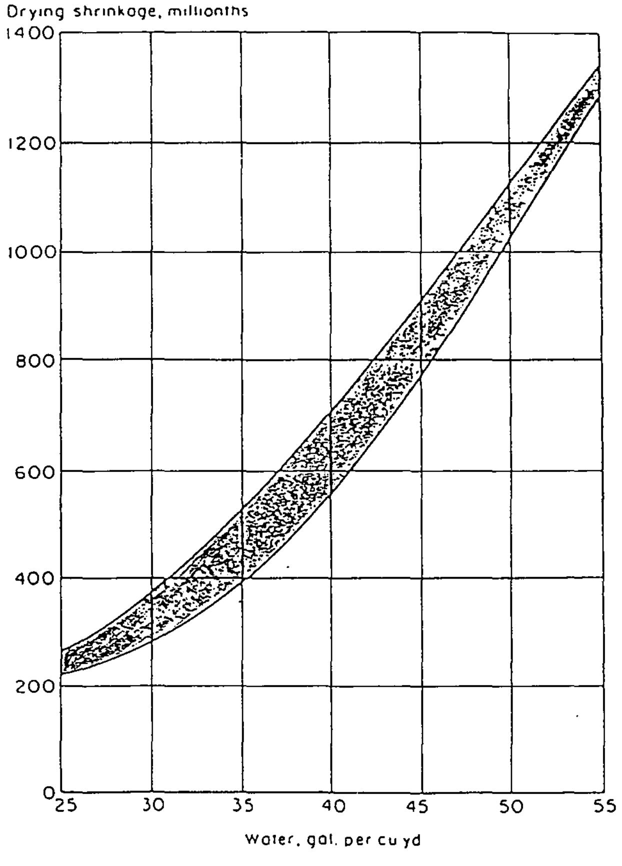


Fig. 2.10. Relationship of Total Water Content and Drying Shrinkage [22]

this study does not focus on long-term shrinkage effects as shown in Fig. 2.9, the plot shows that increased humidity reduces shrinkage in the first month.

According to Kosmatka and Panarese [22], tests of plain concrete specimens with no reinforcement indicate drying shrinkage from about 400 to 800 millionths when exposed to air at 50% humidity. Concrete with a unit shrinkage of 550 millionths shortens about the same amount as the thermal contraction caused by a temperature decrease of 100°F. The most important controllable factor affecting drying shrinkage is the amount of water per unit volume of concrete. The results of tests illustrating the water content-shrinkage relationship are shown in Fig. 2. 10. Shrinkage can be minimized by keeping the water content of concrete as low as possible. This is achieved by keeping the total coarse aggregate content of the concrete as high as possible. Therefore, use of low slumps and placement methods that minimize water requirements are major factors in controlling concrete shrinkage. Any practice that increases the water requirement of the cement paste, such as the use of high slumps, excessively high freshly mixed concrete temperatures, high fine-aggregate contents, or small-size coarse aggregate, will increase shrinkage. Experiments performed at Massachusetts Institute of Technology showed that for each 1% increase in mixing water, concrete shrinkage increased by about 2%.

Kosmatka and Panarese [22] also discuss a testing program to measure drying shrinkage of concrete. The test specimens were moist-cured for 14 days at 70°F then stored at the same temperature in an environment with 50% relative humidity. An average of 34% of the drying shrinkage occurred in the first month. Fig. 2.11 presents these results in bar graph form. Fig. 2.12 displays the effect of alternate wetting and drying on shrinkage.

Mindess and Young [26] present Fig. 2.13 to illustrate that some of the shrinkage that results from initial drying is irreversible and subsequent volume changes due to rewetting and redrying are smaller. They also provide Fig. 2.14 which plots shrinkage against percent weight loss (water loss) as it relates to humidity and then temperature.

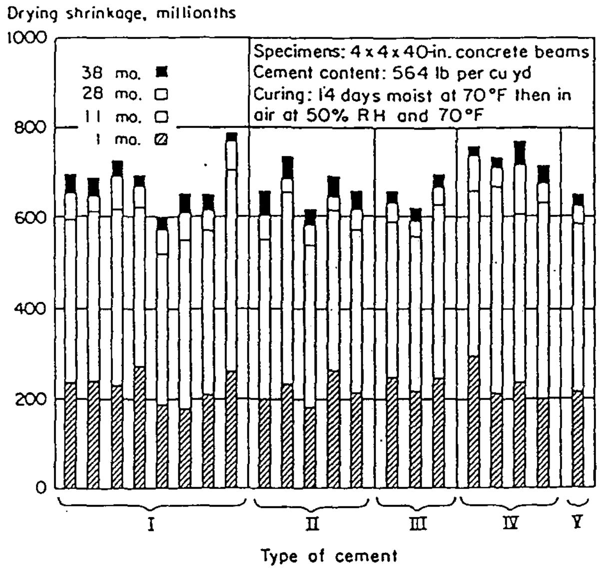


Fig. 2.11. Results of Long-Term Drying Shrinkage Tests [22]

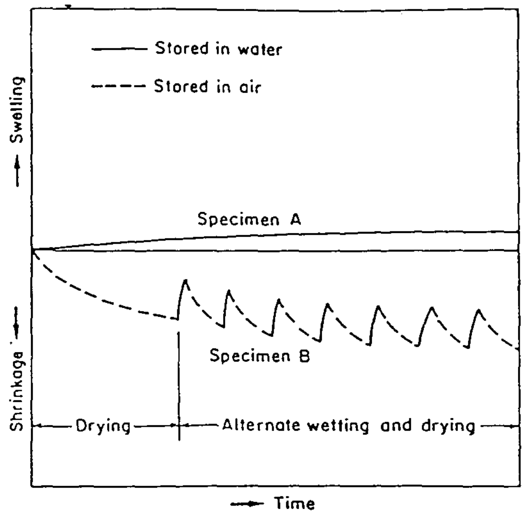


Fig. 2.12. Schematic Illustration of Moisture Movements in Concrete [22]

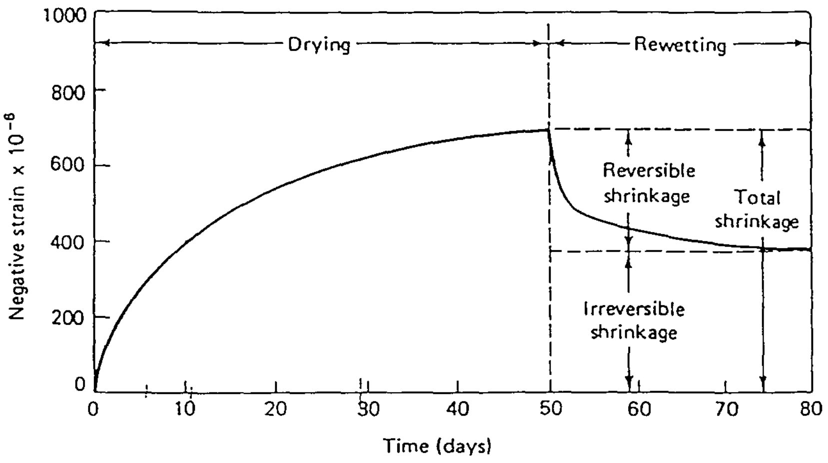


Fig. 2.13. Typical Behavior of Concrete on Drying and Rewetting [26]

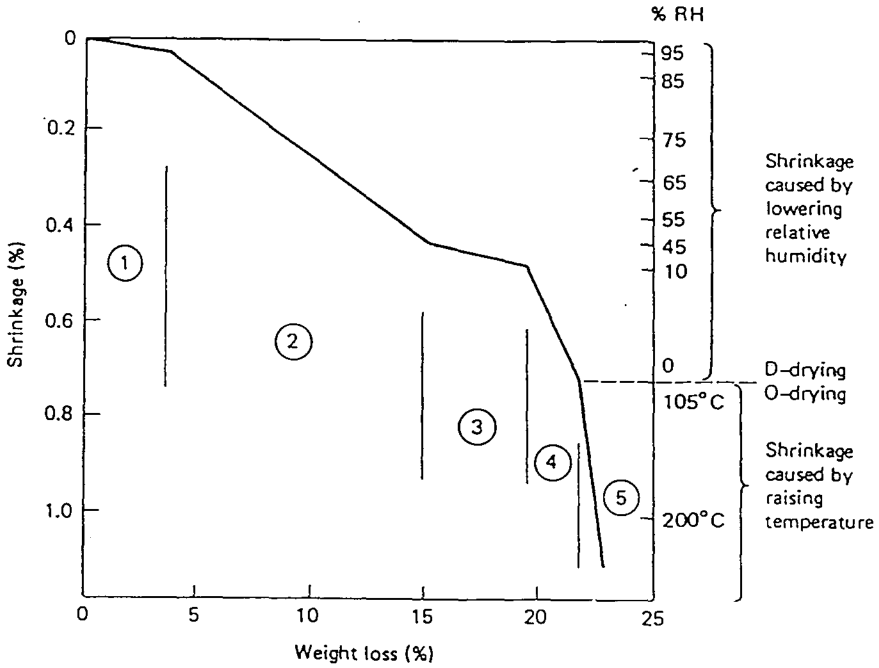


Fig. 2.14. Effect of Relative Humidity and Temperature on Concrete Shrinkage [26]

Mindess and Young [26] also report the effects of volume-to-surface ratio on the drying shrinkage of concrete to be as shown in Fig. 2.15. Note that in case of bridge decks,

$$\textit{Volume-to-Surface Ratio} = \frac{SAxt}{SA} \approx t \tag{2.2}$$

For 6" deck thickness, t, = 152 mm; for 8", t = *203* mm.

Thus, the ultimate shrinkages for bridge decks are at the lower levels in Fig. 2.15; however, these shrinkages occur more quickly than those for structures with small values of volume-to-surface ratio.

Differential shrinkage due to drying shrinkage is discussed by Neville [28]. This shrinkage refers to the relationship of shrinkage relative to the distance from the concrete surface. Fig. 2.16 is a plot of shrinkage vs. distance from the surface for different ages of concrete. It is evident that shrinkage is higher at the surface than away from the surface.

Drying shrinkage is mostly a concern over the long-term life of a concrete member. Raina [32] contends that if adequate reinforcement and sufficient movement joints are provided against other forms of movement, the contribution of drying shrinkage to cracking is often too small to be of consequence. Drying shrinkage is usually in the order of magnitude of 30 x 10^{-6} after 5 years and the tensile strain capacity of concrete is considered to be 80-150 x 10^{-6}. When unacceptable long-term drying shrinkage cracking does occur, it is usually attributable to the mixture design, properties and proportions of the mixture constituents, and construction methods. Also, the more water available to evaporate from the concrete, the higher tendency to shrink on drying.

2.4 Early Thermal Shrinkage Cracking

Most commonly, the subject of concrete volume changes deals with the expansion and contraction due to temperature and moisture cycles. Thermal expansion and contraction of concrete

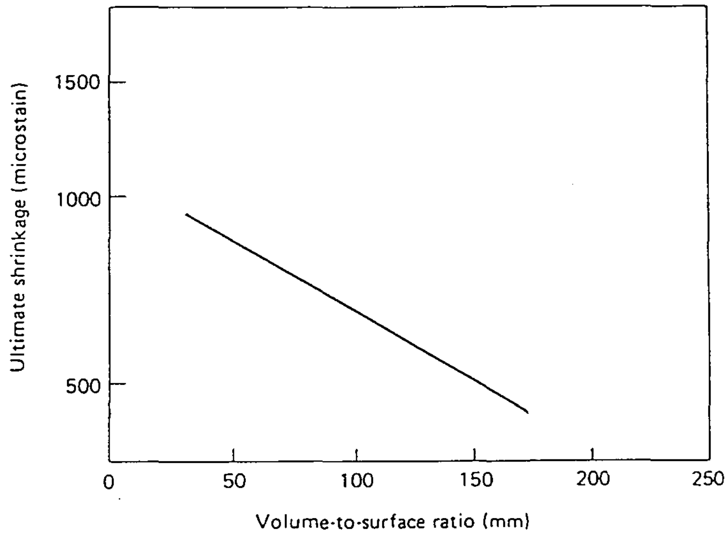


Fig. 2.15. Effect of Volume-to-Surface Ratio on the Shrinkage of Concrete [26]

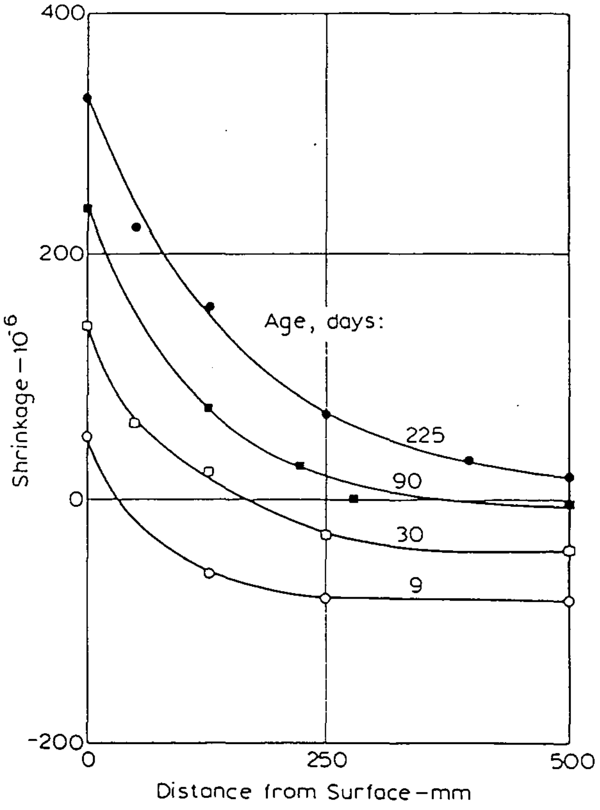


Fig. 2.16. Progress of Shrinkage with Time as a Function of Distance from Drying Surface [28]

varies with factors such as aggregate type, cement content, water cement ratio, temperature range, concrete age, and relative humidity. Of these, aggregate type has the greatest influence. An average value for the coefficient of thermal expansion of unreinforced and reinforced concrete is 5.5 and 6.0 millionths per degree Fahrenheit, respectively.

According to Raina [32], early thermal contraction strains far exceed drying shrinkage strains and are primarily responsible for early cracking in retaining walls and similar reinforced concrete bridge deck structures. The reaction of cement with water, known as hydration, is a chemical reaction which produces heat. If insulated and large enough, the rate of heat gain in a concrete element is likely to exceed the rate of heat loss to the atmosphere, causing a rise in temperature. After the first day, the rate of heat gain falls below the rate of heat loss and the concrete member begins to cool, resulting in contraction. Cracking can result if the concrete is restrained internally or externally and adequate strength has not developed to resist tensile stresses caused by the contraction. Internal restraint occurs due to rebar mats and differential cooling of the member; e.g., the surface of the member cools faster than the core. External restraint refers to restraint provided by external supports. Raina indicates that the core of the concrete cools to ambient in 7 to 14 days. Hence, thermal movement cracks are more likely to occur during this period. One of the most important factors which assists in differentiating between thermal movement cracks and long-term drying shrinkage cracks is knowledge of when the crack forms. A crack which develops in the first few weeks is unlikely to be a drying shrinkage crack unless the deck is subjected to extreme drying conditions.

Krauss and Rogalla [23] write that the first thermal stresses develop in a deck in the first 1-2 days after placement. When concrete is still plastic or of very low strength, it can adjust to the changing temperatures, which result from heat of hydration and subsequent cooling, without developing stresses. However, after the concrete hardens, contractions due to temperature changes cause stress.

Krauss and Rogalla also provide information concerning early thermal cracking with regard to the type of the bridge. When a deck is cast monolithically with concrete girders, thermal stresses caused by heat of hydration are often minimized because both the deck and the girders develop heat and cool at close to the same rate and the temperature difference is minimized. Stresses usually develop from heat of hydration in this bridge type because the deck cools quicker than the more massive girders. Thermal stresses are worse in a steel girder bridge and worst in a concrete bridge when the deck is cast after the girders. Concrete conducts heat at a slower rate than steel, and the greater mass of the girders will cause the girders to respond slower to the changing deck temperatures. Steel girders typically conduct heat at a faster rate than concrete girders, and upper flanges will warm and cool more with the deck, reducing the temperature difference at the deck-girder interface. A 50°F temperature change in the deck relative to the girders can cause stresses greater than 200 psi.

2.5 Measures for Prevention of Early Cracking

Lerch [25] provides several measures to prevent plastic shrinkage cracking. The measures can be divided into two categories: concreting steps and placement methods. Concreting steps which reduce or eliminate plastic shrinkage cracking are: 1) dampen subgrade and forms; 2) dampen aggregates if dry and absorptive; 3) lower concrete temperatures in hot weather; 4) avoid overheating concrete in cold weather. Placement methods for prevention of plastic shrinkage include: 1) reduce time between placement and start of curing by improved construction procedures; 2) start curing the concrete as soon as possible after placing and finishing; 3) protect concrete with fog spray if any appreciable delay between placing and finishing is unavoidable; 4) erect windbreaks to reduce wind velocity; 5) provide sunshades to control concrete surface temperature.

To emphasize the importance of these steps, Lerch cites a runway project in which liquid membrane was applied to a concrete surface 1.5-2 hours after finishing. One day, the temperature was 93-96°F, relative humidity 30-45%, and wind velocity 5-8 mph. The next day, humidity dropped to 15-25% and wind velocity increased to 10-15 mph. On the first day, no cracks were observed, but the next day, cracking was a problem. Construction procedures were modified so the membrane could be applied earlier and cracking was virtually eliminated. Field investigations have also shown that application of a fog spray or a cover of wet burlap during the initial hardening, prior to troweling or between successive passes of the trowel, prevented cracking.

ACI 305 [7] discusses the problems of hot weather concreting and states that plastic shrinkage cracking is a potential problem, and precautions to prevent plastic shrinkage are necessary. The concrete should be protected against moisture loss at all times. Procedures for keeping exposed surfaces from drying must be promptly initiated and continued without interruption. Failure to do so may result in excessive shrinkage and cracking which will impair the surface durability and strength of the concrete. A very important factor is controlling concrete temperature, i.e., keeping it low during hot weather. A more detailed discussion of concrete temperature is given in Chapter 4. ACI 305 also lists precautions concerning planning and construction methods. If economic necessity forces construction in extremely hot weather, the job should be planned to avoid adverse exposure of the concrete to environmental conditions. Placement should also be scheduled for times of day or night when conditions are favorable. Measuring and recording of weather reports and conditions at the jobsite at frequent intervals can be used with knowledge of actual or projected concrete temperatures as a helpful tool to prevent shrinkage cracking. Raina points out that night pours are only effective if they produce lower concrete temperatures or wind velocities. The lowering of ambient temperature, relative humidity, and exposure to solar radiation helps but is not enough to compensate for the effects of the first two.

ACI 306 [8] discusses problems associated with concreting in cold weather. Plastic shrinkage cracks occur with rapid moisture loss due to differential temperature between warm concrete and cold air. Concrete should be placed at no more than 20°F above the minimum ambient temperature during placement.

ACI 308 [9] provides standards of practice for curing of concrete. The specification requires that if plastic shrinkage cracking begins, initial curing should be fog spraying, cover by presoaked burlap, or measures to reduce wind velocity and temperature. Exposed surfaces should be kept wet or sealed until strong enough to allow foot traffic without damage.

FIP [19] suggests that planning in hot weather conditions should account for resources at the site and means and methods of reducing concrete temperature, temperature of transport equipment, and temperature of placing equipment. Forms should be cooled before placement, and reinforcement should be shaded or sprayed with water. Effective coordination between mixing, transportation, and placement is essential. Hot weather also tends to reduce the efficiency of supervisors and work crews, and this factor should be considered in planning.

The prevention of early drying shrinkage is promoted by implementing precautions against plastic shrinkage. The primary method of reducing drying shrinkage cracking is proper curing. ACI 305 [7] indicates that of the different curing procedures, moist curing is the best method for developing the strength of concrete and minimizing early drying shrinkage. Forms should be covered and kept continuously moist during the early curing period. Curing should continue for 7 days. If a change in curing method is implemented, it should be done only after three days and the concrete surface should not be permitted to dry during transition. During form removal, newly exposed surfaces should promptly receive a wet cover. After curing, covering should be left in place (4 days is suggested) so the concrete will dry slowly and be less subject to surface shrinkage cracking. The effects of drying can also be minimized by application of a sprayable compound at the end of moist curing. FIP [19] stipulates that it is important to keep the moist cure covering wet at all times.

According to ACI 345 [10], a guide for bridge deck construction, other methods of curing which are acceptable are surface sealants, also known as liquid membrane curing compound, and surface coverings such as polyethylene sheeting or waterproof paper. These types of curing are water retaining instead of water adding, like continuous moist cure. Curing compound should meet requirements of ASTM C309 [13] (AASHTO M148 [31]) having a water release rate of no more than 0.55 kg/m^2 (0.11 lb/ft^2) over 72 hours. Polyethylene film should meet requirements of ASTM C171[12] (AASHTO M171[4]) and have the same moisture loss rate of 0.55 k g/m^2 (0.11 lb/ft^2)

To prevent thermal stresses and shrinkage, control of concrete temperature is the key. ACI 308 [9] says curing methods should be implemented which prevent or minimize large temperature differences. ACI 306 [8] specifies to limit rapid temperature changes until the concrete has developed adequate strength. Large temperature differences between concrete and adjacent structures should be avoided. Failure to follow these steps may cause cracking plus loss of strength and durability at the end of temperature protection. The surface of the concrete should be allowed to cool gradually over 24 hours. As stated in ACI 305 [7], cracking due to thermal stresses is more severe in spring and fall due to the larger 24-hour temperature change. Chapter 4 includes discussion of control of concrete temperature, which will reduce thermal cracking.

2.6 Curing Concrete by Moisture Retention

In ALDOT specifications [2], the only required curing is covering of the concrete surface with white-pigmented membrane curing compound meeting ASTM C309 as soon as possible after finishing. Polyethylene sheeting should be placed over the concrete no later than the following day and should meet the requirements of ASTM C171. After reading the comments of many sources, it appears that curing by use of liquid membrane curing compound has its advantages but is not the best form of curing.

The use of curing compounds is advantageous in many ways. It is more economical than moist cure due to ease of application. ACI 345 [10] lists three advantages: liquid membrane is usually applied sooner than moist cure; the curing extends over a larger period; and the curing procedure is not cut off sharply. Transportation Research Circular No. 308 states that the quickest, most effective way to cure patched areas is by spraying on heavy membrane curing compound. Curing compounds can also be quite effective in cold weather. ACI 306 [8] claims, that except for within heated enclosures, little or no supply of external moisture is needed in cold weather conditions. A curing compound meeting ASTM C309 with an impervious cover (polyethylene sheeting is an example) is recommended over water curing which may ice. A study conducted by Rhodes [34] provides, that in cold weather construction, membrane curing is advantageous to moist curing due to less freezable water in the cement paste and the concrete is able to withstand lower temperatures without frost damage. Also retention of 80% of original net mix water at the end of a 7-day curing period is sufficient for continued hydration and development of required strength. Neville L28] points out that since wet curing in practice may be intermittent, sealing compounds may produce better results.

Despite the previously stated advantages, there are many shortcomings related with curing by use of curing compounds. Mindess and Young [26] state that liquid membranes provide the least effective method of curing. They do not prevent evaporation from the concrete. For concretes with water cement ratios of 0.42, there is theoretically enough water for hydration, yet it is desirable to provide additional moisture during curing for maximum hydration. If internal relative humidity drops below 80%, hydration will stop and this can occur in environments of low relative humidity. Neville [28] writes that impermeable membrane (curing compounds) effectively prevents evaporation but not self-desiccation which can lead to plastic settlement cracking. Curing compounds produce lower strengths than water curing because rapid evaporation of curing water is allowed when using curing compounds. Also, if cracks due to restrained shrinkage occur at an early age and moisture has access to the cracks, as is the case when wet curing, many of the cracks will become closed due to autogenous healing. Neville also indicates that proper and prolonged moist curing is essential for resistance to abrasion , and some types of membrane curing can be detrimental. In dry weather, wetting concrete and allowing the water to evaporate is an effective means of cooling, but there is no cooling of this nature when utilizing curing compound. Therefore, higher temperatures may be reached. Large areas such as roads and airfields are particularly vulnerable to high temperatures.

Many sources claim that curing by liquid membrane curing compound can be improved and adequate by implementing various steps. ACI 345 [10] requires that curing compound be placed as soon as the bleedwater sheen leaves the surface with the surface still damp. Rhodes [34] indicates that curing compound should be applied as soon as surface moisture disappears without delay to avoid excess surface drying which may combine with temperature effects to crack the pavement. Delay of placement may result in a discontinuous film caused by compound penetrating the concrete rather than bridging the voids. If delay is unavoidable, the surface should be resaturated with water before application of the membrane.

Liquid membrane curing can also be enhanced by combining with other forms of curing. Rhodes [34] states that an initial 24-hour moist curing period can be advantageous. Blanks et al. [16] reports considerable difficulty occurred on a job with cracks appearing in concrete placed as a lining on the side slopes of a canal. Troweling closed the cracks, but they would reappear after application of the liquid membrane. By wet curing the concrete for a 24-hour period prior to compound placement, cracking was eliminated. Economically, it may not be desirable to implement an initial moist curing period, but it is an effective way to mitigate early shrinkage cracking. Transportation Research Circular [39] adds that after set of the curing compound, it can be helpful to sprinkle the concrete surface with water. This action should be discontinued, however, if the temperature drops at more than 3 °F per hour. Mindess and Young [26] state that waterproof paper or plastic sheeting should be placed as soon as the surface has hardened enough to prevent damage, and the concrete has been thoroughly wetted. Ravina and Shalon [33] describe a field experiment in which prevention of evaporation by covering with polyethylene sheeting immediately after placement precluded cracking. Several sealing compounds were not effective in extreme climatic conditions.

Another concern is the quality of the curing compound. Blanks *et al.* [16] warns that indiscriminate selection of sealing compound without testing is dangerous. Covarrubius [17] found in studies that controlling the problem of inadequate curing compound may require a change in ASTM C156 [11], the standard test method for liquid membrane curing compounds. The research revealed it is important to determine which curing compounds work well on slabs when placed over bleeding concrete. Compounds which worked well when placed on the concrete surface before bleeding had stopped, retained more water than when placed after bleeding. ACI 302 [6] emphasizes if floors in which high wear resistance, optimum top surface strength, and minimal cracking are required, the curing compound should have a moisture loss of no more than 0.30 kg/m^2 (0.06 lb/ft^2) in a 72-hour period. This is less than 50% of the ASTM C309 requirement. Some agencies have set a more restrictive limit of 0.39 kg/m^2 (0.08 lb/ft^2) for moisture loss rate.

2.7 Concrete Properties Relevant to Early Deck Cracking

Early bridge deck cracking (but after the concrete has hardened) is primarily the results of drying shrinkage characteristics and tensile strength properties of the concrete. The concrete thermal, stiffness, and creep properties are also important in early cracking considerations. Temperature and humidity exposure conditions discussed in Chapter 3 are also important, as are the curing conditions applied to the deck concrete when it was first placed. This section examines the primary concrete material properties and characteristics which are relevant to early bridge deck cracking. Three figures used in this section were presented earlier, but are repeated here for convenience of the reader as the relevant topis are discussed.

2.7.1 Drying Shrinkage.

Concrete expands slightly with a gain in moisture and contracts with a loss in moisture. The effects of these moisture movements are illustrated schematically in Fig. 2.17. Specimen A in that figure represents concrete stored continuously in water from time of casting; Specimen B represents the same concrete exposed first to drying in air and then to alternate cycles of wetting and drying [22]. It should be noted that the swelling that occurs during continuous wet storage over a period of several years is usually less than 150 millionths or about one-fourth of the shrinkage of air-dried concrete for the same period.

Tests indicate that the drying shrinkage of small, plain concrete specimens (without reinforcement) ranges from about 400 to 800 millionths when exposed to air at 50% humidity [22]. Drying shrinkage values decrease as relative humidities increase as can be seen in Fig. 2.18. It can be noted that concrete with a unit shrinkage of 550 millionths shortens about the same amount as the thermal contractions caused by a decrease in temperature of 100°F.

The shrinkage of large concrete components is less than that of small test specimens because of movement restraints offered by other components of the structure, and by the concrete reinforcing steel. In reinforced concrete structures with normal amounts of reinforcement, drying shrinkage is commonly assumed to be 200 to 300 millionths. This is approximately the same strain level as for 50°F change in temperature.

The most important controllable factor affecting the drying shrinkage of normal portland cement concrete is the amount of water per unit volume of concrete. The results of tests illustrating the water content-shrinkage relationship are shown in Fig. 2.19. This figure indicates that shrinkage is a direct function of the unit water content of fresh concrete. The close grouping of these curves shows that drying shrinkage is governed mainly by unit water content. (Note narrowness of band of water content on shrinkage regardless of cement content or water-cement ratio.)

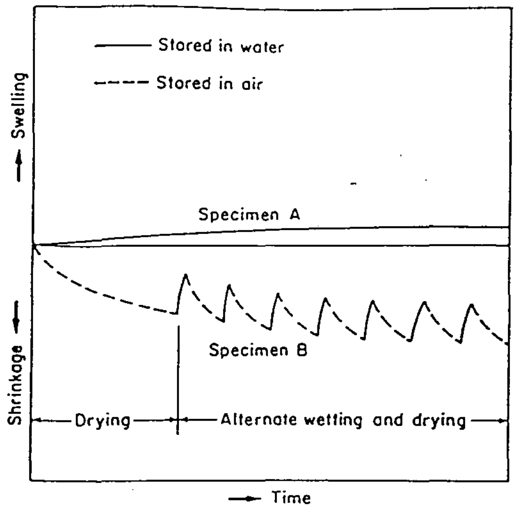


Fig. 2.17. Illustration of Moisture Movements in Concrete [22].

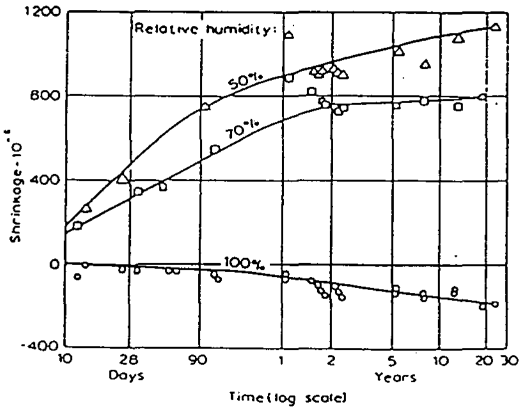


Fig. 2.18. Shrinkage vs. Time for Concretes Stored at Different Relative Humidities [28].

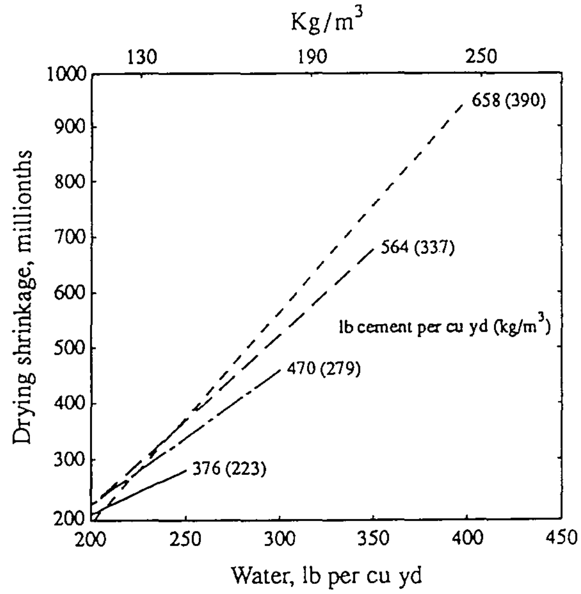


Fig. 2.19. Interrelation of Shrinkage, Cement Content, and Water Content [Unknown Source].

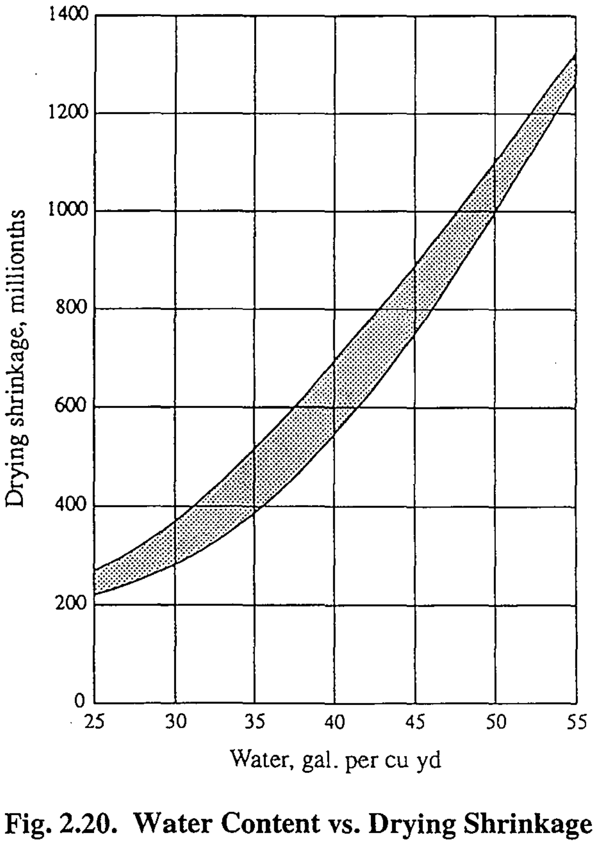
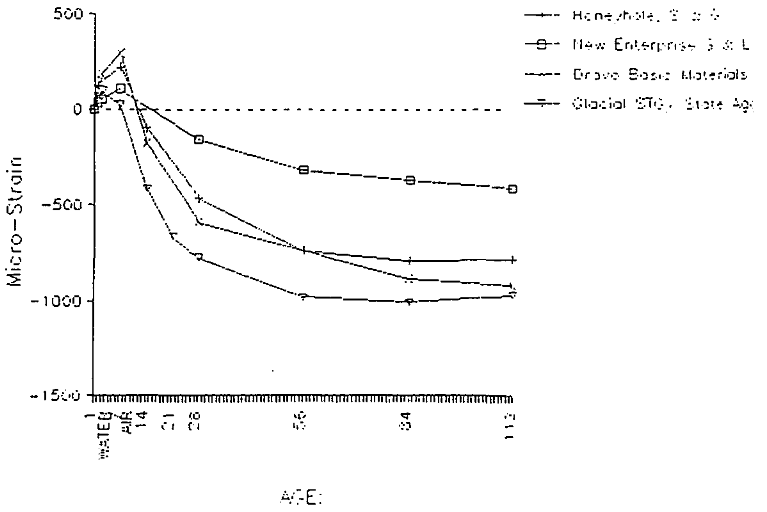


Fig. 2.20. Water Content vs. Drying Shrinkage [22].

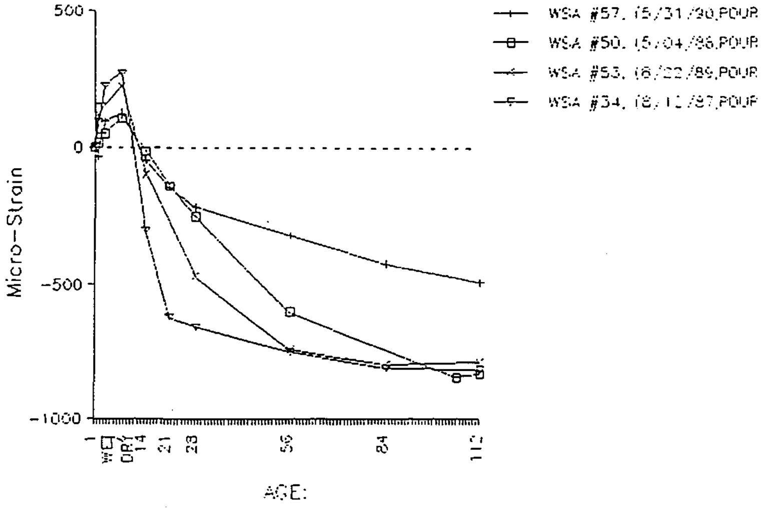
The curves of Fig. 2.19 along with results from other mixtures testing can be banded as shown in Fig. 2.20, and illustrate the dramatic increases in drying shrinkage with increasing water content. Thus, shrinkage can be minimized by keeping the water content of concrete as low as possible (and still achieve the required workability). This is achieved by keeping the total coarse aggregate content of the concrete as high as possible. Use of low slumps and placing methods that minimize water requirements are thus major factors in controlling concrete shrinkage [22]. Additionally, prolonged and careful curing is beneficial for shrinkage control. Any practice that increases the water requirement of the cement paste, such as the use of high slumps, excessively high freshly mixed concrete temperatures, high fine-aggregate contents, or small-size coarse aggregate, will increase shrinkage.

Any workable concrete mixture contains more water than is needed for hydration. If the concrete is exposed to air, the larger part of this free water evaporates in time, with the rate and completeness of drying dependent on ambient temperature and humidity conditions. As the concrete dries, it shrinks in volume as indicated above. If this volume reduction is unrestrained then no shrinkage stresses, and cracks, are produced. However, if the concrete is restrained by other structure components or by embedded reinforcing steel, then the drying shrinkage results in shrinkage tensile stresses which in turn may result in concrete cracking. Also, as drying takes place, concrete near the surface dries and shrinks faster than the inner concrete, causing surface tensile stresses and possible cracking. Thus the effects of drying shrinkage are the same as those of thermal shrinkage, i.e., stresses are developed only when movement is restrained.

Unfortunately, the water content of the concrete is not the only mixture component which significantly affects drying shrinkage. Wilbur Smith Associates [15] conducted limited laboratory testing to assess the effects of aggregate type/source, mixture proportions, cement type/source, and fly ash on drying shrinkage. The results of their testing are shown in Fig. 2.21 and indicate a large variability in drying shrinkage for all of the mixture parameters shown. This points to the desirability of evaluating the

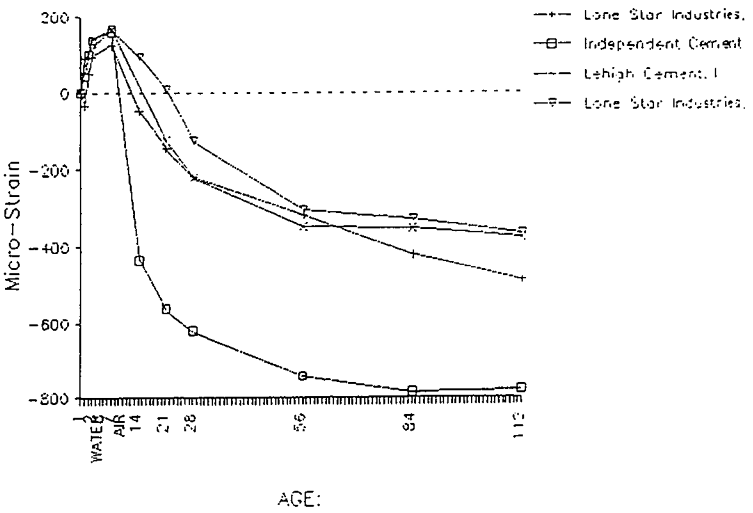


a) Effect of Aggregate Source

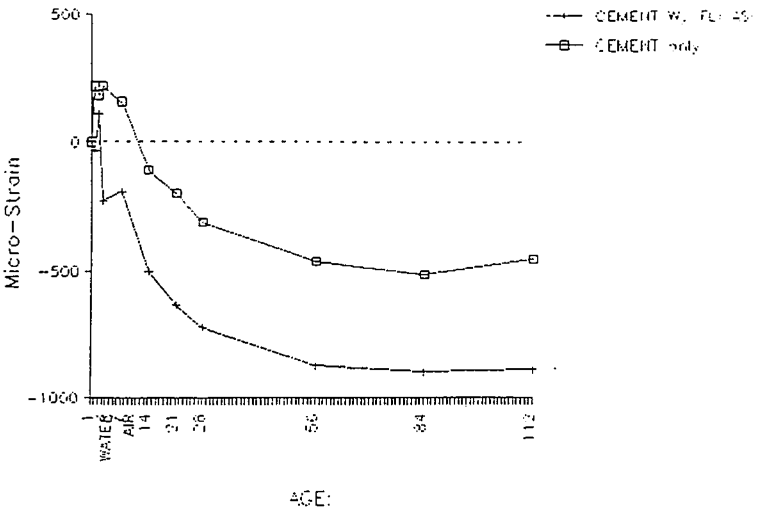


b) Effect of Mixture Design

Fig. 2.21. Effect of Some Mixture Parameters on Concrete Drying Shrinkage [15]



c) Effect of Cement Type/Source



d) Effect of Flyash

Fig. 2.21.(cont.) Effect of Some Mixture Parameters on Concrete Drying Shrinkage [15]

characteristics of each concrete mixture/material source for concrete components, such as bridge decks, where drying shrinkage is important. Note in Fig. 2.21 that most of the drying shrinkage took place during the first 2 months. For larger concrete "specimens," such as bridge decks, the time period of significant shrinkage would probably be extended to approximately 1-year.

Typical concrete initial swelling and following drying shrinkage curves fall within the range of the curves shown in Fig. 2.22. Typically early age behavior is that of swelling during wet curing of 7 days as indicated in Fig. 2.22. This is followed by drying shrinkage to ultimate shrinkage strain levels of 600 to 800 u in. per in. Weight loss and drying shrinkage time history curves for some concrete cylinders are shown in Fig. 2.23. An equation sometimes used in estimating shrinkage values at different times in concrete components in the field is

$$\epsilon_{sh}^{T} = \left(\frac{t}{35+t}\right)\epsilon_{sh}^{u} \tag{2.3}$$

where, T = total time in days after placement of concrete

t = time in days after wet cure period

For a 7-day cure period, this equation yields a $\epsilon_{sh}^{T} = 0.50\ \epsilon_{sh}^{u}$ at 42 days as can be seen in Table 2.3

Table 2.3. Variation of $\epsilon_{sh}^{T}/\epsilon_{sh}^{u}$ from Eqn 2.3 with Time*

Time		
T	t	$\epsilon_{sh}^{T}/\epsilon_{sh}^{u}$
7 days	0	0
35 days	28 days	0.44
42 days	35 days	0.50
	3 mos.	0.72
	6 mos.	0.84
	1 yr.	0.91
	2 yrs.	0.95
	5 yrs.	0.98
	10 yrs.	0.99
	20 yrs.	1.00

*For 7-days of wet curing

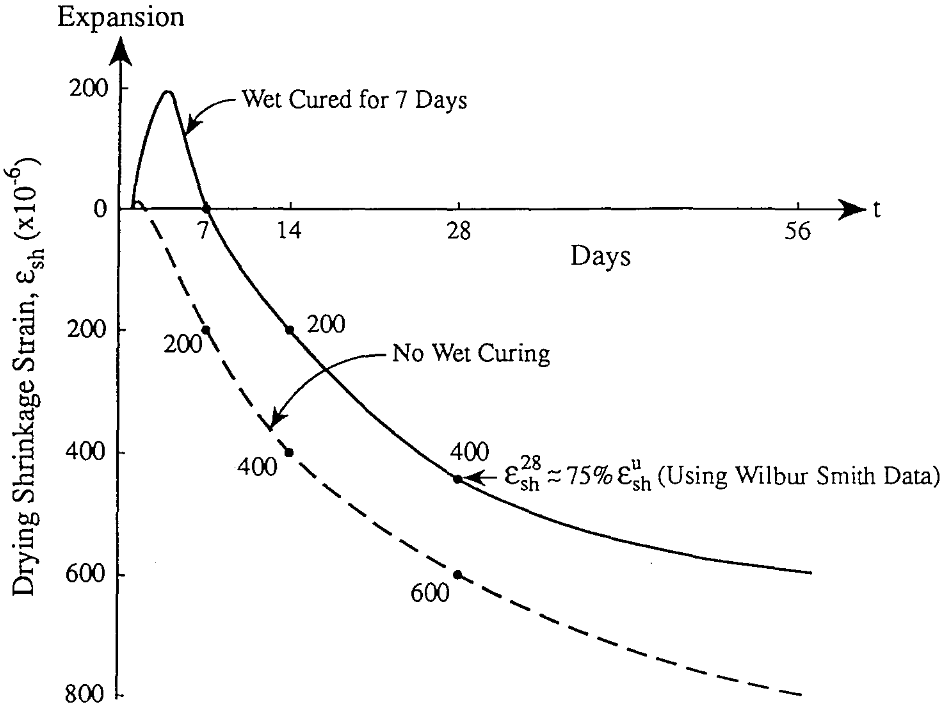


Fig. 2.22. Approximate Drying Curves for Laboratory Test Prism Specimens.

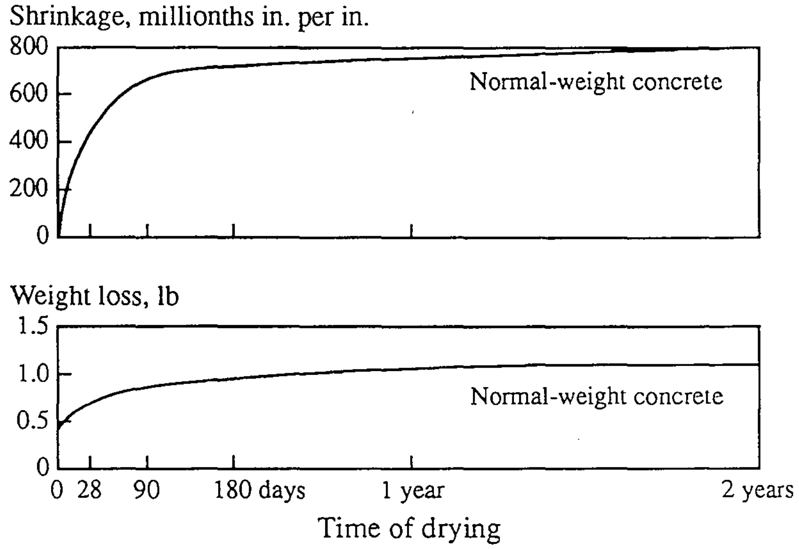


Fig. 2.23. Weight Loss and Drying Shrinkage Curves for Concrete Cylinders [22].

Concrete mixtures can be classified based on drying shrinkage as follows:

No Shrinkage : <0.004 % shrinkage (Shrinkage Compensating Concrete)

Low Shrinkage : 0.004 - 0.04% shrinkage

Moderate Shrinkage: 0.04% - 0.08% shrinkage

High Shrinkage: >0.08% shrinkage

Note, for comparative purposes,

$\epsilon_{\text{thermal}} = 0.00055\%$

Thermal Shrinkage = 0.0055% per 10°F

Thus, normal concrete temperature changes and movements are analogous to those of low drying shrinkage concrete.

2.7.2 Temperature Shrinkage. Like most materials, concrete expands with increasing temperature and contracts with decreasing temperature. The effects of such volume changes are similar to those caused by shrinkage. That is, temperature contraction can lead to cracking, particularly when superposed on shrinkage [40].

Thermal expansion and contraction of concrete varies with factors such as aggregate type, cement content, water-cement ratio, temperature range, concrete age, and relative humidity. Of these, aggregate type has the greatest influence [22]. Table 2.4 shows some experimental values of the thermal coefficient of expansion of concretes made with aggregates of various types.

The coefficient of thermal expansion of concrete is generally in the range of 4.5-6.5 x 10^{-6} in. per in. per °F. A value of 5.5 x 10^{-6} is the generally accepted value used in calculating thermal deformations and stresses in plain concrete, and a value of 6.0 x $10\text{-}6^{-6}$ is typically used for reinforced concrete (average of 5.5 for concrete and 6.5 for steel rebar).

Table 2.4 Effect of Aggregate Type on Thermal Coefficient of Expansion of Concrete [22]

Aggregate type (from one source)	Coefficient of expansion millionths per °F
Quartz	6.6
Sandstone	6.5
Gravel	6.0
Granite	5.3
Basalt	4.8
Limestone	3.8

The rate of cement hydration in concrete is directly proportional to the heat evolution, which can be measured. Fig. 2.24 shows a typical time history curve of rate of heat evolution for concrete. Thus, temperature increases in concrete are caused very early in fresh and "green" concrete by hydration of the cement. This is illustrated in Fig. 2.25 which indicates a 10-20°F rise in temperature due to hydration, and that the heat of hydration peaks about 12 hours after mixing (for Type I cement) and is close to initial ambient temperature after about 24 hours (for Type I cement). To further illustrate the heat of hydration build-up and subsidence in fresh concrete, the temperature vs. time curves for some common Penn DOT concrete mixtures [15], demonstrating the effects of aggregate type/source, cement type/source, and mixture design, are shown along with the effect of fly ash in Fig. 2.26

After about 2-days, changes in concrete temperature normally result only from change in environmental/weather conditions. Ambient temperatures vary daily and through the annual seasonal cycle, as does radiant heating from the sun. For bridge decks, temperature changes on the top and bottom of the deck are normally substantially different. This causes temperature gradients through the deck, and these in conjunction with deck constraints from the supporting girders result in significant deck thermal stresses and possible cracking. It should be noted that prolonged and careful wet curing can be utilized to

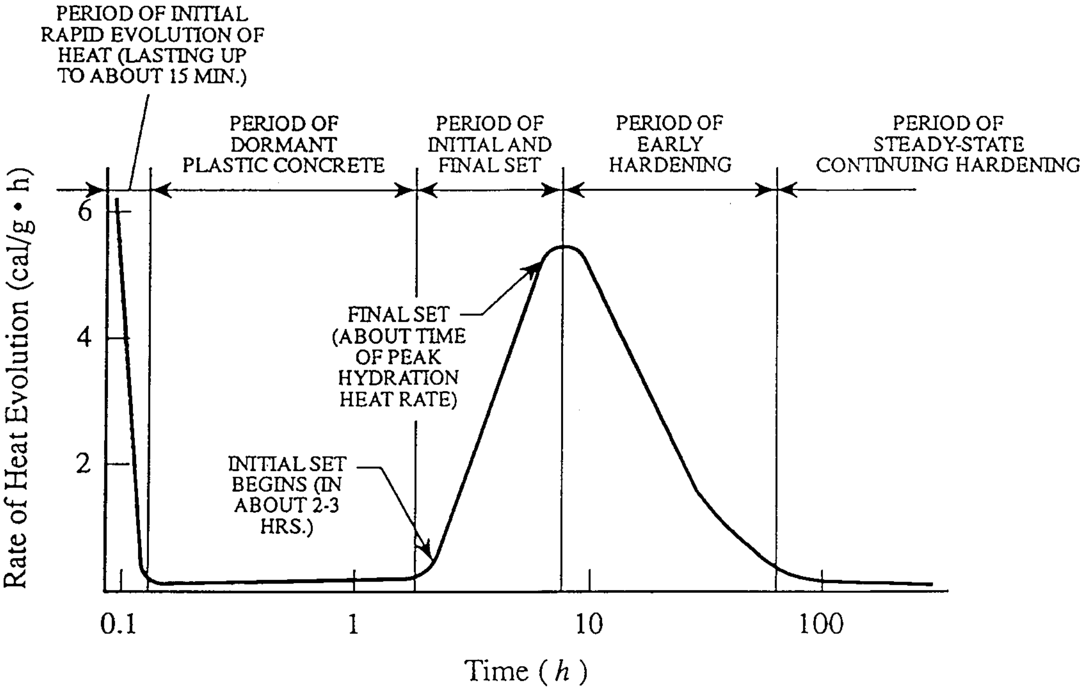


Fig. 2.24. Typical Concrete Rate of Heat Evolution Time History (Adapted from Ref. [26]).

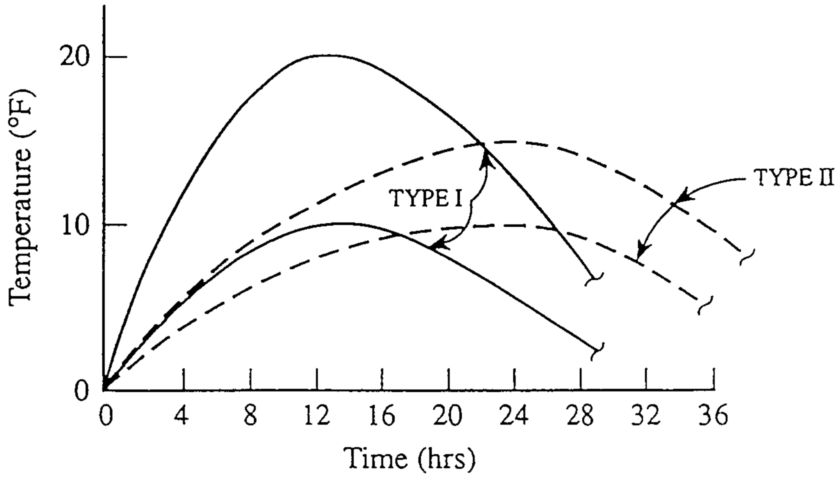
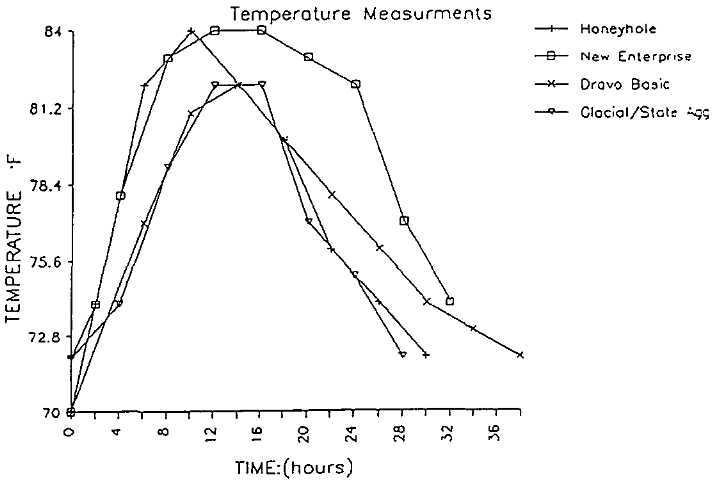
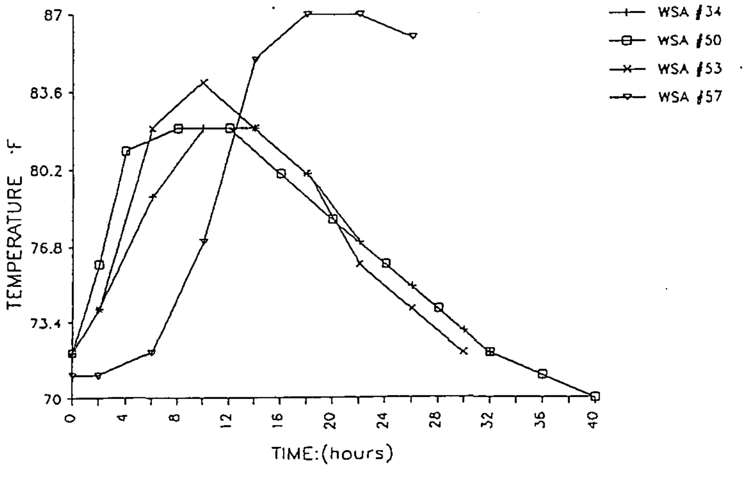


Fig. 2.25. Estimated Heat of Hydration vs. Time Curves for Typical Concrete Mixtures.

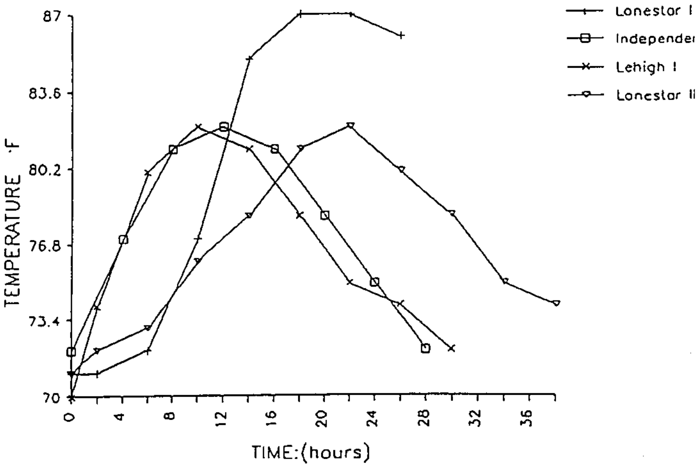


a) Effect of Aggregate

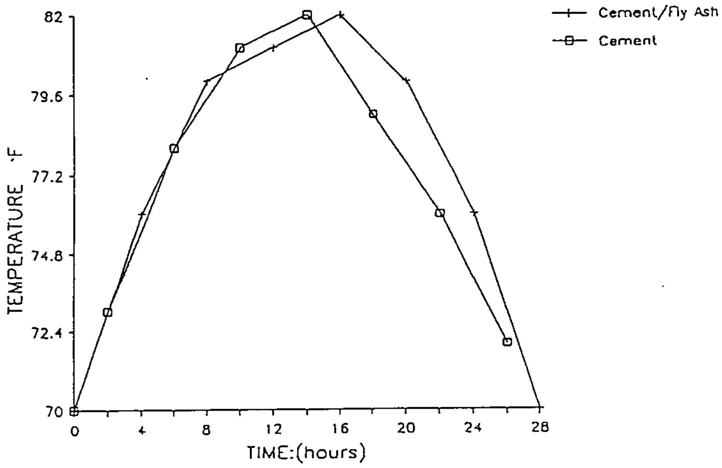


b) Effect of Mixture Design

Fig. 2.26. Effect of Some Mixture Parameters on Concrete Heat of Hydration [15]



c) Effect of Cement Type/Source



d) Effect of Flyash

Fig. 2.26. (cont.) Effect of Some Mixture Parameters on Concrete Heat of Hydration [15]

minimize thermal gradients and temperature changes, and these minimize early thermal strains, stresses, and cracks.

2.7.3. Compressive Strength. Concrete gains compressive strength rapidly with time early on, and then slows down as indicated in Figs. 2.27 and 2.28. In design, the strength gain after 28 days is ignored or assumed to be zero. The following expression for moist-cured concrete using Type I cement can be used to calculate concrete compressive strength $f'_{c,t}$, at any time, t, in days [28]:

$$f'_{c,t} = \frac{t}{4.0+0.85t} f'_c \tag{2.4}$$

Where f'_c is the 28 day compressive strength of the concrete.

Using Fig. 2.27 and linear interpolation, the compressive strength gain curve for a w/c = 0.44 (that used by the Alabama Department of Transportation (ALDOT) for bridge deck concrete) would be as shown in Fig. 2.29 . For f'_c = 4000 psi (that used by ALDOT), Fig. 2.29 yields Fig. 2.30.

2.7.4 Tensile Strength. The tensile strength of concrete is much lower than the compressive strength. Although tensile strengths are usually not considered directly in design (being assumed to equal zero), they are quite important in concrete cracking considerations. In general, concrete tensile strength increases with compressive strength; however, the relationship is not linear and is not simple but varies with a number of parameters.

In general, as the age (or the strength level) increases, the ratio of tensile to compressive strength (f_t/f_c) decreases, as can be seen in Fig. 2.31. Also, since crushed coarse aggregate seems to improve the tensile strength more than it does the compressive strength, the f_t/f_c ratio also depends on the type of aggregate. It has been found that, compared to moist curing, air curing reduces the tensile strength more than it does the compressive strength, probably because of the effect of drying shrinkage microcracking. Therefore, the f_t/f_c, ratio is less for air-cured than it is for moist-cured concretes [26].

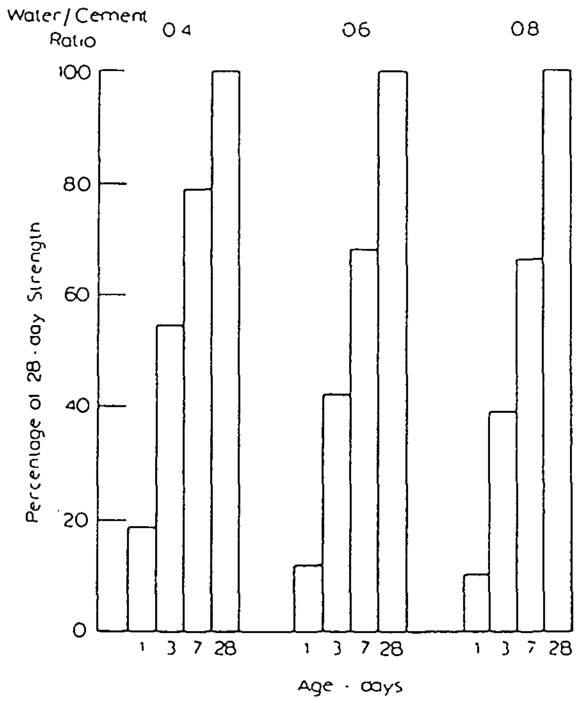


Fig. 2.27. Relative Gain of Strength with Time in Concretes with Different Water-Cement Ratios made with Ordinary Portland Cement [26]

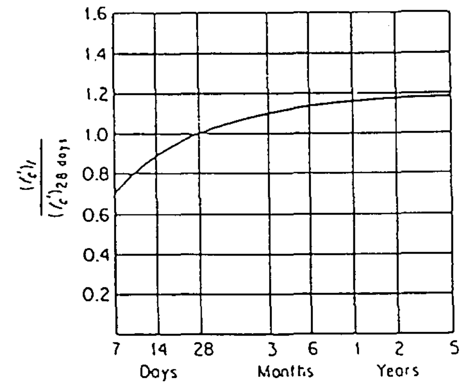


Fig. 2.28 General Gain in Compressive Strength with Time Curve for Ordinary Portland Cement [40]

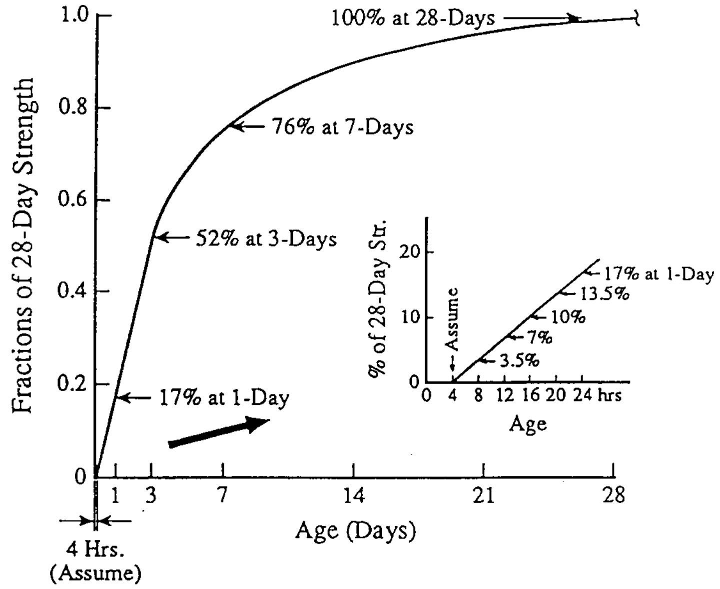


Fig. 2.29. Early Age $\tilde{f}'_c$ as a Fraction of f'_c.

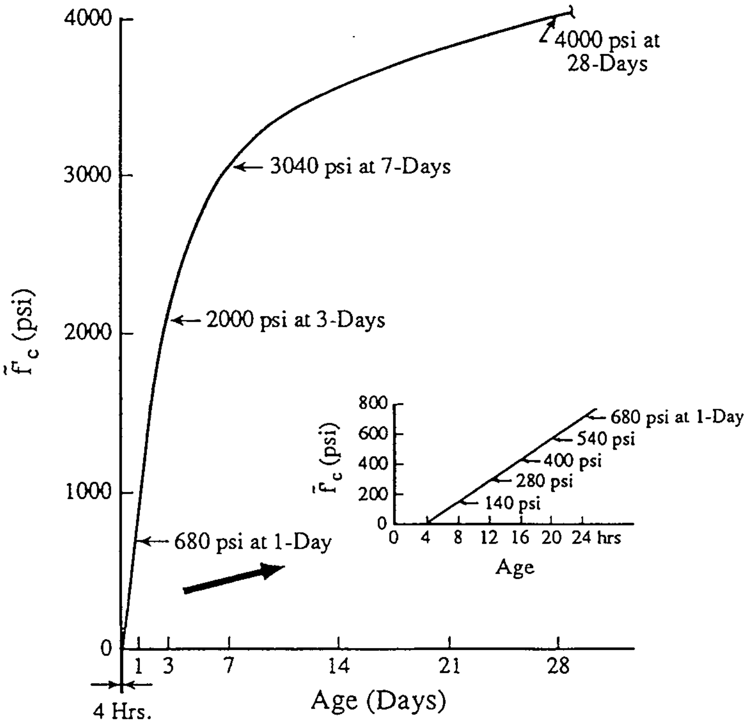


Fig. 2.30. Early Age $\tilde{f}'_c$ for 4000 psi Concrete.

The ACI reports and recommends using the value of tensile strength of concrete as

$$f'_t = f_r = 7.5\sqrt{f'_c} \tag{2.5}$$

where f_r = modulus of rupture.

Split-cylinder tests/results are felt to be a better measure of concrete tensile strength in uniform axial tension. For shrinkage tension stresses, a uniform stress state is probably more representative than the bending stress distribution of the modulus of rupture testing. Winter and Nilson [40] report split-cylinder tensile strengths of 6 to 7 times the square root of f'_c . Thus, a reasonable estimate of f'_c would be,

$$f'_t = f_{st} = 6.5\sqrt{f'_c} \tag{2.6}$$

Assuming the concrete tensile strength varies with compressive strength at all age and strength levels, as indicated in Eqn. 2.6 yields an early age tensile strength vs. time curve for 4000 psi concrete as indicated in Fig. 2.32.

2.7.5 Modulus of Elasticity. The modulus of elasticity of concrete (E_c), that is, the slope of the initial portion of the stress-strain curve, increases with concrete strength as is evident in Fig. 2.33. Recall that concrete strength increases with time, thus E_c also increases with time. The ACI recommends the following empirical equation for estimating E_c

$$E_c = 33w^{1.5}\sqrt{f'_c} \tag{2.7a}$$

where w is the unit weight of the hardened concrete in pcf, and f'_c is the cylinder strength in psi. For normal weight concrete, w = 145 pcf and,

$$E_c = 57,000\sqrt{f'_c} \tag{2.7b}$$

Using Eqn. 2.7b for E_c for all concrete strength levels (as they increase with time), and the f'_c curve of Fig. 2.30, yields the E_c vs. time curve of Fig. 2.34 for 4000 psi concrete.

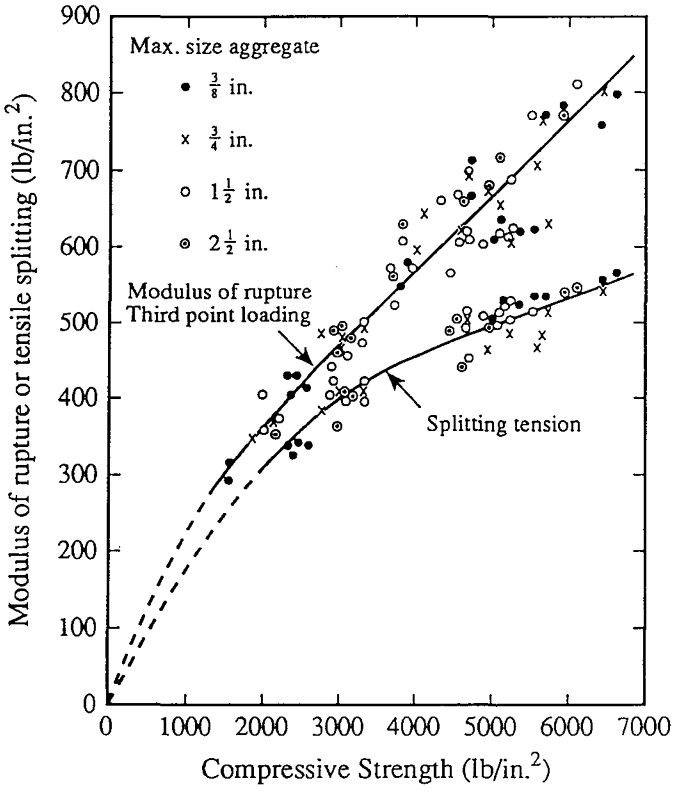


Fig. 2.31. Relationships of Compressive to Flexural and Tensile Strengths of Concrete [26].

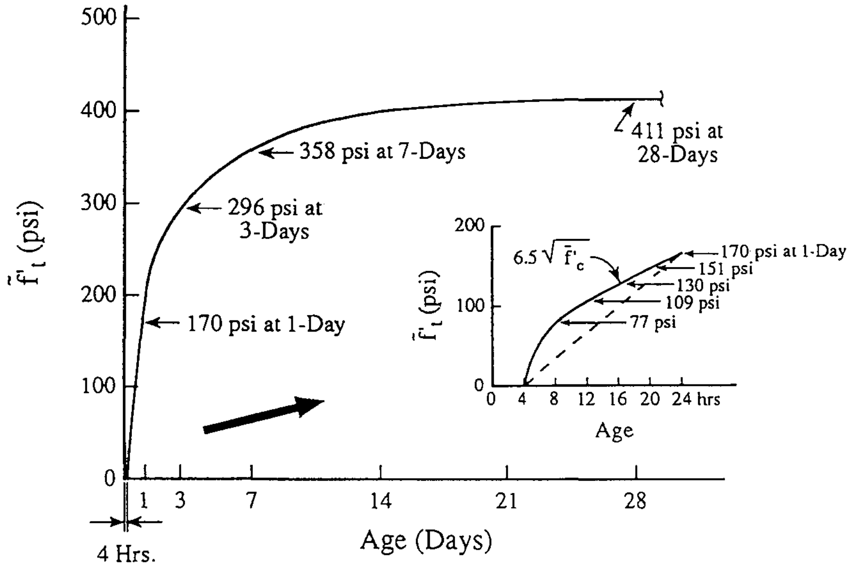


Fig. 2.32. Early Age $\tilde{f}'_t$ for 4000 psi Concrete.

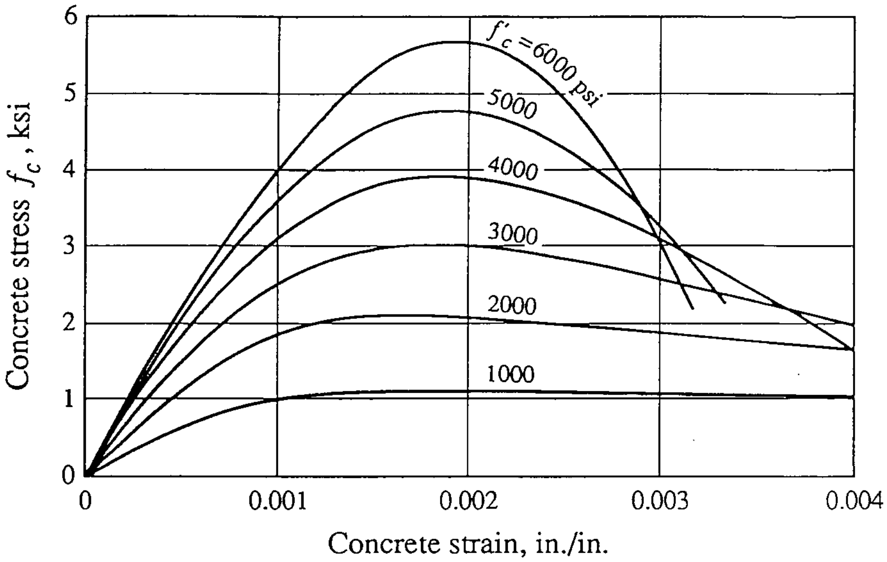


Fig. 2.33. Typical Concrete Stress-strain Curves [40].

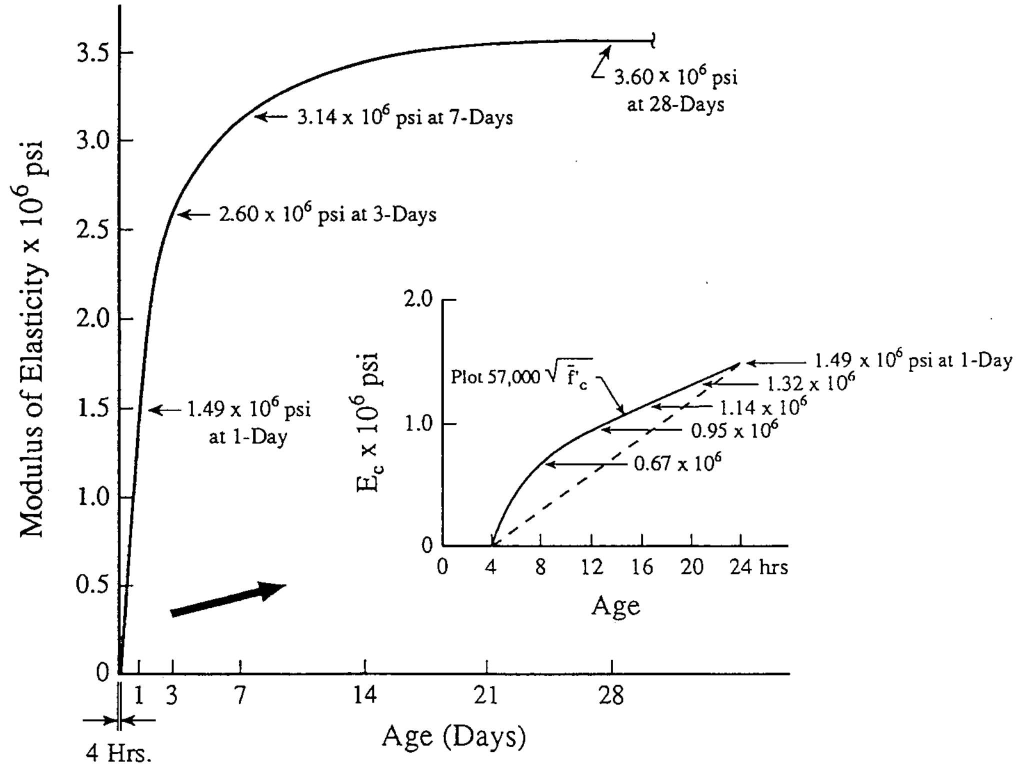


Fig. 2.34. Early Age E_c for 4000 psi Concrete.

In working with concrete cracking, the tension modulus would be the modulus of elasticity of interest. It is commonly assumed to be the same as that in compression as given by Eqn. 2.7b. This is probably a little high, as microcracking should render $E_t < E_c$. In turn, the assumption of $E_t = E_c$ should be a little conservative in predicting concrete cracking. Utilizing the values obtained from Eqn. 2.7b for modulus of elasticity and Eqn. 2.2 for tensile strength, a cracking strain of 114 microstrain (6.5/57000) is obtained for all f'_c and concrete age values.

2.7.6 Creep. Creep or lateral material flow is the increase in strain with time due to substained load. Initial deformation due to load is the elastic strain, while the additional strain due to the same sustained load is the creep strain. Fig. 2.35 illustrates the increase in creep strain with time, and as in the case of shrinkage, it can be seen that the rate of creep decreases with time [27]. A popular equation used to estimate creep with time is [5]

$$v_t = \frac{t^{0.60}}{10+t^{0.60}} v_u \tag{2.8}$$

t= time in days after loading and assuming a loading age of 7 days.

Values of the v_t/v_u ratio with time from this equation are shown in Table 2.5.

Table 2.5. Increase of Creep with Time

t	v_t/v_u
0	0
7 days	0.24
28 days	0.42
3 mos.	0.60
6 mos.	0.69
1 yr.	0.78
2 yrs.	0.84
5 yrs.	0.90
10 yrs.	0.93
20 yrs.	0.95

Although shrinkage and creep are not independent phenomena, it can be assumed that superposition of strains is valid; hence

total strain (ϵ_t) = elastic strain (ϵ_e) + creep (ϵ_c) + shrinkage (ϵ_{sh}). (2.9)

As in the case of shrinkage, creep is not completely reversible. If a specimen is unloaded after a period under a sustained load, an immediate elastic recovery is obtained which is less that the strain precipitated on loading. The instantaneous recovery is followed by a gradual decrease in strain, called creep recovery [27]. This is illustrated in Fig. 2.36. As in shrinkage, creep increases the deflection of beams and decks, and causes loss of prestress in prestressed elements. Creep can and usually does relax concrete stresses and improves the member's capability to sustain strain without cracking. An "effective" modulus of elasticity of concrete can be used in lieu of E_c to incorporate the effect of creep. The "effective" modulus of elasticity is determined as follows.

$$E_e = E_c / (1+v) \tag{2.10}$$

in which

E_e = Effective modulus of elasticity

v = Concrete creep factor or creep coefficient (ratio of creep strain to instantaneous strain)

$\approx 2 - 3$

Thus $E_e \approx ⅓ E_c$ to $¼ E_c$.

It should be noted that in current bridge deck construction, SIP metal forms are used in almost all cases (at least in Alabama). Thus, there should be no deck self weight/dead load carried by the deck concrete, and thus there should be very little creep in the bridge deck due to self-weight.

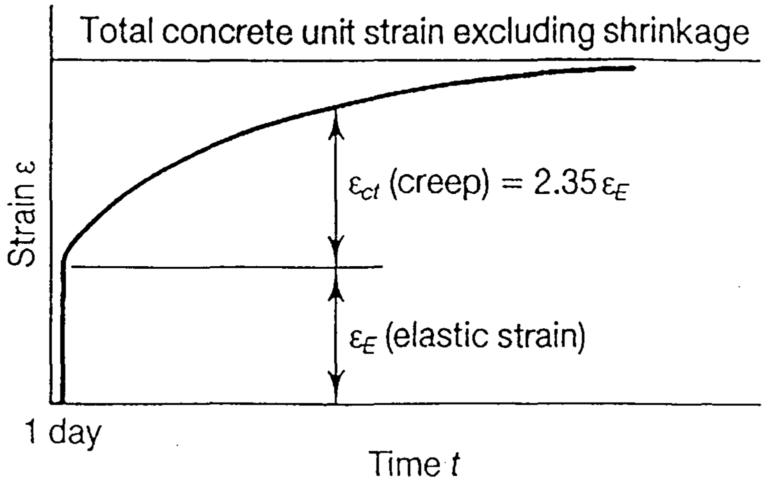


Fig. 2.35. Long-Term Creep Stress vs. Time Curve [27]

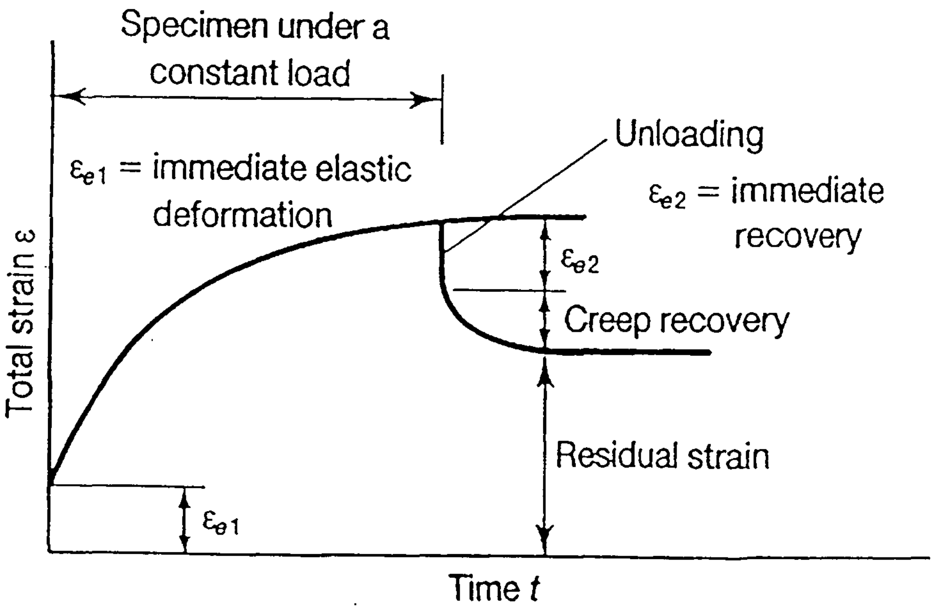


Fig. 2.36. Creep Recovery vs. Time [27]

3. ALABAMA CONCRETE CURING RELATED WEATHER DATA AND EXPOSURE CONDITIONS

3.1 General

In order to properly obtain evaporation rates for placement of concrete bridge decks in Alabama, a detailed analysis of weather conditions across the state is necessary. The evaporation rates drawn from the ACI 305 Surface Evaporation Chart are dependent upon three weather conditions: temperature; relative humidity; wind speed. Since construction of bridge decks in Alabama takes place throughout the year, it is important to determine how these three conditions vary with the seasons. These conditions also change over the 24-hour cycle of the day as evident in Fig. 3. 1, therefore, the evaporation rate differs throughout the day. This hourly variation may influence concrete placement time and early curing requirements for bridge decks.

Before analysis of the weather data was conducted, it was anticipated that weather exposure conditions categories could possibly be developed for the state. These categories would be geographical and seasonal. Geographically the state could be divided into three regions: northern region; central region; coastal region. Three seasonal categories would also be developed: cold weather conditions (winter months); moderate weather conditions (spring and autumn months); hot weather conditions (summer months).

The primary set of weather data analyzed for this study was obtained from the Southeast Regional Climate Center (SRCC) in Columbia, South Carolina. The data consisted of hourly recordings of temperature, relative humidity, and wind speed for every day from January 1, 1964, to the end of December 1993. The data was obtained for the four major cities in Alabama: Mobile; Montgomery;

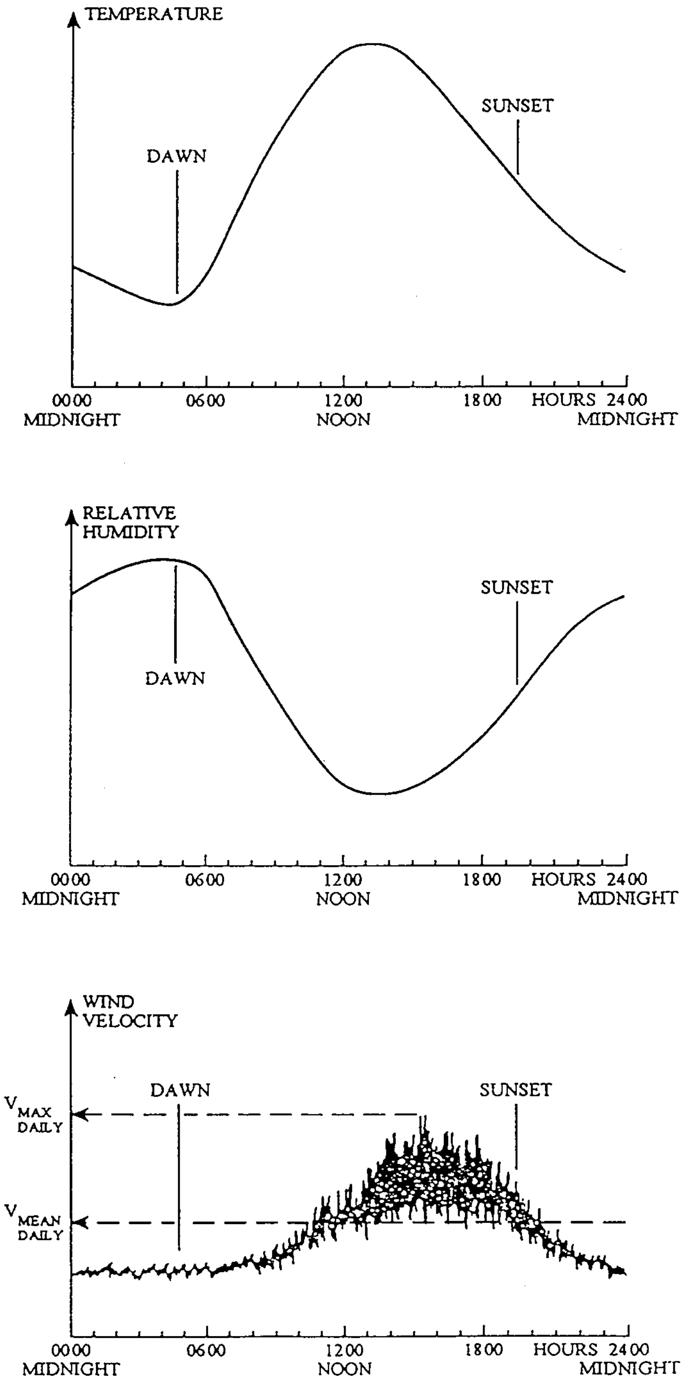


Fig.3.1. Typical Diurnal Variation in Temperature, Relative Humidity, and Wind Velocity in Clear Summer Weather.

Fig. 3.2. Geographical Locations of 4-Major Cities in Alabama.

Birmingham; Huntsville, and was recorded at the municipal airport for each city. It should be noted that the four major cities are geographically located in approximately equal increments from south to north as indicated in Fig. 3.2.

The data was originally received in the format of a text data file for each city. Each row of the data files contained the year number (1964-1993), the month number (1 (January) - 12 (December)), the day number (1 -28, 29, 30, or 31), the hour number (0 (12 a.m.) - 23 (11 p.m.)), temperature in °F, relative humidity in percent (%), and wind speed in miles per hour (mph). The data file size for each city was between nine and ten megabytes of computer space, therefore, a statistics program was required to provide meaningful trends from the data.

The key idea was to extract the essential information from the data files and obtain the variation of temperature, relative humidity, and wind speed over the diurnal cycle and months of the year. A program written in SAS, a common programming language used for statistical analysis, was used to perform the calculations. First, the program produced the mean daily cycles for temperature, relative humidity, and wind speed for each date. For example, the mean daily temperature cycle for January 31 from 1964 to 1993 was calculated. Next, the daily cycle from the previous step was averaged to provide a mean daily cycle for each month. For instance, the mean daily temperature cycle for a day in January was found by averaging the mean temperature cycle of the thirty-one dates in January. The end results of this procedure were mean daily cycles of temperature, relative humidity, and wind speed for a typical day in each month for each of the four major cities.

Presentation of the weather data for the four major cities in Alabama, results of the analysis of the data, and recommended weather parameter values to use in design and construction planning are given in the following sections of this chapter.

Table 3.1a

Ten-Year (1965-1974) Mean and Extreme Weather Conditions for Mobile, AL

MONTH	TEMPERATURE (°F)					PRECIPITATION (INCHES)			RELATIVE HUMIDITY (%)					SURFACE WIND SPEED (KT)	
	MEAN			EXTREME		TOTAL			MEAN						
	DAILY		MONTH						LST				MONTH		
	MAX	MIN		MAX	MIN	MEAN	MAX	MIN	00	06	12	18		MEAN	MAX
JAN	62	43	53	79	13	4 2	9.4	1.0	81	83	64	72	75	8.7	30+
FEB	63	42	53	81	18	5.3	9.0	2.9	76	80	55	62	68	8.9	30+
MAR	70	50	60	89	27	5.7	11.6	.6	81	84	56	64	71	9.0	28+
APR	80	59	70	91	36	3.2	9.9	.6	84	87	54	64	72	8.9	30+
MAY	85	65	75	96	46	5.0	8.8	2.3	83	85	53	61	71	7.8	30+
JUN	91	71	81	101	56	3.6	7.7	1 2	83	86	53	64	72	6.5	35+
JUL	92	74	83	100	62	7.0	14.1	2.2	86	89	60	71	77	5.7	28+
AUG	90	73	82	102	60	7.1	12.1	2.4	88	90	63	74	79	5.5	55+
SEP	87	70	79	97	42	6.7	12.7	2.0	86	88	61	72	77	6.3	28+
OCT	80	59	70	92	38	2.5	6.7	T	81	84	53	67	71	6.6	24+
NOV	70	49	60	87	24	2.4	5.7	.4	82	85	55	70	73	7.3	30+
DEC	65	46	55	81	24	5.8	10.7	4.0	81	84	64	74	76	8.3	28+
ANN	78	58	68	102	13	58.6	14.1	T	83	86	58	68	74	7.5	55+

Table 3.2a

Ten-Year (1965-1974) Weather Conditions Mean Number of Days of Occurrence for Mobile, AL

MONTH	PRECIPITATION (INCHES)					TEMPERATURE (°F)					
	TOTAL P ≥				RAIN	$T_{MAX} \geq$			$T_{MIN} \leq$		
	.01	.1	.5	1.0		90	65	32	45	32	0
JAN	11	7	2	1	14	0	15	31	19	7	0
FEB	9	7	4	2	11	0	14	28	19	5	0
MAR	10	7	4	2	14	0	23	31	10	1	0
APR	6	4	2	1	8	1	30	30	2	0	0
MAY	7	5	3	2	10	5	31	31	0	0	0
JUN	11	7	2	1	13	19	30	30	0	0	0
JUL	15	11	5	2	18	24	31	31	0	0	0
AUG	16	11	5	2	19	19	31	31	0	0	0
SEP	11	7	3	2	13	11	30	30	#	0	0
OCT	6	4	1	1	7	2	31	31	2	0	0
NOV	8	4	2	#	10	0	22	30	11	1	0
DEC	11	7	4	2	13	0	16	31	17	4	0
ANN	121	80	38	19	151	82	305	365	79	17	0

#Indicates less than 0 5 day

Table 3.1b
Ten-Year (1965-1974) Mean and Extreme Weather Conditions for Montgomery, AL

MONTH	TEMPERATURE (°F)					PRECIPITATION (INCHES)			RELATIVE HUMIDITY (%)					SURFACE WIND SPEED (KT)	
	MEAN			EXTREME		TOTAL			MEAN						
	DAILY		MONTH						LST				MONTH		
	MAX	MIN		MAX	MIN	MEAN	MAX	MIN	00	06	12	18		MEAN	MAX
JAN	58	37	48	79	5	4.1	6.4	1.9	78	83	62	66	72	6.4	32
FEB	59	37	48	81	14	4.5	8.1	1.9	72	78	54	56	65	7.1	39
MAR	68	45	57	87	25	5.7	10.8	2.0	74	82	54	55	66	7.2	40
APR	78	54	66	91	33	2.7	7.7	.9	79	86	52	56	68	6.5	33
MAY	83	60	72	94	40	3.2	5.5	1.3	83	89	55	59	72	5.5	41
JUN	89	67	78	101	50	3.7	7.8	1.6	85	89	55	61	73	5.2	35
JUL	91	71	81	102	61	5.3	7.9	2.6	88	90	61	67	77	5.0	33
AUG	89	70	80	100	57	3.9	10.4	1.8	89	92	62	71	79	4.4	33
SEP	86	66	76	97	39	4.2	6.5	1.1	87	91	59	70	77	4.8	28
OCT	78	54	66	91	31	2.3	6.1	.3	85	89	54	67	74	4.8	22
NOV	67	43	55	86	18	3.1	5.9	.7	82	87	54	65	72	5.5	27
DEC	61	40	50	83	20	5.3	8.5	3.6	80	84	61	68	73	6.2	37
ANN	76	54	65	102	5	47.9	10.8	.3	82	87	57	63	72	5.7	41

Table 3.2b
Ten-Year (1965-1974) Weather Conditions Mean Number of Days of Occurrence for Montgomery, AL

MONTH	PRECIPITATION (INCHES)					TEMPERATURE (°F)					
	TOTAL P ≥					$T_{MAX} \geq$			$T_{MIN} \leq$		
	.01	.1	.5	1.0	RAIN	90	65	32	45	32	0
JAN	12	8	3	1	16	0	11	31	23	12	0
FEB	9	7	3	2	11	0	9	28	24	10	0
MAR	10	8	4	2	13	0	20	31	16	3	0
APR	7	5	2	1	10	#	29	30	6	0	0
MAY	9	6	2	1	11	3	31	31	#	0	0
JUN	9	7	2	1	11	16	30	30	0	0	0
JUL	11	8	4	1	15	21	31	31	0	0	0
AUG	11	7	3	1	15	17	31	31	0	0	0
SEP	7	5	2	1	9	11	30	30	#	0	0
OCT	5	3	1	1	7	1	30	31	6	#	0
NOV	8	5	2	1	11	0	19	30	19	4	0
DEC	10	8	4	2	13	0	12	31	22	9	0
ANN	108	76	33	14	142	70	282	365	116	39	0

#Indicates less than 0.5 day

Table 3.1c
Ten-Year (1965-1974) Mean and Extreme Weather Conditions for Birmingham, AL

MONTH	TEMPERATURE (°F)					PRECIPITATION (INCHES)			RELATIVE HUMIDITY (%)					SURFACE WIND SPEED (KT)	
	MEAN			EXTREME		TOTAL			MEAN						
	DAILY		MONTH						LST				MONTH		
	MAX	MIN		MAX	MIN	MEAN	MAX	MIN	00	06	12	18		MEAN	MAX
JAN	53	34	44	77	-4	5.3	9.3	2.5	77	81	63	67	72	6.5	33
FEB	55	33	44	79	10	4.5	9.3	1.2	71	77	55	57	65	7.1	39
MAR	65	42	53	87	19	5.8	11.4	1.8	72	79	53	53	64	7.3	36
APR	75	50	63	89	26	4.7	8.4	1.4	76	82	52	52	66	6.6	43
MAY	81	57	69	95	36	5.1	11.1	1.4	83	86	55	57	70	5.2	50
JUN	87	64	76	98	42	3.8	8.2	.7	84	86	57	61	72	4.6	39
JUL	89	69	79	102	51	5.8	9.4	2.9	86	88	61	66	73	4.2	36
AUG	88	68	78	98	55	5.1	10.9	1.8	88	90	62	68	77	4.1	32
SEP	83	63	73	95	37	4.1	8.1	1.1	87	89	61	72	77	4.8	36
OCT	75	51	63	88	28	2.6	7.0	.7	84	87	56	73	75	5.0	28
NOV	63	40	52	83	13	3.6	6.4	1.8	80	84	57	68	72	5.7	33
DEC	57	37	47	78	15	5.8	11.5	2.1	78	81	62	70	73	6.5	32
ANN	73	51	62	102	-4	56.2	11.5	.7	81	84	58	64	72	5.6	50

Table 3.2c
Ten-Year (1965-1974) Weather Conditions Mean Number of Days of Occurrence for Birmingham, AL

MONTH	PRECIPITATION (INCHES)					TEMPERATURE (°F)					
	TOTAL P ≥				RAIN	$T_{MAX} \geq$			$T_{MIN} \leq$		
	.01	.1	.5	1.0		90	65	32	45	32	0
JAN	12	8	4	2	16	0	6	30	26	16	#
FEB	10	7	3	1	12	0	6	28	25	16	0
MAR	11	8	4	2	15	0	17	31	20	7	0
APR	9	7	3	2	12	0	27	30	10	1	0
MAY	10	7	3	2	13	2	30	31	3	0	0
JUN	10	6	2	1	13	9	30	30	#	0	0
JUL	14	9	4	2	18	14	31	31	0	0	0
AUG	11	8	3	2	16	10	31	31	0	0	0
SEP	9	7	3	1	13	5	30	30	1	0	0
OCT	6	4	2	1	10	0	28	31	11	1	0
NOV	9	7	2	1	12	0	15	30	22	8	0
DEC	11	8	4	2	14	0	8	31	24	13	0
ANN	120	85	37	18	162	39	259	364	141	62	#

#Indicates less than 0.5 day

Table 3.1d
Ten-Year (1958-1967) Mean Weather Conditions for Huntsville, AL

MONTH	MEAN TEMPERATURE (°F)	MEAN RELATIVE HUMIDITY (%)	MEAN SURFACE WIND SPEED (KT)	PRECIPITATION			
				PERCENT DAYS WITH MEASURABLE (%)	MEAN (IN)	MAX (IN)	MIN (IN)
JAN	39	71.6	7.2	33.0	4.39	8.53	1.76
FEB	44	69.2	8.3	36.6	4.91	9.13	1.88
MAR	51	64.2	8.6	31.9	6.61	10.75	1.63
APR	62	61.5	7.7	33.3	5.11	12.55	2.09
MAY	71	65.4	5.8	28.0	4.02	6.48	1.55
JUN	76	69.4	5.3	33.0	4.42	6.54	2.90
JUL	79	71.2	4.8	36.2	5.22	14.81	2.16
AUG	79	72.0	4.9	31.9	3.86	6.30	.72
SEP	74	69.5	6.3	25.0	3.27	4.53	.49
OCT	62	68.8	5.6	18.4	2.55	4.69	TRACE
NOV	51	70.6	6.6	30.7	3.35	5.47	64
DEC	41	70.9	7.5	32.9	5.04	12.17	.76
ANN	60	68.8	6.5	30.7	52.75		

Table 3.2d
Ten-Year (1958-1967) Mean Number of Days of Precipitation Occurrence for Huntsville, AL

MONTH	PRECIPITATIONS (INCHES)				
	TOTAL P ≥				RAIN
	.01	.1	.5	1.0	
JAN	10	7	4	1	12
FEB	10	8	3	1	13
MAR	10	7	5	2	13
APR	10	6	4	1	13
MAY	9	6	3	1	12
JUN	10	7	3	1	13
JUL	11	7	3	1	16
AUG	10	6	2	1	13
SEP	8	5	2	1	10
OCT	6	4	2	1	9
NOV	9	6	2	1	12
DEC	10	6	3	2	13
ANN	112	74	35	15	148

3.2 Mean and Extreme Weather Data

The first weather data secured for the four major cities was for mean and extreme conditions as indicated in Tables 3.la-3.ld and Tables 3.2a-3.2d. The data in these tables was obtained from the National Climate Data Center (NCDC) in Asheville, North Carolina. These tables give ten-year means and extremes for temperature, relative humidity, surface wind speed, and precipitation. It can be noted in Tables 3.ld and 3.2d that the data for Huntsville was somewhat different and less comprehensive than for the other cities. It should be noted that throughout this chapter, table and figure number designations will include the letters a-d. In each case, (a) will represent Mobile (b) Montgomery, (c) Birmingham, and (d) for Huntsville, i.e., they will be lettered and presented sequentially from south to north in the state.

Tables 3.l a-3.l d and Tables 3.2a-3.2d provide an excellent summary of means and extreme weather for the four major cities. They reflect significant variations over the seasons/months of the year, and as will be seen later, there are significant diurnal variations. However, the variations between the cities, i.e., the geographical variations, are minimal and rather insignificant. Additional normals, means, and extremes data is provided for each of the four major cities in Tables A.la-A.1d in Appendix A. Seasonal, geographical, and diurnal values and variations of the temperature, relative humidity, and surface wind speed are presented and examined in the following sections.

3.3 Seasonal Weather Variations

Seasonally, temperature for Alabama varies significantly, as evident in Figs. 3.3a-3.3d. January is the coldest month, with December and February slightly milder. March and November are a little warmer on average. October and April are significantly warmer and are really quite mild. September and May are quite warm but mild weather on occasions reduces the mean temperature. June, July, and August are the hottest months with not much difference in mean temperature.

Mean maximum temperatures for each month for each of the four cities are shown plotted in Fig. 3.4. (Data for this figure was supplied by SRCC and was not generated from the primary data set). Due to its proximity to the Gulf of Mexico, Mobile experiences moderations of both summer and winter

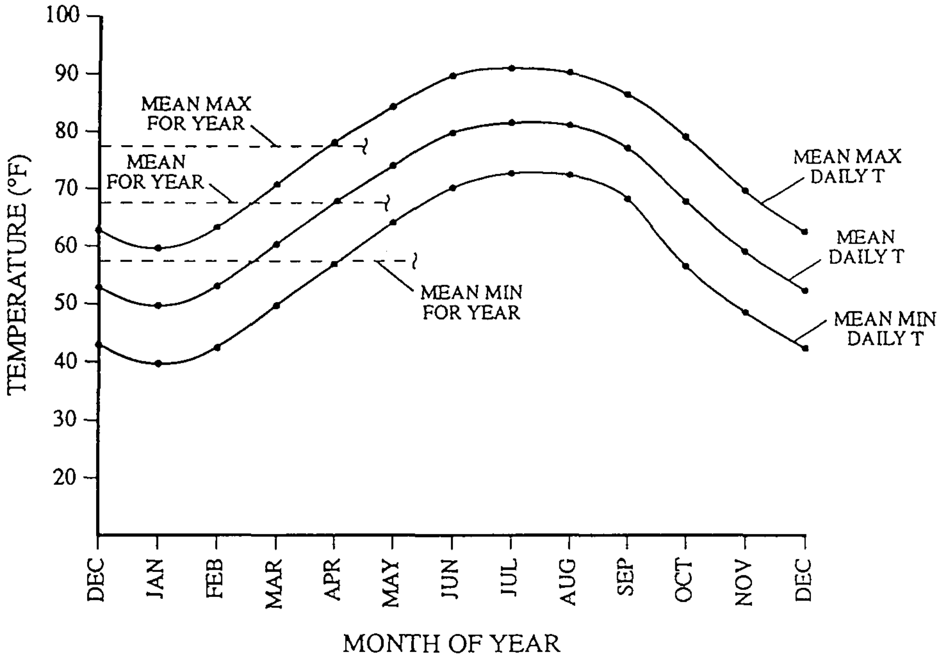


Fig. 3.3a. Mean Temperatures for Mobile, AL.

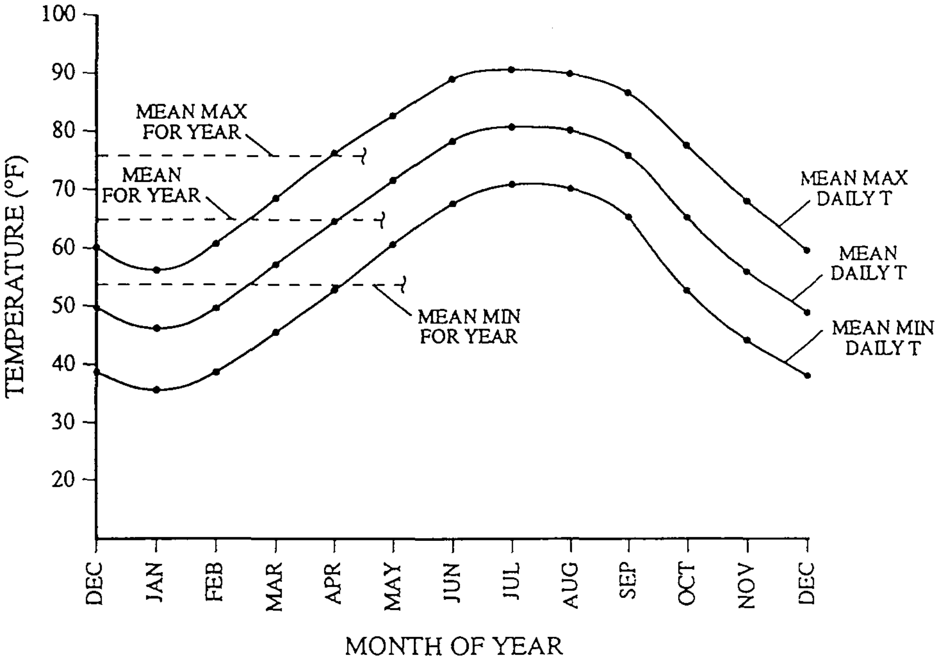


Fig. 3.3b. Mean Temperatures for Montgomery, AL.

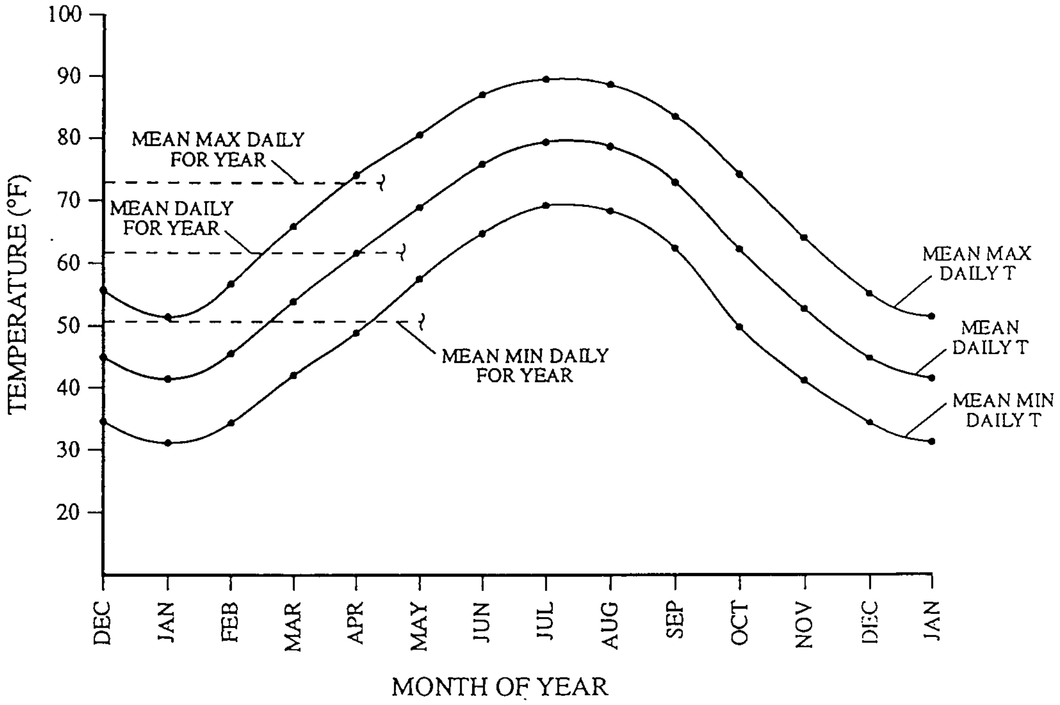


Fig. 3.3c. Mean Temperatures for Birmingham, AL.

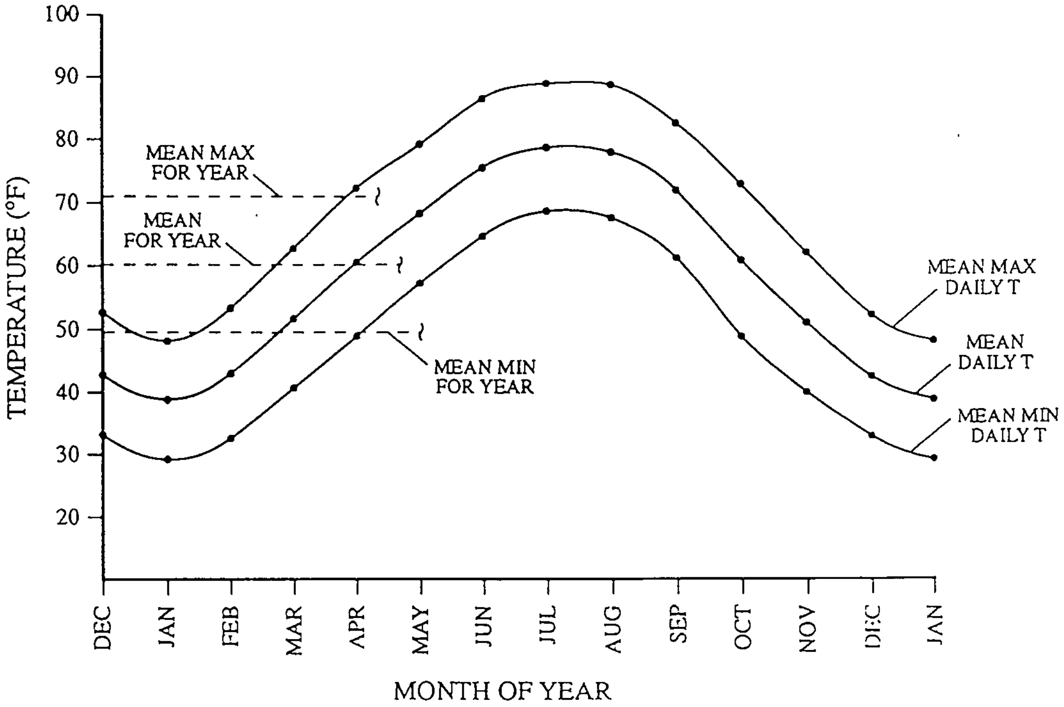


Fig. 3.3d. Mean Temperatures for Huntsville, AL.

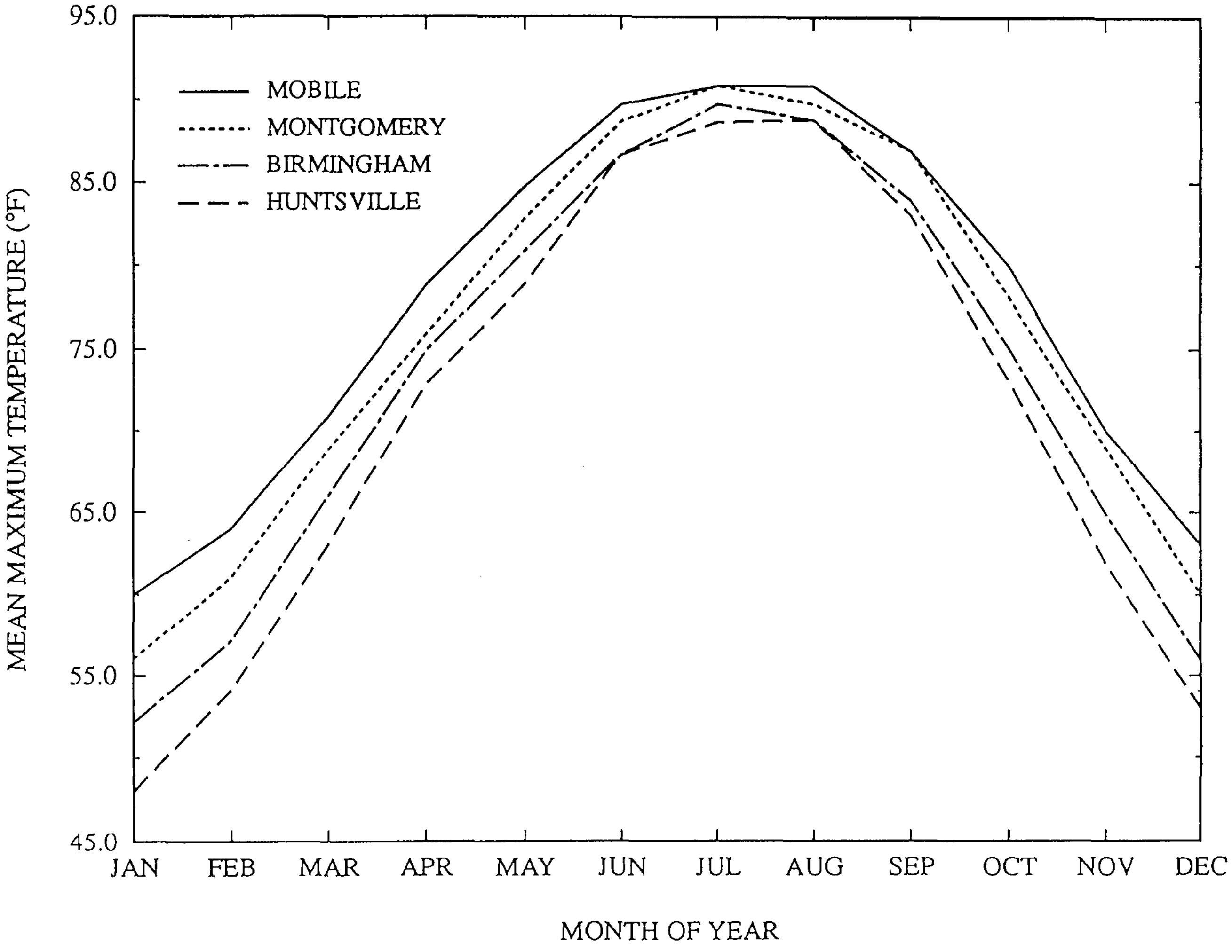


Fig. 3.4. Annual Cycle of Mean Maximum Temperatures.

temperatures. Huntsville, being the most northern city has a slightly cooler climate. Fig. 3.4 indicates a very small temperature difference between Mobile and Huntsville during the summer months (approximately 2°F) but a much larger difference (approximately 10°F) during the winter months.

Mean maximum and minimum relative humidities for each month for each of the four cities are plotted in Figs. 3.5a-3.5d. Shown superimposed on these plots are the mean annual relative humidity values. Mean monthly wind speeds for each month along with the mean annual value are shown for each of the four cities in Figs. 3.6a-3.6d.

Of the three weather parameters being studied and considered, wind speed is much more random, variable, and unpredictable as evident in Fig. 3. 1, Fig. 3.7, and Fig. 3.8. Because of its wide variability, mean wind speed values are of limited value in assessing the effect of this parameter on the deck surface evaporation rate and curing requirements.

Due to the random nature of wind, a different type of data was needed. Recall that for rainfall, which is also a random event, frequency charts are used to predict the number of rainy days during the course of a project. Thus, frequency data for wind speeds can provide the number of days wind speed can be expected to exceed a certain value. Wind speed frequency data was obtained from NCDC. Tables 3.3a-3.3d contain wind speed frequency of occurrence data for each month for the four major cities of Alabama. Numbers given in the tables are percentage of time for the occurrence of wind speed in each range. The numbers were generated using recordings between 1965-1974. Data for Huntsville was recorded during a different period (1959-1964) but the information is of the same nature. Graphical representations of the data shown in Tables 3.3a-3.3d are given in Figs. 3.9a-3.9d.

Presentation of the data in the form of Tables 3.3a-3.3d and Figs. 3.9a-3.9d makes it easy to detect seasonal trends in wind speeds and wind speed activity. From an analysis of the wind data, March is the windiest month of the year for all cities. A higher frequency of occurrence of winds above 11 knots (1 knot = 1. 15 mph) occurs in March, but February and April are close behind. May and October show a

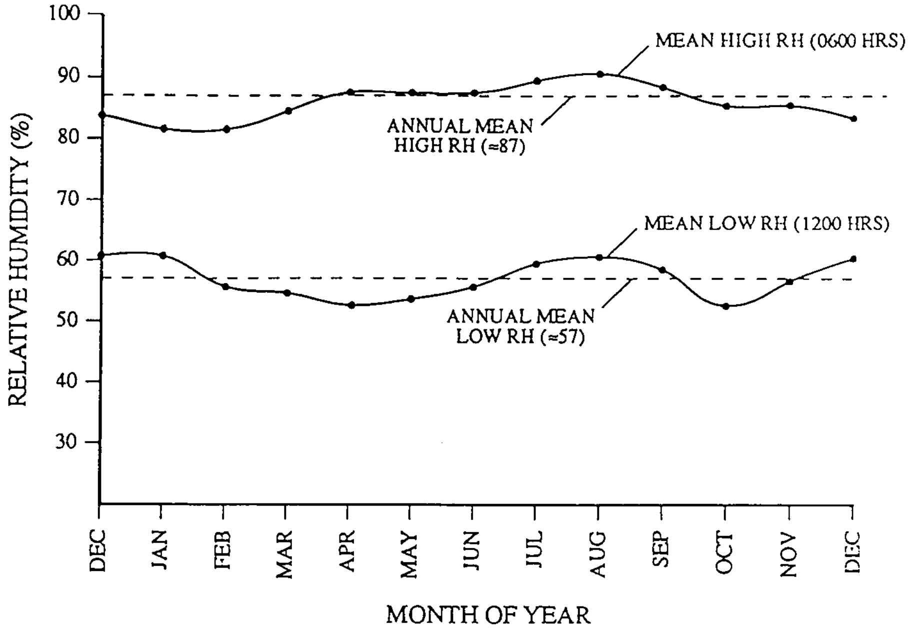


Fig. 3.5a. Mean Relative Humidity for Mobile, AL.

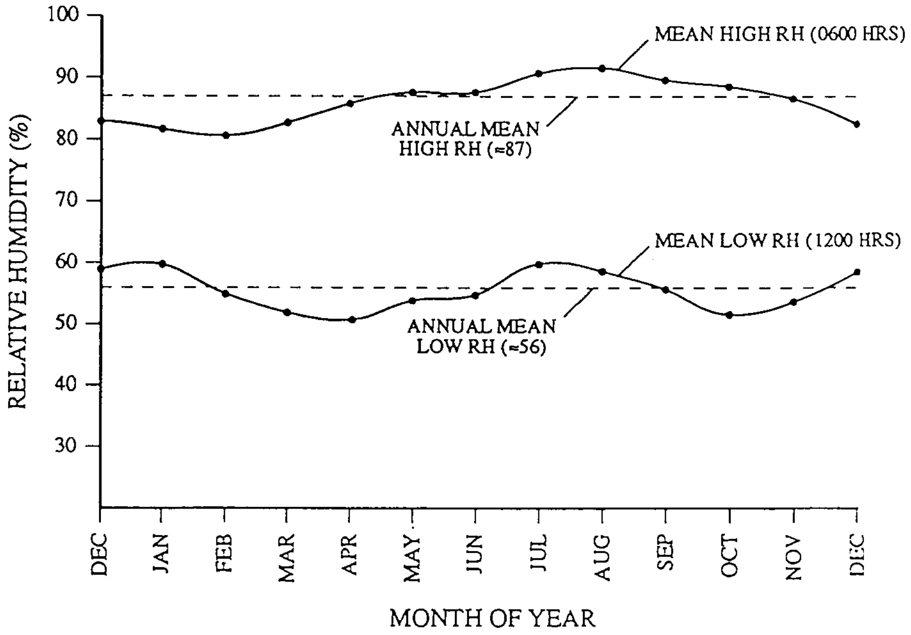


Fig. 3.5b. Mean Relative Humidity for Montgomery, AL.

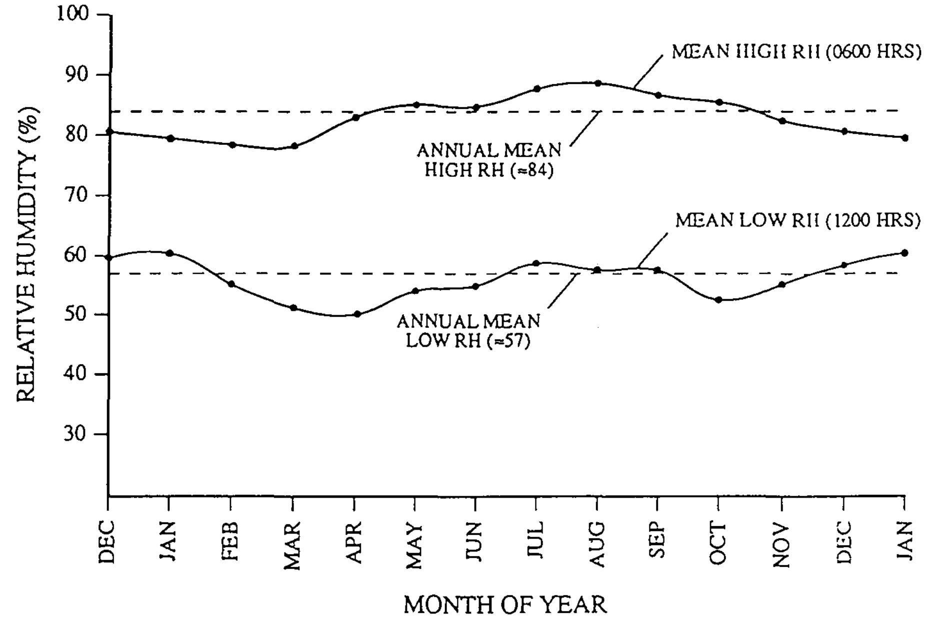


Fig. 3.5c. Mean Relative Humidity for Birmingham, AL.

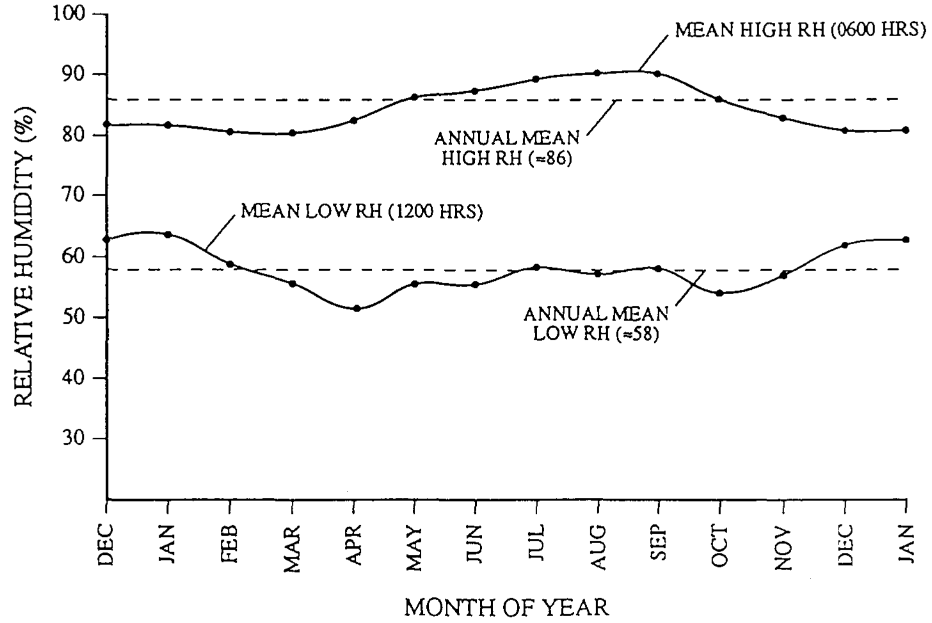


Fig. 3.5d. Mean Relative Humidity for Huntsville, AL.

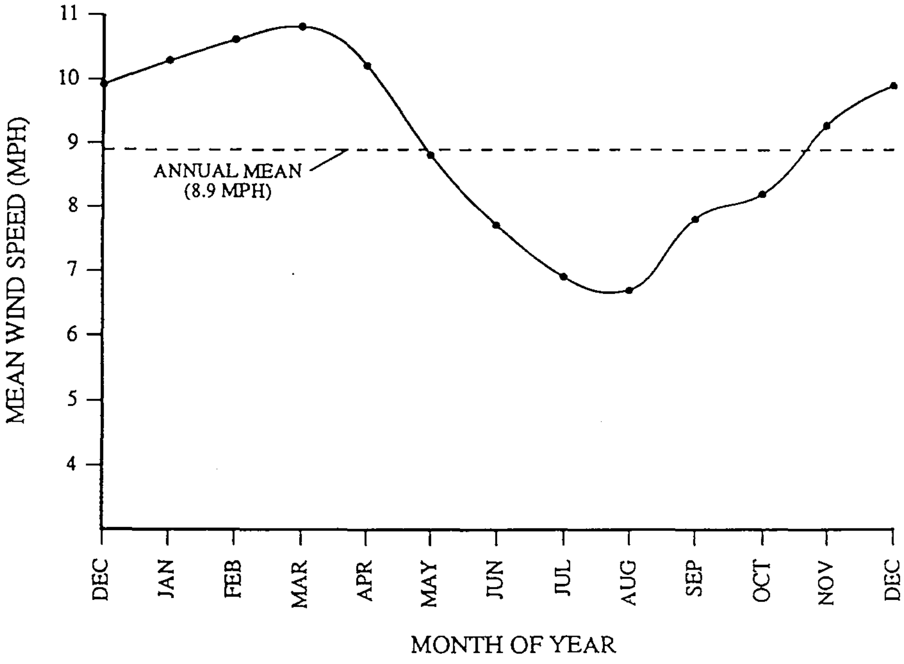


Fig. 3.6a. Mean Wind Speed for Mobile, AL.

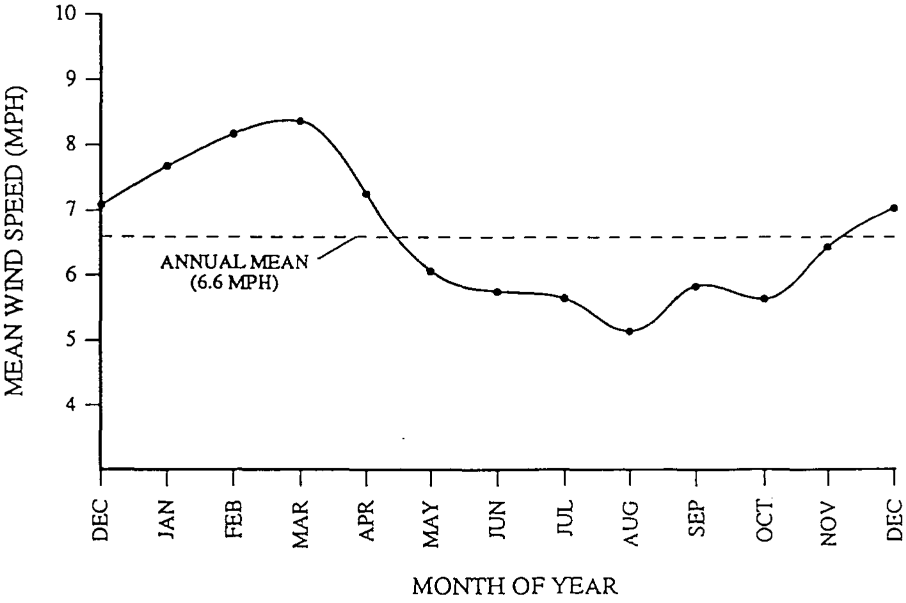


Fig. 3.6b. Mean Wind Speed for Montgomery, AL.

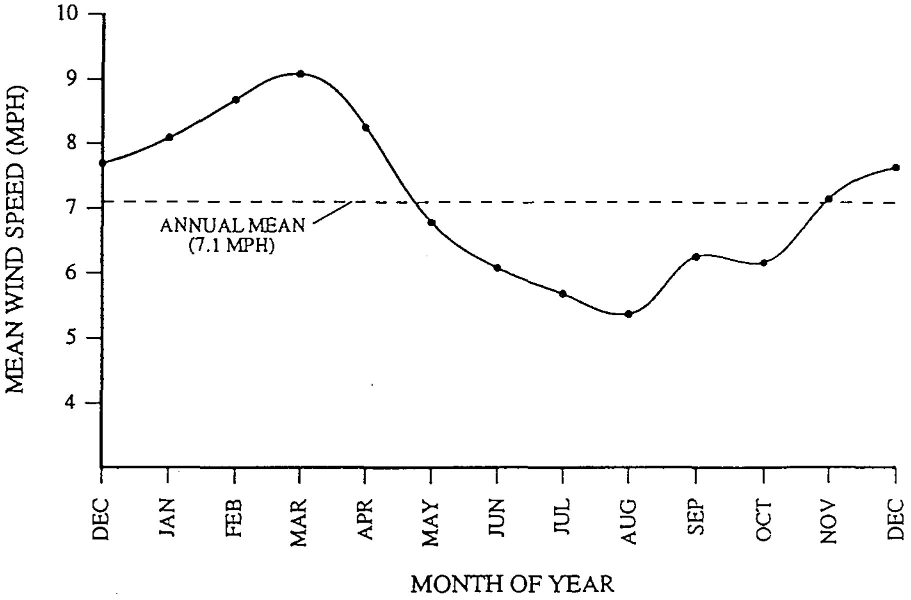


Fig. 3.6c. Mean Wind Speed for Birmingham, AL.

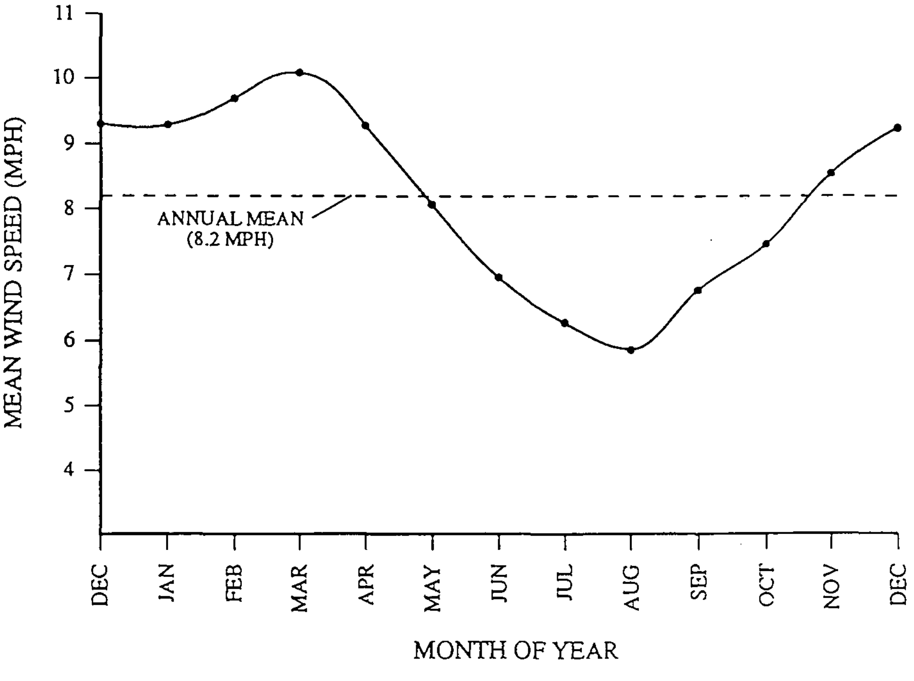


Fig. 3.6d. Mean Wind Speed for Huntsville, AL.

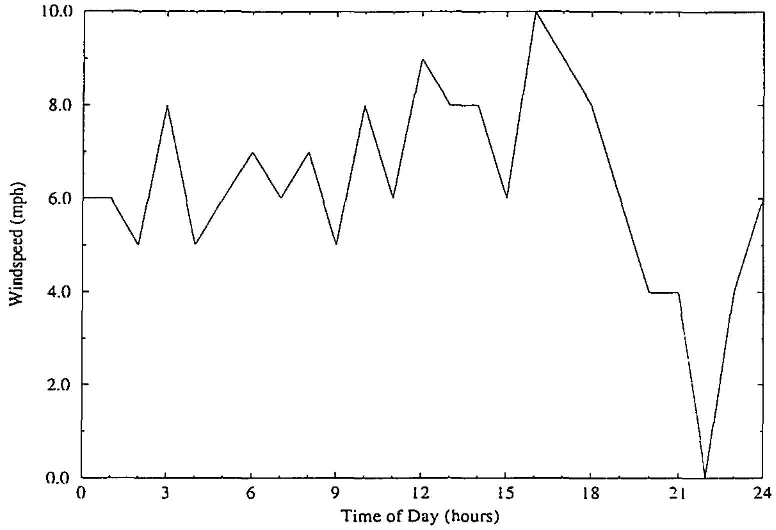


Fig. 3.7. Wind Speed Cycle for Day in March 1985 - Mobile

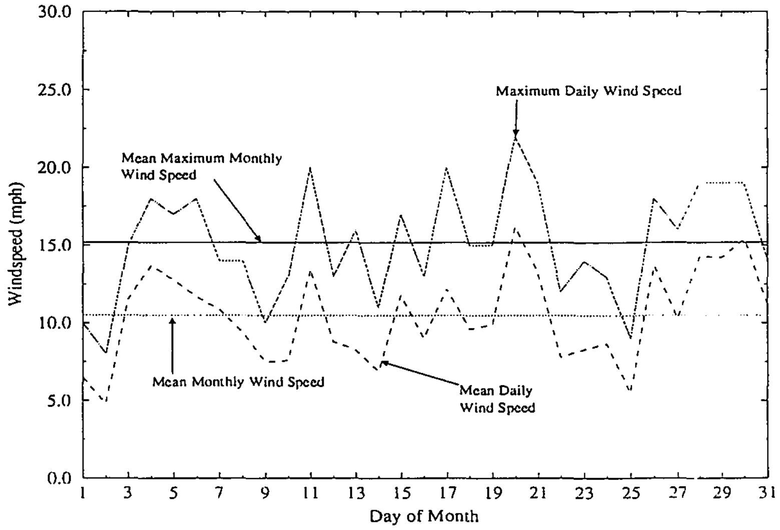


Fig. 3.8. Wind Speed Cycles for March 1985 - Mobile

Table 3.3a
Ten-Year (1965-1974) Wind Speed - Frequency of Occurrence for Mobile, AL

Month	Wind Speed (Knots)						
	0-3	4-6	7-10	11-16	17-21	Over 21	Avg. Speed
JAN	6.0	26.1	38.6	25.2	3.8	.4	8.8
FEB	7.3	24.0	37.5	25.7	4.9	.6	8.9
MAR	7.2	22.1	37.2	28.0	5.0	.5	9.0
APR	6.5	24.0	36.3	28.2	4.4	.6	9.0
MAY	8.8	31.8	36.4	20.6	2.3	.1	7.8
JUN	12.3	39.6	36.8	11.1	.1		6.6
JUL	17.8	45.8	29.2	6.9	.2		5.7
AUG	19.5	45.7	29.0	5.2	.3	.1	5.6
SEP	16.5	39.7	31.7	11.1	.9	.1	6.4
OCT	14.0	37.9	34.5	13.2	.4		6.6
NOV	11.4	33.3	36.1	17.3	1.8	.1	7.4
DEC	7.8	28.3	36.5	24.4	2.9	.2	8.4
ANN	11.3	33.2	35.0	18.0	2.2	.2	7.5

* 1 knot = 1.15 mph

Table 3.3b
Ten-Year (1965-1974) Wind Speed - Frequency of Occurrence for Montgomery, AL

Month	Wind Speed (Knots)						
	0-3	4-6	7-10	11-16	17-21	Over 21	Avg. Speed
JAN	22.4	31.4	31.0	14.2	.8	.1	6.5
FEB	18.0	30.2	33.2	16.0	2.3	.4	7.1
MAR	17.4	30.6	31.9	17.9	2.0	.2	7.2
APR	23.0	30.4	30.3	14.6	1.6	.2	6.6
MAY	28.7	33.8	28.2	8.8	.6		5.6
JUN	30.1	37.7	25.4	6.0	.7	.1	5.2
JUL	29.2	42.0	24.3	4.1	.4		5.1
AUG	34.8	43.5	19.0	2.6			4.5
SEP	32.6	39.6	22.7	4.9	.3		4.9
OCT	35.4	35.8	21.9	6.9			4.9
NOV	32.0	31.2	25.7	10.5	.6		5.5
DEC	25.6	31.2	27.7	14.6	.8		6.2
ANN	27.5	34.8	26.7	10.0	.8	.1	5.8

* 1 knot = 1.15 mph

Table 3.3c
Ten-Year (1965-1974) Wind Speed - Frequency of Occurrence for Birmingham, AL

Month	Wind Speed (Knots)						
	0-3	4-6	7-10	11-16	17-21	Over 21	Avg. Speed
JAN	23.2	28.7	30.7	16.5	.9		6.6
FEB	21.4	24.6	32.3	19.0	2.5	.3	7.2
MAR	20.4	23.6	31.7	22.1	2.1	.1	7.4
APR	25.9	23.8	30.8	17.7	1.5	.4	6.7
MAY	35.4	28.5	25.6	9.9	.5		5.2
JUN	37.5	33.7	23.9	4.8	.1	.1	4.7
JUL	43.3	32.4	20.6	3.5	.1	.1	4.2
AUG	43.0	34.6	18.7	3.5	.1		4.2
SEP	37.5	31.9	24.7	5.8	.1		4.8
OCT	36.9	28.9	25.9	8.1	.2		5.0
NOV	34.5	25.7	25.2	13.2	1.1	.3	5.8
DEC	26.0	27.3	28.0	17.0	1.5	.2	6.5
ANN	32.2	28.7	26.5	11.7	.9	.1	5.7

* 1 knot = 1.15 mph

Table 3.3d
Six-Year (1959-1964) Wind Speed - Frequency of Occurrence for Huntsville, AL

Month	Wind Speed (Knots)						
	0-3	4-6	7-10	11-16	17-21	Over 21	Avg. Speed
JAN	20.9	26.2	28.2	21.7	2.8	.2	7.2
FEB	15.0	22.6	31.8	24.7	4.9	.9	8.3
MAR	14.5	19.9	32.3	26.8	5.3	1.2	8.6
APR	17.2	23.8	32.3	23.6	2.8	.3	7.7
MAY	26.9	30.2	29.5	12.6	.8		5.8
JUN	26.6	36.6	28.1	8.4	.3		5.3
JUL	30.5	39.0	25.0	5.0	.4		4.8
AUG	31.6	36.1	25.7	6.3	.3		4.9
SEP	23.8	29.3	31.9	13.4	1.5	.1	6.3
OCT	31.7	26.2	28.5	12.1	1.3	.1	5.6
NOV	26.7	25.7	26.4	18.0	2.4	.5	6.6
DEC	18.7	24.3	32.1	21.3	3.1	.6	7.5
ANN	23.8	28.2	29.3	16.1	2.1	.3	6.5

* 1 knot = 1.15 mph

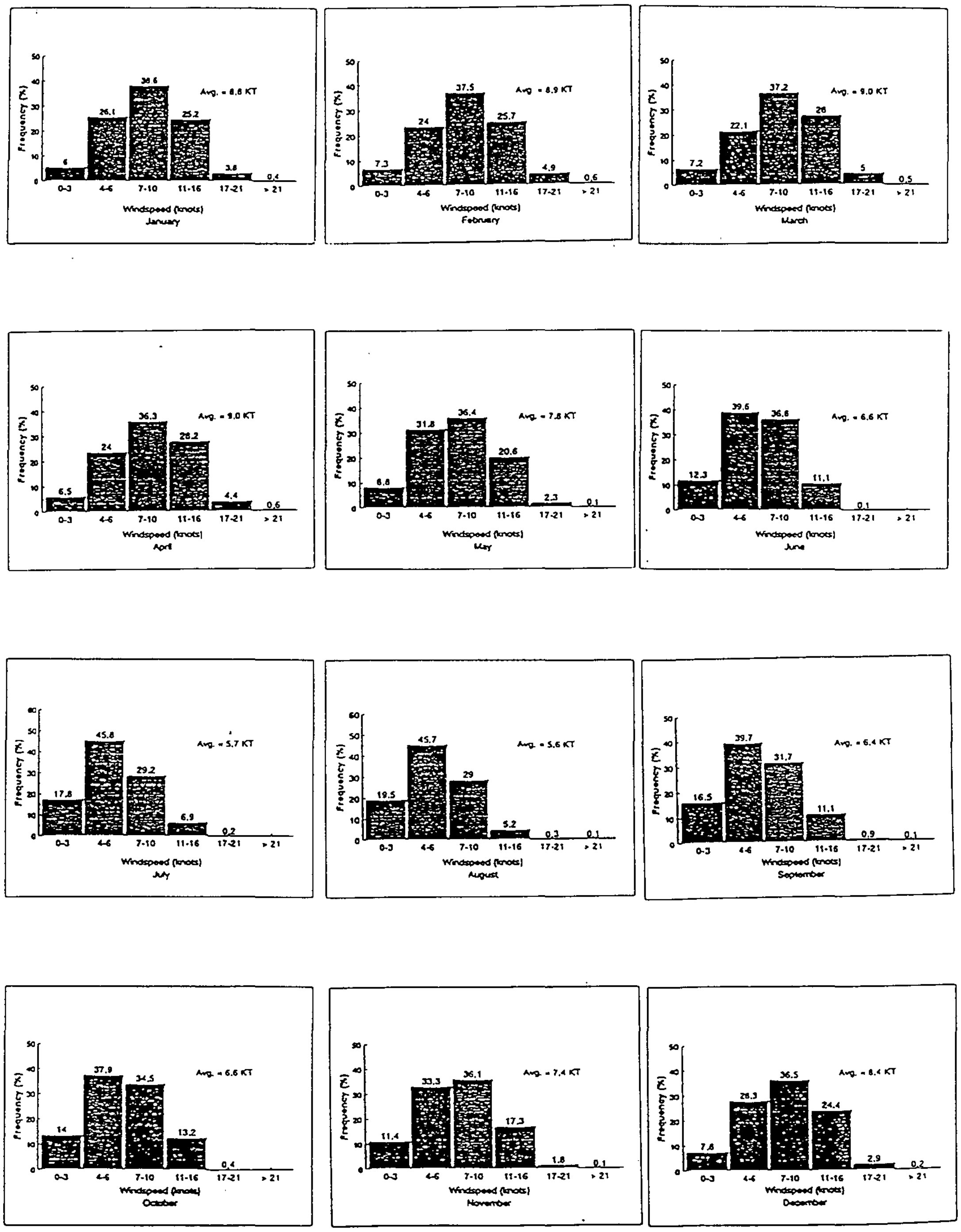


Fig. 3.9a. Monthly Frequency of Occurrence vs. Wind Speed for Mobile, AL for Period 1965-1974 (1 knot = 1.15 mph)

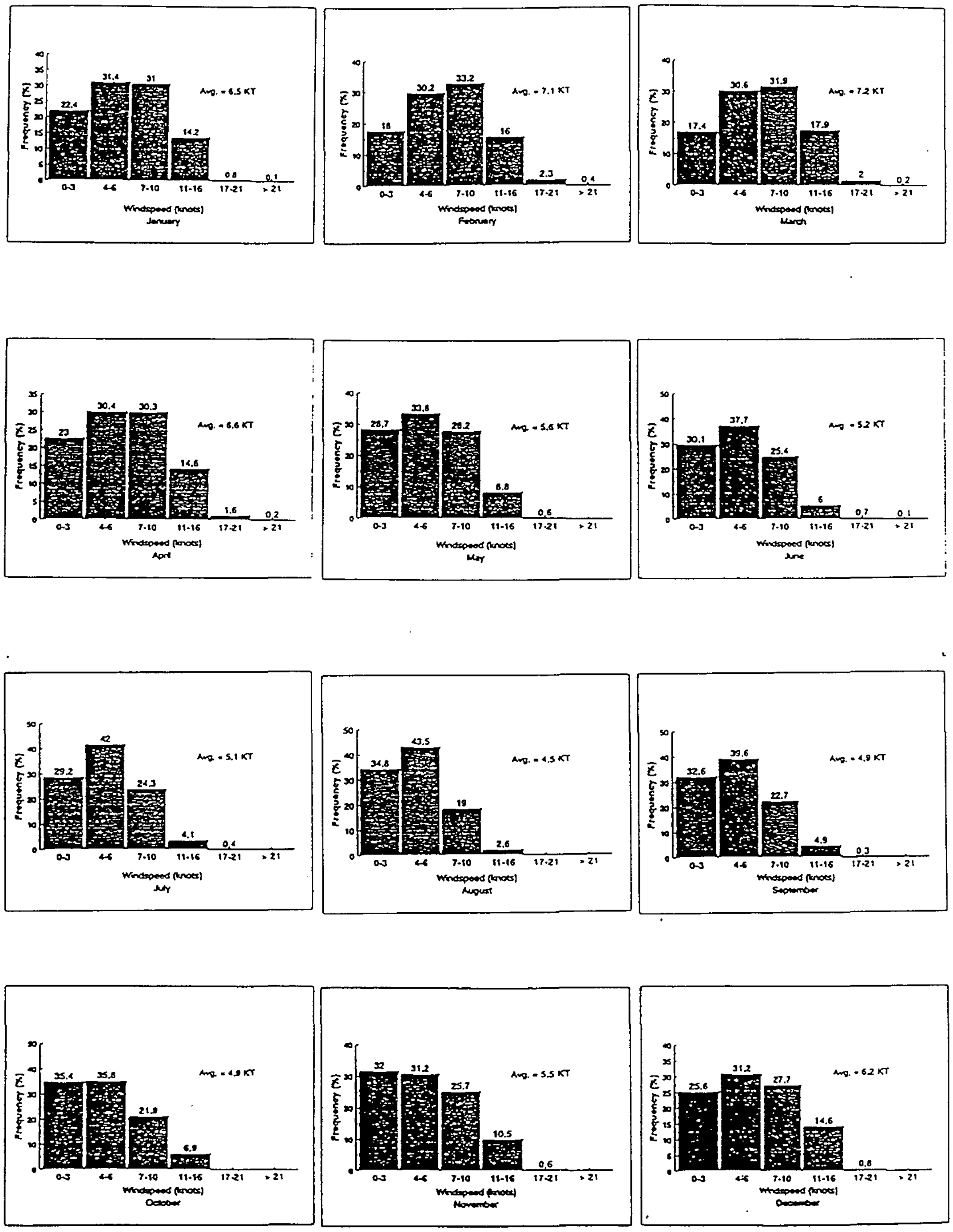


Fig. 3.9b. Monthly Frequency of Occurrence vs. Wind Speed for Montgomery, AL for Period 1965-1974 (1 knot = 1.15 mph)

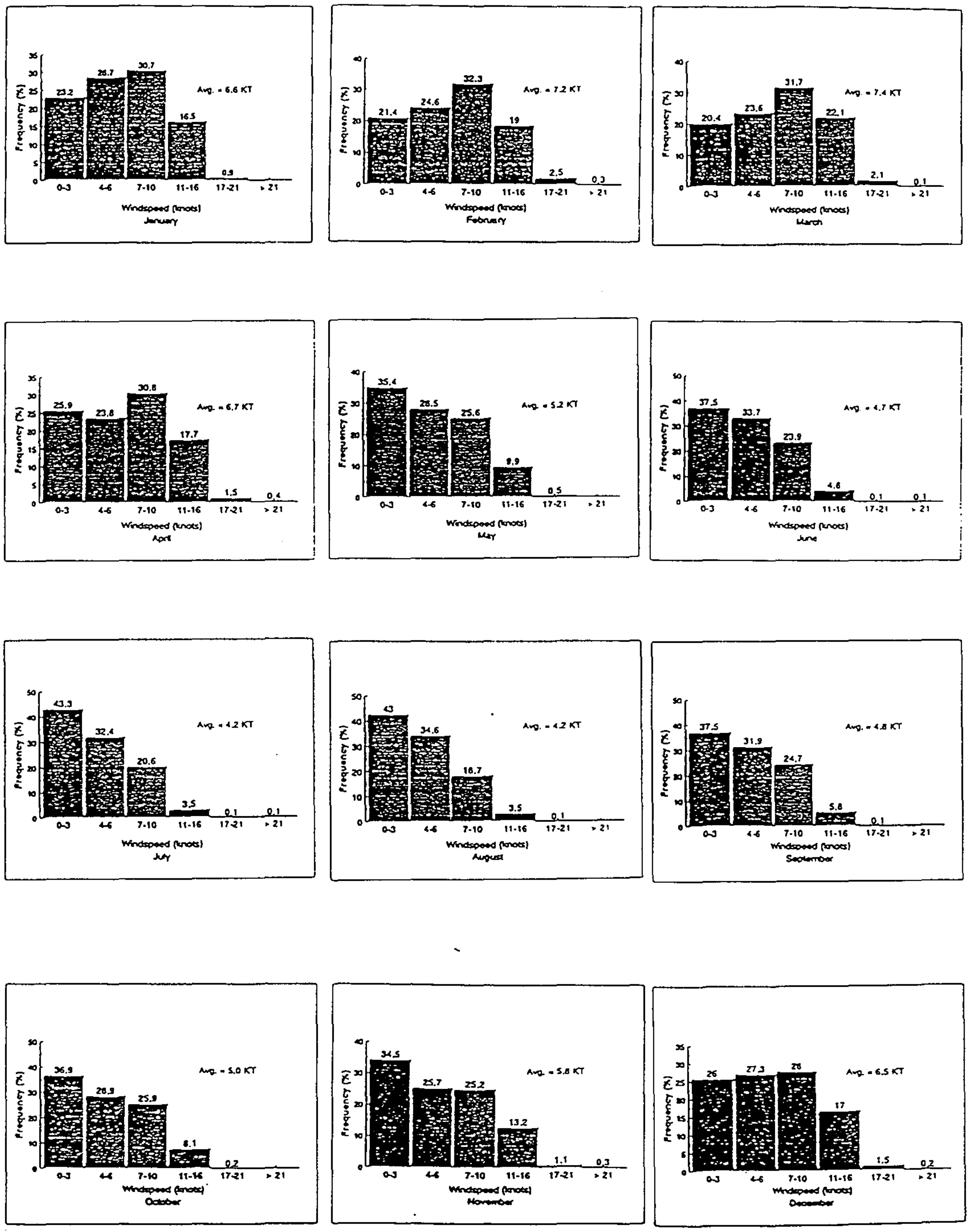


Fig. 3.9c. Monthly Frequency of Occurrence vs. Wind Speed for Birmingham, AL for Period 1965-1974 (1 knot = 1.15 mph)

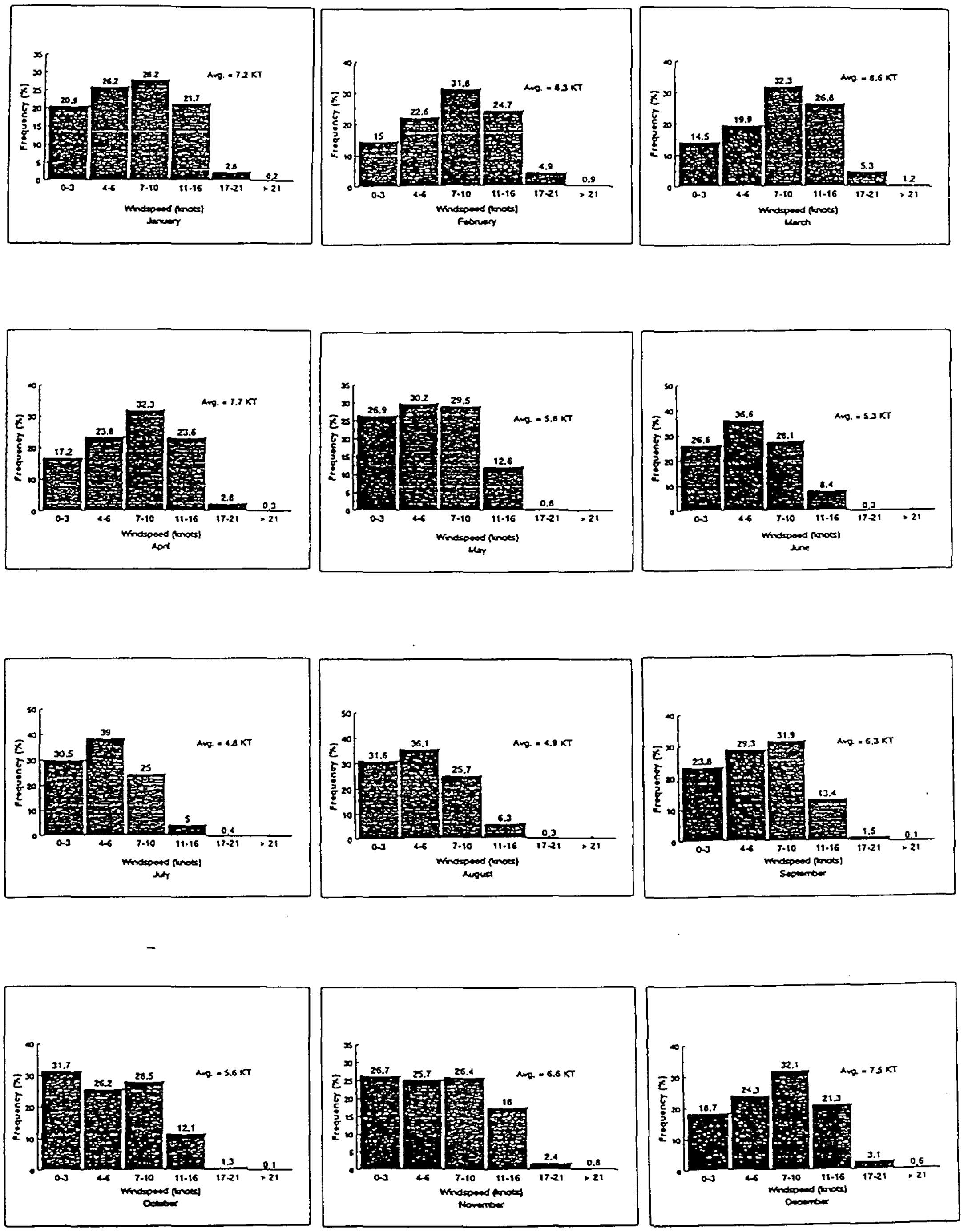


Fig. 3.9d. Monthly Frequency of Occurrence vs. Wind Speed for Huntsville, AL for Period 1959-1964 (1 knot = 1.15 mph)

great decrease in wind from the early spring and winter months. Winds are lowest during the summer months of June to September. Throughout the year, the occurrence of winds above 17 knots is rare. However, during winter and early spring, winds in the 16-21 knot range can occur quite often, depending upon the location in the state.

There are discernable differences in wind speeds among the four cities. Huntsville and Mobile data are very similar as are Montgomery and Birmingham. Huntsville and Mobile tend to show a significantly greater frequency of wind speeds in the 11-16 knot range than Montgomery and Birmingham. In February, March, and April, wind speeds from 11-16 knots have a frequency of occurrence of 25-30% for Mobile and Huntsville. For the same months and wind speed range in Montgomery and Birmingham, the frequency of occurrence is less than 20% except for 22.1 % for Birmingham in March. All four cities show a significant decrease in wind speeds from May to October except for Mobile in May. July and August are significantly the calmest months for all four cities.

3.4 Geographical Weather Variations

As indicated earlier, the weather variations geographically across Alabama are rather minimal. For example, Fig. 3.10 is a graph depicting the annual mean daily temperatures shown in Tables 3.1a-3.1d, and reflects a temperature decrease of only approximately 7-8°F from Mobile to Huntsville.

The mean annual relative humidity values for Alabama's four major cities shown in Figs. 3.5a-3.5d are shown in bar graph form in Fig. 3.11. As evident in that figure, both the high and low annual mean relative humidity values do not vary geographically in the state. It can be noted that a mean of the relative humidities shown in Fig. 3.11 is 72% which is in good agreement with the map of Fig. 3.12. Annual mean, mean maximum, and mean minimum monthly wind speeds (rounded to the nearest mph) were taken from Figs. 3.6a-3.6d, and are shown in bar graph form in Fig. 3.13. This figure indicates the greatest wind speeds at Mobile, following by Huntsville, with Montgomery and Birmingham showing the same, smaller wind speeds. However, the difference across the state is small (9 to 11 mph). Fig. 3.14

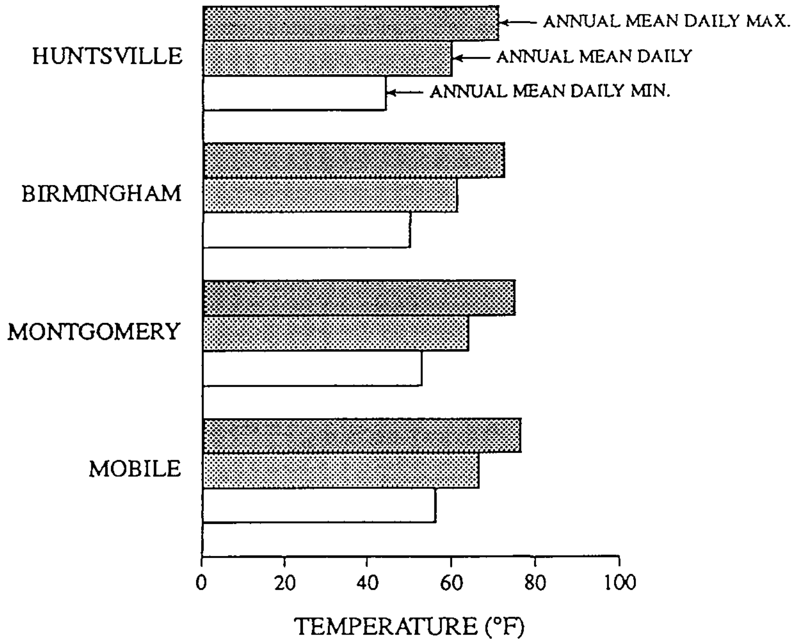


Fig. 3.10. Annual Mean Daily Temperatures for Four Major Cities.

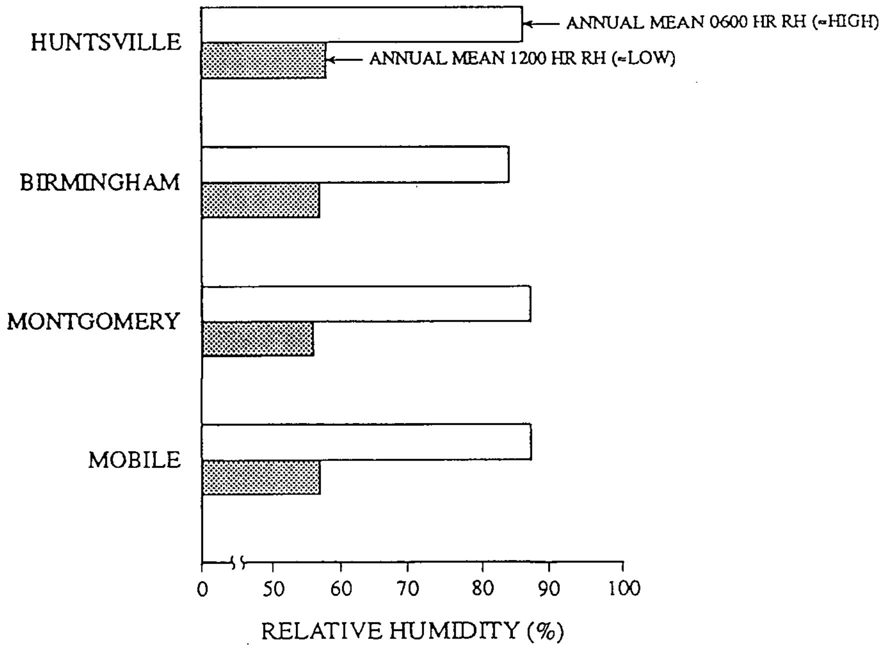


Fig. 3.11. Annual Mean High and Low Relative Humiditites for Four Major Cities.

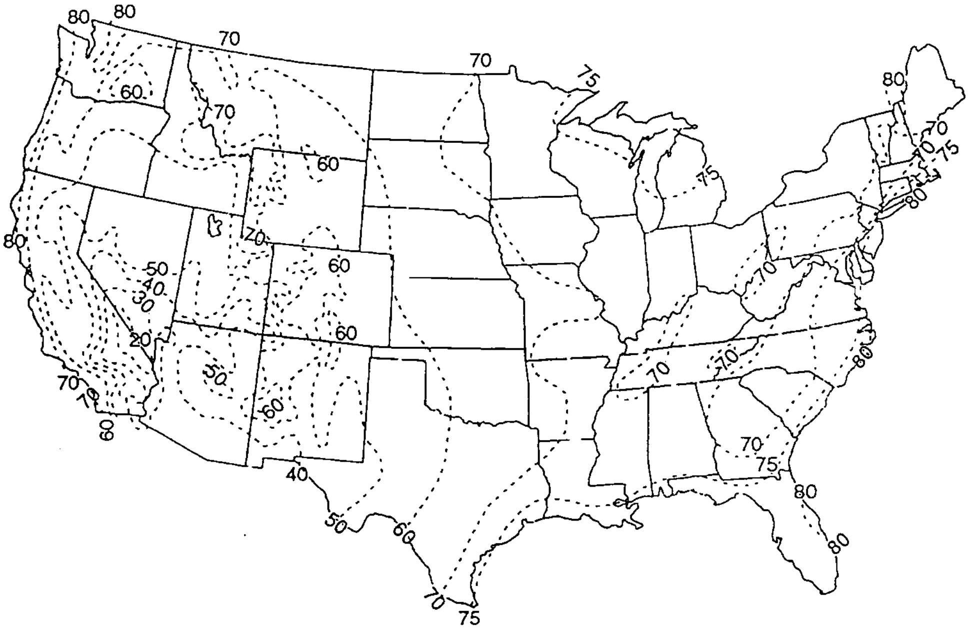


Fig. 3.12. Mean Annual Relative Humidity for Continental United States in Percent [18].

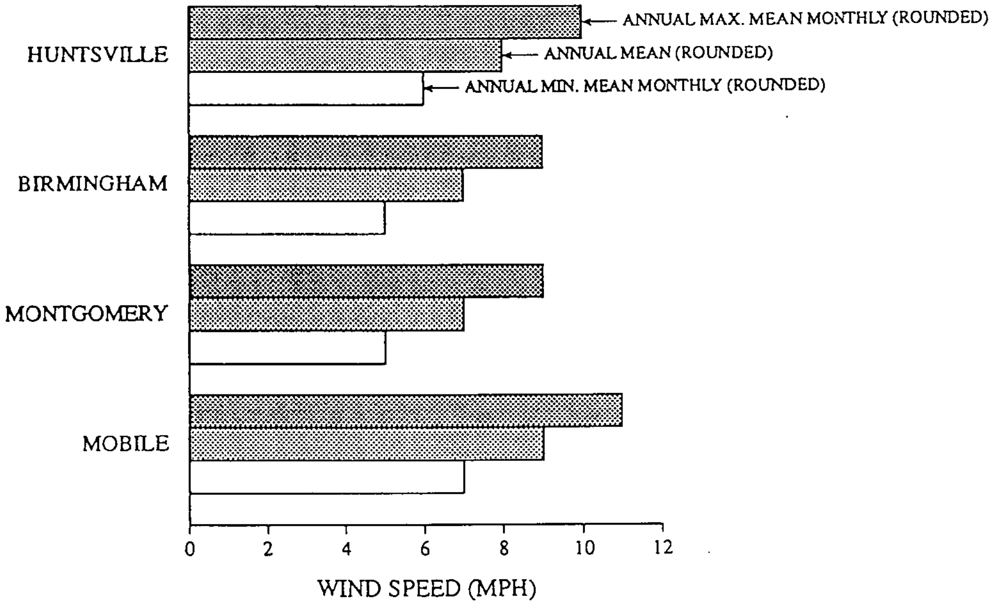
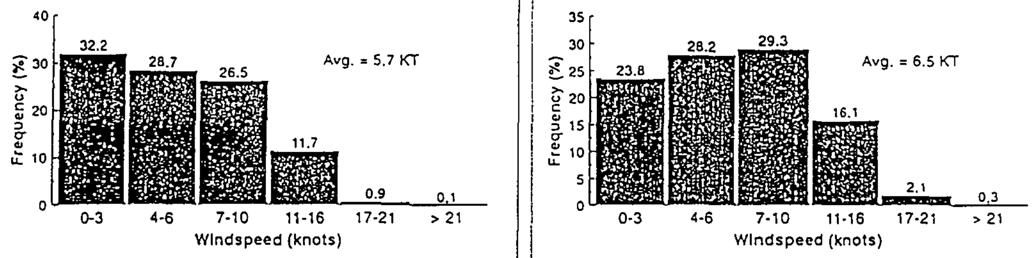
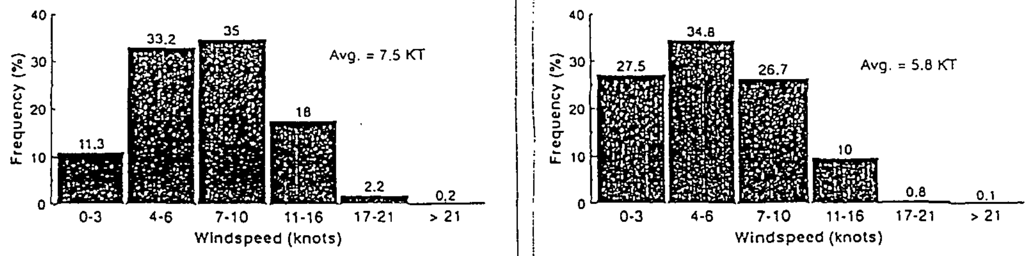


Fig. 3.13. Mean Wind Speeds for Four Major Cities.



Windspeed vs. Frequency of Occurrence
(Birmingham, Alabama, 1965-1974)

Windspeed vs. Frequency of Occurrence
(Huntsville, Alabama, 1959-1964)



Windspeed vs. Frequency of Occurrence
(Mobile, Alabama, 1965-1974)

Windspeed vs. Frequency of Occurrence
(Montgomery, Alabama, 1965-1974)

Fig. 3.14. Annual Frequency of Occurrence vs. Wind Speed (1 knot = 1.15 mph)

shows annual frequency of occurrence curves for the four major cities and indicates that Mobile is the windiest city, followed by Huntsville with Montgomery and Birmingham exhibiting very similar wind activity.

Mean annual values of the weather parameters considered in this investigation for the four major cities in Alabama are shown in Figs. 3.15-3.17. Also, shown in the figures are estimated contour lines depicting the variation of the parameters across the state.

3.5 Diurnal Weather Variations

As indicated in Fig. 3.1, the diurnal variations in the weather parameters are substantial, and quantifying the variations shown in Fig. 3.1 was needed for the four major cities in Alabama. Fig. 3.18 is a plot of the mean daily temperature cycle, Fig 3.19 is a plot of the mean daily relative humidity cycle, and Fig. 3.20 is a plot of the mean daily wind speed cycle for January for the four major cities. Plots for all twelve months are presented in Appendix A.

A daily temperature cycle for any month in any city indicates that temperature is lowest at 5-6 a.m. The peak temperature occurs between 12-3 p.m. with 2 p.m. as the most common hour for peak temperature. The temperature tends to rise faster from the low in the morning to the afternoon peak than it descends from the afternoon peak to the morning low. For inland cities, Montgomery, Birmingham, and Huntsville, the peak in the winter months (December-March) and April tends to be at 3 p.m. with 2 p.m. as the peak for the remaining months. For Mobile, the most common peak temperature is at 2 p.m. for the fall, winter, and spring months (September-May). During the hot summer months (June-August), the peak is at 12 p.m. or 1 p.m. This earlier peak is due to Mobile's close proximity to the Gulf of Mexico. Around noon, during the summer, a cooling sea breeze curbs temperature rise and also brings rainstorms into the area which also create a cooling effect.

Note in Figs. 3.18 and 3.19 that relative humidity varies inversely with the cycle of temperature. The high value for relative humidity occurs in the morning around dawn and the low value is

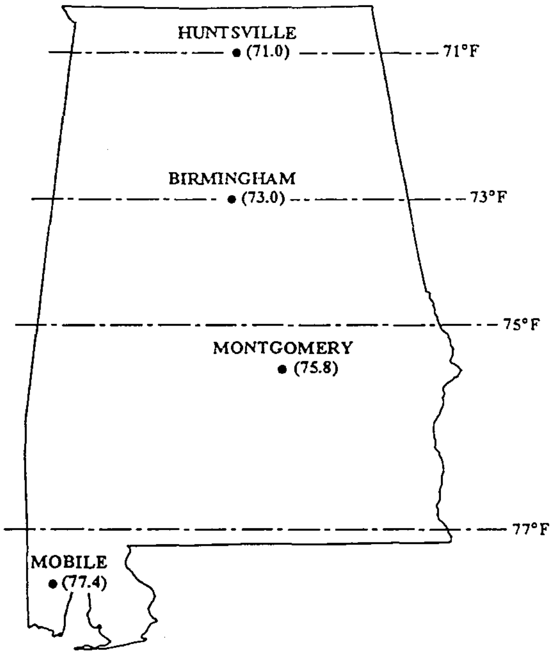


Fig. 3.15. Mean Annual Maximum Temperatures; Values and Distributions for Alabama.

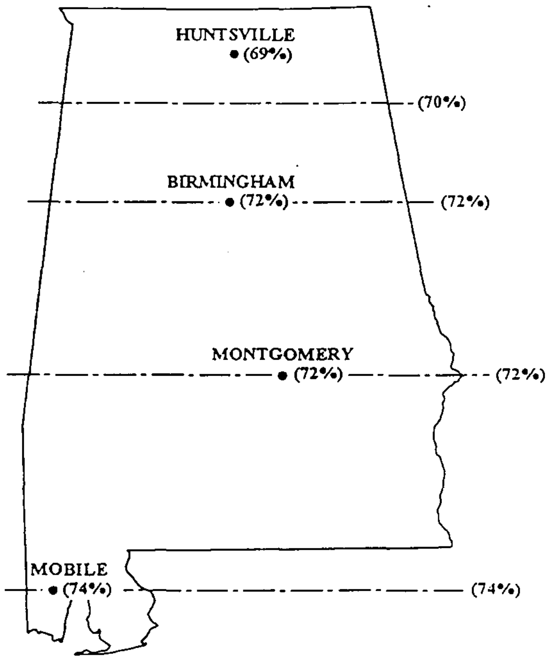


Fig. 3.16. Mean Annual Relative Humidity; Values and Distributions for Alabama.

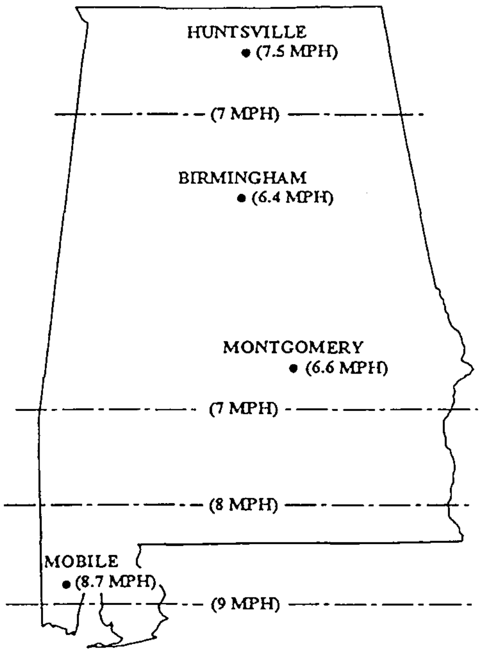


Fig. 3.17. Mean Annual Wind Speed; Values and Distributions for Alabama.

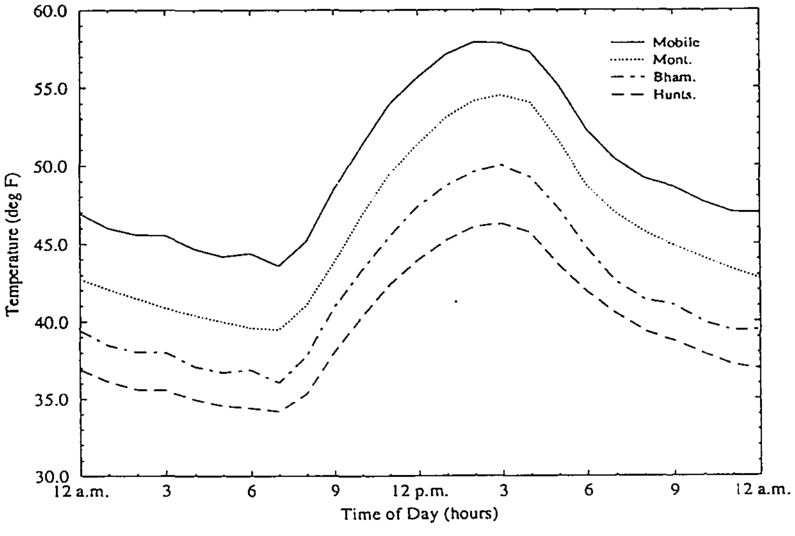


Fig. 3.18. Mean Daily Temperature Cycle - January

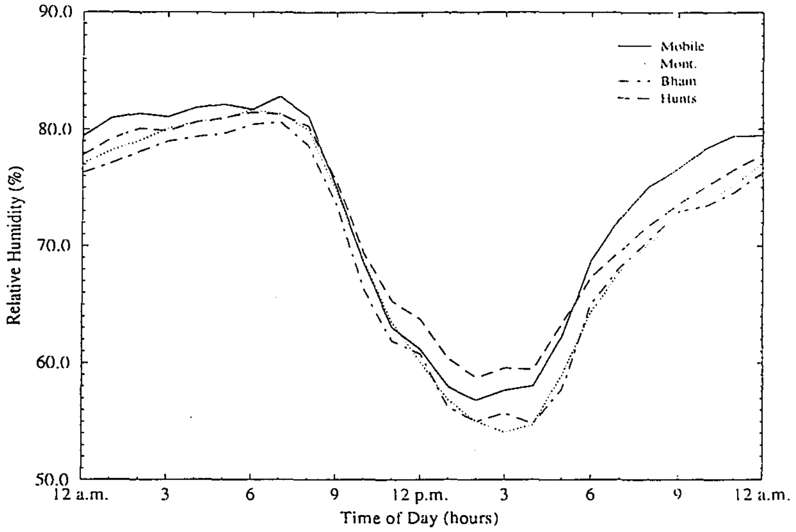


Fig. 3.19. Mean Daily Relative Humidity Cycle - January

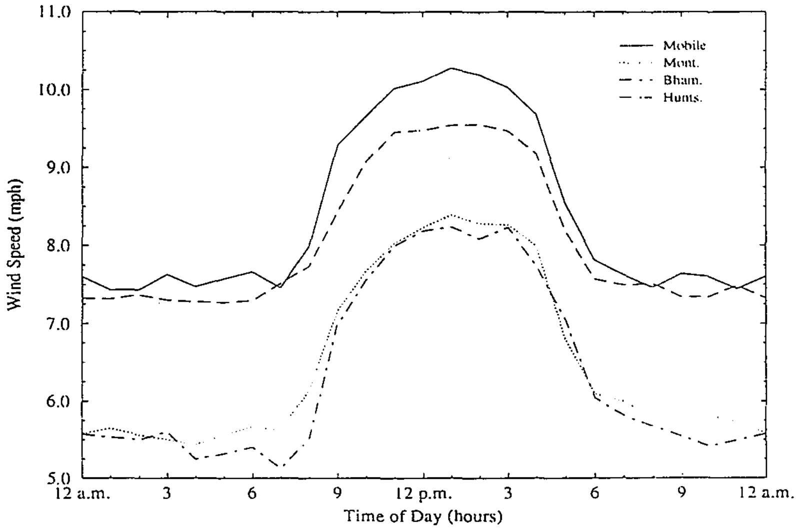


Fig. 3.20. Mean Daily Wind Speed Cycle - January

simultaneous with the temperature peak in early to mid-afternoon. Humidity decreases more rapidly in the morning than it increases in the evening hours due to its inverse relation to temperature.

Mean midday humidity values show little change throughout the year, usually falling in the upper-50% range to the low-60% range, with the exception being March, April, October, and November. During these four months, mean relative humidity drops into the mid-40% range for the low value. During hot and warm months (May to October) the mean relative humidity in early morning (high value) is around 90%. This indicates that during these warm months, as temperature increases with the rise of the sun. humidity drops rapidly. Fig. 3.19 reflects that across the state there is little variation in relative humidity. This is consistent with seasonal variations across the state discussed in the previous section.

Due to the close relationship between the daily cycles of relative humidity and temperature, it is helpful to consider their contribution to evaporation rate together. During the daily cycle, low value of relative humidity occurs simultaneously with the high temperature, and, likewise, high relative humidity is coupled with low temperature. The combination of low relative humidity and high temperature produces high evaporation rates. Therefore, evaporation rate will "peak" with the afternoon combination of low relative humidity and high temperature. From this point on, "peak" conditions will refer to this critical time for evaporation rate.

Analysis of the mean daily wind speed cycle for January, shown in Fig. 3.20, reveals that the wind speed is relatively constant and low between 6 p.m. and 6 a.m. Wind speed increases from 6 a.m. or near dawn until the early to mid-afternoon time of peak evaporation rate conditions. As evident in Fig. 3.20 wind speed is greatest around midday (12-1 p.m.). The mean wind speed then decreases until 6 p.m. or around sundown. Geographically, Mobile has the highest mean wind speeds with Huntsville a close second. Montgomery and Birmingham show little difference in mean wind speed curves and are approximately 2 mph below Huntsville.

Table 3.4a. Ten - Year (1965 - 1974) Wind Speed - Mean Number of Days (by hour of day) for Mobile, AL

Month	Wind Speed (Knots)	Hour of Day							
		0000	0300	0600	0900	1200	1500	1800	2100
JAN	Calm	2.1	2.3	1.6	.5	.7	.3	5	2.6
	1-6	10.0	9.9	9.8	6.1	5.8	5.7	11.2	10.3
	7-10	12.0	11.9	12.3	12.9	10.9	12.3	11.8	11.5
	11-16	5.6	6.0	6.6	10.3	11.3	9.8	6.9	5.9
	17-21	1.2	.8	.5	1.0	2.1	2.8	.4	.6
	over 21	1	.1	.1	.2	.2	.1	2	.1
FEB	Calm	2.7	2.6	2.0	.9	.5	.2	.4	1.5
	1-6	8.8	9.6	10.8	4.9	4.4	4.5	7.5	9.3
	7-10	9.7	11.4	9.3	11.5	8.8	9.1	13.7	11.1
	11-16	5.6	3.6	5.2	9.6	11.6	11.7	5.9	4.8
	17-21	1.3	.8	.8	1.2	2.7	2.5	.4	1.3
	over 21	.1	.2	.1	.1	.2	.2	.3	.2
MAR	Calm	2.4	2.7	3.5	.4	.5	.3	.2	2.3
	1-6	10.7	11.6	10.0	4.4	5.3	3.4	5.3	9.6
	7-10	11.1	10.7	12.0	12.0	9.7	9.6	15.3	11.9
	11-16	5.9	5.1	5.1	12.2	12.1	14.3	8.8	5.9
	17-21	9	9	.4	2.0	3.0	2.8	1.1	1.2
	over 21					.4	.6	.3	1
APR	Calm	2.4	2.6	2.5	7	4	1	3	9
	1-6	11.5	13.5	13.1	3.6	4.0	2.9	3.2	11.2
	7-10	10.4	9.7	9.5	11.7	8.9	8.6	15.3	12.8
	11-16	4.8	3.7	4.1	11.3	12.8	15.4	10.7	4.6
	17-21	.5	4	5	2.3	3.3	2.7	4	4
	over 21	.3		.1	3	5	.2		
MAY	Calm	3.4	2.8	2.8	.4	7	.4	1	2.2
	1-6	16.7	18.2	15.9	6.7	5.3	4.1	5.5	15.5
	7-10	9.1	8.1	9.2	13.9	12.4	10.9	16.2	10.5
	11-16	1.7	1.8	3.0	8.8	10.6	13.7	8.8	2.6
	17-21	1	1	1	1.1	2.0	1.9	4	2
	over 21				.1				
JUN	Calm	3.8	5.2	3.3	.5	.6	.3	3	3.2
	1-6	19.4	18.3	17.7	10.1	8.4	6.4	8.1	19.0
	7-10	6.3	5.9	8.3	14.9	15.3	14.0	16.7	7.0
	11-16	.5	.6	7	4.5	5.6	9.1	4.8	8
	17-21					1	1		
	over 21						1	.1	

Month	Wind Speed (Knots)	Hour of Day							
		0000	0300	0600	0900	1200	1500	1800	2100
JUL	Calm	6.6	7.6	5.6	1.5	.8	.5	9	5.3
	1-6	21.5	19.7	20.5	13.3	12.2	8.5	11.7	21.6
	7-10	2.9	3.7	4.8	14.1	13.3	14.2	15.4	4.0
	11-16			1	2.0	4.7	7.4	2.9	1
	17-21				1		4	1	
	over 21								
AUG	Calm	7.7	7.4	5.4	1.2	.4	.4	1.4	5.2
	1-6	19.0	20.3	19.8	15.1	12.8	9.8	15.5	20.3
	7-10	4.1	3.1	5.6	12.9	14.1	14.4	12.6	5.2
	11-16		.1	.1	1.7	3.4	6.1	1.4	2
	17-21					3	.3		
	over 21		.1	.1	1			.1	.1
SEPT	Calm	7.2	5.9	3.9	1.0	.8	6	1.1	5.7
	1-6	15.6	16.8	17.3	10.3	7.4	7.8	17.6	15.9
	7-10	5.9	5.6	7.4	13.7	14.0	13.7	9.1	6.6
	11-16	1.2	1.4	1.2	4.7	7.0	7.5	1.9	1.7
	17-21		3	2	3	8	4	1	1
	over 21	.1						2	
OCT	Calm	6.2	4.9	3.7	6	5	6	1.6	4.7
	1-6	15.1	15.7	15.7	8.1	8.5	8.0	18.7	16.1
	7-10	7.6	8.7	9.4	14.9	12.7	14.0	9.6	8.7
	11-16	2.1	1.6	2.2	6.9	9.1	8.2	1.1	1.5
	17-21		1		.5	1	2		
	over 21					1			
NOV	Calm	4.6	3.9	2.9	1.2	3	3	1.5	3.9
	1-6	12.8	13.0	14.0	6.3	7.8	7.0	15.3	12.4
	7-10	8.9	10.1	9.8	14.4	11.0	12.7	9.8	10.0
	11-16	3.4	2.7	2.9	7.4	9.5	9.2	3.1	3.4
	17-21	3	3	4	7	1.3	7	3	3
	over 21					1	.1		
DEC	Calm	1.9	2.1	1.6	4	3	8	1.4	2.3
	1-6	12.0	12.2	12.2	6.5	5.9	6.2	12.9	10.7
	7-10	11.0	10.0	10.9	14.1	12.3	10.5	10.0	11.7
	11-16	5.3	5.8	5.8	9.5	11.0	12.0	5.8	5.4
	17-21	7	8	5	5	1.5	1.5	8	.8
	over 21	.1	1					1	1

Month	Wind Speed (Knots)	Hour of Day							
		0000	0300	0600	0900	1200	1500	1800	2100
ANNUAL	Calm	51.0	50.0	38.8	9.3	6.5	4.8	9.7	39.8
	1-6	173.1	178.8	176.8	95.4	87.8	74.3	132.5	171.9
	7-10	99.0	98.9	108.5	161.0	143.4	144.0	155.5	111.0
	11-16	36.1	32.4	37.0	88.9	108.7	124.4	62.1	36.9
	17-21	5.0	4.5	3.3	9.8	17.2	16.3	4.0	4.9
	over 21	.8	.5	.5	.7	1.5	1.3	1.3	.6

Table 3.4b. Ten - Year (1965 - 1974) Wind Speed - Mean Number of Days (by hour of day) for Montgomery, AL

Month	Wind Speed (Knots)	Hour of Day							
		0000	0300	0600	0900	1200	1500	1800	2100
JAN	Calm	5.5	5.9	5.6	2.3	.8	.6	3.1	5.3
	1-6	13.7	13.3	14.0	11.8	11.2	10.5	15.6	14.3
	7-10	8.0	8.3	8.7	12.0	11.4	11.7	8.7	8.0
	11-16	3.6	3.3	2.4	4.6	6.9	7.7	3.4	3.3
	17-21	.1	.1	3	3	.6	.4	2	1
	over 21		.1			.1	1		
FEB	Calm	4.7	5.7	5.1	.8	.3	1	1.8	3.1
	1-6	11.5	12.2	12.3	9.6	7.5	8.1	13.9	12.0
	7-10	8.3	7.5	8.1	11.8	11.3	10.1	8.5	9.3
	11-16	3.4	2.5	2.0	5.4	7.9	7.8	3.8	3.2
	17-21	.2	3	.7	.6	.9	1.7	.2	.5
	over 21	.1				.3	.4		.1
MAR	Calm	4.1	5.7	4.9	.8	.1	.4	1.4	3.2
	1-6	14.3	15.6	15.5	10.0	8.0	8.0	14.3	12.7
	7-10	8.9	6.4	8.0	12.8	11.2	11.9	9.7	10.3
	11-16	3.3	3.1	2.4	6.2	10.1	9.5	5.4	4.3
	17-21	.4	.1	.1	1.2	1.5	1.0	.2	.4
	over 21		.1	.1		.1	.2		.1
APR	Calm	5.3	6.4	7.0	.7	.4	.3	1.4	5.7
	1-6	15.1	15.5	15.0	9.7	8.5	8.6	14.9	13.5
	7-10	8.0	6.3	6.5	11.5	10.9	12.3	10.1	7.2
	11-16	1.4	1.6	1.5	7.2	9.0	7.8	2.9	3.6
	17-21	.1	.2		.8	1.2	.9	.6	
	over 21	.1			.1		.1	.1	
MAY	Calm	8.7	10.5	8.9	.5	.3	.2	1.7	8.6
	1-6	15.4	16.2	16.9	13.7	9.6	9.6	17.8	16.3
	7-10	6.0	3.5	4.5	13.4	14.1	14.2	9.5	4.7
	11-16	.9	7	6	3.1	6.9	6.4	1.9	1.2
	17-21		.1	1	3	.1	.6	1	2
	over 21								
JUN	Calm	9.1	10.9	7.4	.9	.4	.3	1.3	7.5
	1-6	16.4	16.2	17.8	17.4	13.3	11.6	15.3	17.0
	7-10	4.0	2.6	4.2	8.1	12.0	13.5	11.7	4.8
	11-16	.5	.3	6	3.3	3.7	3.7	1.6	.6
	17-21				3	5	7	1	1
	over 21					.1	.2		

Month	Wind Speed (Knots)	Hour of Day							
		0000	0300	0600	0900	1200	1500	1800	2100
JUL	Calm	6.7	9.1	6.9	1.3	.4	.3	8	5.3
	1-6	21.0	19.7	20.9	19.7	15.6	11.8	16.3	20.7
	7-10	3.1	2.2	3.2	8.6	11.9	15.1	11.4	4.7
	11-16	2			1.4	3.0	3.1	2.2	3
	17-21					1	7	3	
	over 21								
AUG	Calm	7.9	9.6	8.7	2.0	3	3	1.8	7.7
	1-6	21.2	19.8	20.5	19.8	17.8	15.8	21.3	19.8
	7-10	1.9	1.6	1.7	8.3	11.6	12.5	6.3	3.2
	11-16			1	9	1.3	2.4	1.5	3
	17-21							1	
	over 21								
SEP	Calm	8.8	10.3	8.9	1.4	.5	.6	3.1	8.1
	1-6	17.1	15.5	16.7	16.5	14.5	13.3	20.3	17.6
	7-10	3.5	4.0	3.9	9.8	12.0	12.5	5.5	3.3
	11-16	5	2	5	2.1	2.9	3.5	1.0	1.0
	17-21	1			.2	1	1	1	
	over 21								
OCT	Calm	11.1	10.8	10.1	2.1	.1	6	6.3	9.3
	1-6	15.7	16.8	16.3	14.2	12.9	12.9	20.7	16.6
	7-10	3.6	3.1	3.6	10.8	12.4	13.0	3.5	4.3
	11-16	5	3	1.0	3.9	5.5	4.5	5	8
	17-21					1			
	over 21	.1							
NOV	Calm	9.1	8.5	8.8	2.3	7	.3	5.9	8.0
	1-6	13.6	14.9	13.9	13.4	11.9	10.5	16.1	13.9
	7-10	5.4	5.0	5.4	10.1	11.4	12.7	6.2	5.5
	11-16	1.8	1.4	1.7	4.1	5.6	6.2	1.7	2.6
	17-21	1	.2	2	1	.4	3	.1	
	over 21								
DEC	Calm	7.5	6.4	6.0	1.4	.4	1.0	4.9	6.4
	1-6	13.6	14.0	14.4	14.9	11.3	10.5	15.2	12.8
	7-10	6.1	7.1	7.1	9.7	10.7	12.3	7.7	8.1
	11-16	3.6	3.4	3.5	4.7	8.0	6.4	3.1	3.5
	17-21	2	1		3	6	6	1	2
	over 21						2		

Month	Wind Speed (Knots)	Hour of Day							
		0000	0300	0600	0900	1200	1500	1800	2100
ANNUAL	Calm	88.5	99.8	88.3	16.5	4.7	5.0	33.5	78.2
	1-6	188.6	189.7	194.2	170.7	142.1	131.2	201.7	187.2
	7-10	66.8	57.6	64.9	126.9	140.9	151.8	98.8	73.4
	11-16	19.7	16.8	16.3	46.9	70.8	69.0	29.0	24.7
	17-21	1.2	1.1	1.4	4.1	6.1	7.0	2.1	1.5
	over 21	.3	.2	.1	1	.6	1.2	.1	2

Table 3.4c. Ten - Year (1965 - 1974) Wind Speed - Mean Number of Days (by hour of day) for Birmingham, AL

Month	Wind Speed (Knots)	Hour of Day							
		0000	0300	0600	0900	1200	1500	1800	2100
JAN	Calm	5.9	6.3	7.3	3.4	.4	1.0	3.0	6.4
	1-6	12.9	11.7	10.2	10.4	10.0	9.5	16.9	13.3
	7-10	8.2	9.2	8.9	11.3	12.9	11.2	7.6	6.8
	11-16	3.7	3.7	4.4	5.5	7.1	9.0	3.4	4.2
	17-21	.3	.1	2	4	.6	3	1	3
	over 21								
FEB	Calm	5.8	6.9	6.9	1.9	8	7	1.5	4.2
	1-6	9.5	9.4	10.3	8.0	7.1	6.5	12.7	11.4
	7-10	8.5	8.5	7.2	11.6	10.5	9.9	8.8	7.9
	11-16	3.7	3.0	3.1	5.8	8.6	9.9	4.6	4.1
	17-21	.5	.3	7	8	1.2	1.2	.6	4
	over 21	.2	.1		.1				2
MAR	Calm	6.1	6.4	6.4	1.9	.9	.5	1.4	5.3
	1-6	12.1	12.4	12.3	6.8	5.7	6.4	11.4	13.2
	7-10	7.4	7.8	7.8	13.1	11.5	11.1	11.9	8.1
	11-16	5.1	4.3	4.1	9.1	11.3	11.2	5.7	3.9
	17-21	3	.1	4	1	1.6	1.7	6	.4
	over 21						.1		1
APR	Calm	7.9	9.0	9.4	.6	1.0	1.2	1.1	6.9
	1-6	11.0	9.9	10.1	9.5	7.9	7.7	12.3	13.7
	7-10	7.3	7.2	7.1	12.0	11.4	11.1	11.3	6.4
	11-16	3.5	3.7	3.2	7.1	8.4	9.0	4.9	2.7
	17-21	.2	2	1	7	1.1	9	2	2
	over 21	1		.1	1	.2	.1	.2	1
MAY	Calm	13.6	13.4	12.9	2.1	.8	.8	2.0	11.2
	1-6	12.3	12.0	11.9	12.2	10.4	10.8	17.6	14.7
	7-10	3.4	4.4	4.5	11.6	13.6	12.9	9.3	3.8
	11-16	1.7	1.1	1.7	4.9	5.7	6.0	2.1	1.3
	17-21		.1		2	5	5		
	over 21								
JUN	Calm	12.9	15.3	13.6	1.7	.5	1.0	1.6	10.0
	1-6	14.3	12.3	12.7	15.4	13.3	11.0	18.8	16.4
	7-10	2.2	2.1	3.4	11.4	12.4	14.2	8.2	3.4
	11-16	.6	3	3	1.5	3.6	3.5	1.4	2
	17-21					.1	2		
	over 21					1	1		
JUL	Calm	14.2	15.4	15.9	3.3	1.1	1.3	3.0	10.8
	1-6	14.4	13.5	13.1	17.3	15.8	13.7	17.5	17.3
	7-10	2.1	2.0	1.9	9.5	11.6	12.4	8.9	2.7
	11-16	3	1	1	9	2.2	3.4	1.5	2
	17-21					2	1		
	over 21					1	1	1	
AUG	Calm	12.6	14.7	14.0	2.3	9	1.1	2.4	10.1
	1-6	16.7	14.5	15.5	18.7	15.6	14.7	21.1	17.7
	7-10	1.4	1.6	1.4	9.1	12.3	12.2	5.7	2.7
	11-16	.3	.2	1	8	2.2	2.8	1.8	5
	17-21				1		2		
	over 21								
SEP	Calm	11.6	10.8	11.0	2.3	8	9	3.0	9.7
	1-6	14.1	14.9	13.7	13.6	11.9	12.3	20.9	15.2
	7-10	3.3	3.5	4.5	12.2	13.3	13.1	5.3	4.0
	11-16	1.0	8	7	1.8	4.0	3.6	8	1.1
	17-21			1	1		1		
	over 21								
OCT	Calm	10.6	12.8	11.7	3.2	.5	7	5.0	8.7
	1-6	13.8	11.6	12.3	12.0	11.4	12.2	21.2	15.4
	7-10	5.1	5.2	5.7	11.2	14.1	12.9	4.3	5.8
	11-16	1.5	1.3	1.3	4.6	4.9	5.1	4	1.1
	17-21		1			1	1	1	
	over 21								
NOV	Calm	10.0	10.0	10.0	3.2	8	9	4.0	7.7
	1-6	12.2	12.5	12.5	10.4	9.6	10.2	16.9	13.7
	7-10	4.5	5.0	4.8	10.7	11.8	11.6	6.5	5.6
	11-16	2.8	2.2	2.3	5.4	7.1	6.7	2.2	2.9
	17-21	.2	3	3	3	7	4	4	1
	over 21	.3		1			.2		
DEC	Calm	8.3	7.4	8.1	2.5	6	6	4.6	5.9
	1-6	10.4	11.6	11.4	11.1	11.0	11.5	14.7	12.5
	7-10	6.5	7.3	7.1	10.8	11.3	11.0	7.8	7.6
	11-16	5.1	4.0	4.2	6.3	7.3	7.1	3.7	4.4
	17-21	7	6	2	3	7	6	2	5
	over 21		1			1	2		1

Month	Wind Speed (Knots)	Hour of Day							
		0000	0300	0600	0900	1200	1500	1800	2100
ANNUAL	Calm	119.5	128.4	127.2	28.4	9.1	10.7	32.6	96.9
	1-6	153.7	146.3	146.0	145.4	129.7	126.5	202.0	174.5
	7-10	59.9	63.8	64.3	134.5	146.7	143.6	95.6	64.8
	11-16	29.3	24.7	25.5	53.7	72.4	77.3	32.5	26.6
	17-21	2.2	1.8	2.0	3.0	6.8	6.3	2.2	1.9
	over 21	6	2	2	2	5	8	3	5

Tables 3.4a-3.4c provide the mean number of days in each month, for each city, where wind speed readings fall into a wind speed range at a particular hour of the day. This data was not available for Huntsville, but it could be expected that Huntsville would be similar to Mobile. According to data from Tables 3.4a-3.4c, the windiest period of the day is 12-3 p.m. In every month of the year, a higher mean number of days for the 11-16 knot and 17-21 knot ranges are found in the 1200 or 1500 time slot. In other words, if higher wind speeds occur, they are most likely to occur between 12-3 p.m. Tables 3.3a-3.3c also provide the mean number of days in a month that high wind speeds can be expected, a helpful tool for construction planning. Data in these tables clearly exhibit the same geographical and seasonal trends found in Tables 3.1 a-3.1d. A higher number of mean days fall in the plus 11 knot ranges from February to April, and Mobile has more days in these wind speed ranges than Birmingham and Montgomery.

3.6 Closure

Mean values of the weather parameters are good for long range and general planning. However, they are not adequate for making decisions regarding curing requirements for a concrete deck placement at a given time of the year, time of day, and location in Alabama. For this case, more accurate values of parameters are needed along with there daily cycle variation "signatures". This information is readily available in the figures given In Appendix A. These figures will be later used in Chapter 5 in conjunction with the ACI 305 Surface Evaporation Chart to develop evaporation rate vs. time of day curves for different seasons of the year and locations in Alabama.

For a concrete deck placement at a given location, on a given day, at a given time of day, the construction contractor and inspector should secure the corresponding temperature, relative humidity, and wind speed predictions along with the rainfall forecasts. It is important to know if the values provided are the maximum values or values at a particular time. Knowing this along with the 24-hour cycle signature in Appendix A will allow accurate estimation of the values at any time during the day if needed. The temperature and relative humidity parameters are "well-behaved" and fairly predictable. The wind speed and precipitation parameters are highly variable and are not as predictable. Wind speed conditions should be handled in a somewhat similar manner as precipitation, i.e., as when rain is predicted and concrete placement is rescheduled, placement of concrete in bridge decks should be rescheduled when predicted wind speeds are excessive (20 mph or higher).

Values and variations of temperature, relative humidity, and surface wind speed for various regions of the state, times of year, and time of day have been gathered and presented in this chapter. However, the concern of this investigation is not weather itself, but rather its relation to evaporation rate of concrete water and the associated curing requirements. Thus, before concrete exposure conditions and curing requirements for various exposures can be determined properly, other parameters such as concrete temperatures and water evaporation rates should be considered. These will be examined in the ensuing chapters.

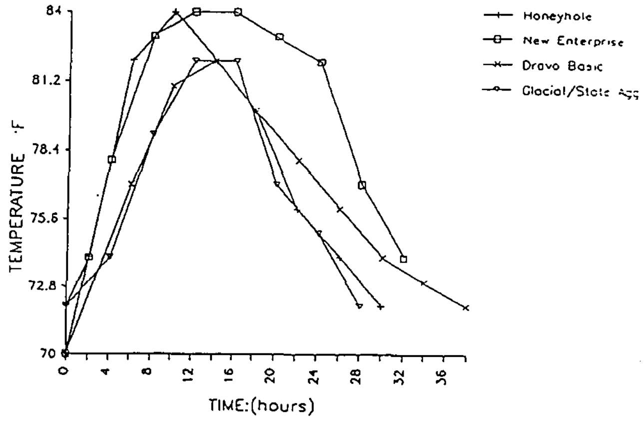
4. CONCRETE TEMPERATURE AND AMBIENT TEMPERATURE RELATIONSHIPS

4.1 General

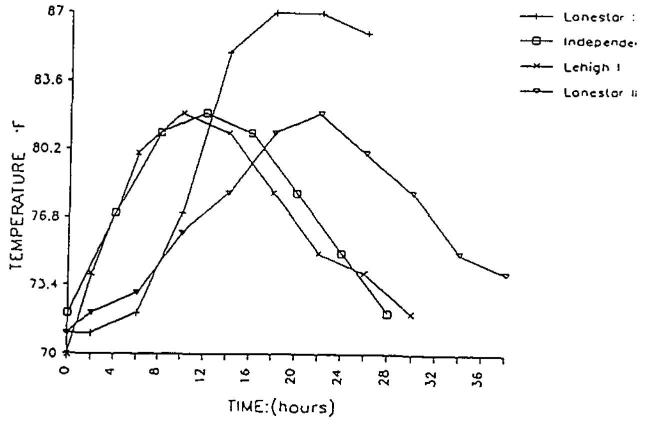
In order to accurately predict evaporative conditions, ambient conditions and concrete temperature must be known or accurately estimated. The value of concrete temperature depends upon the temperature of the mixture ingredients and the heat produced by the chemical reaction between cement and water. It would be helpful if concrete temperature could be estimated using simplified expressions instead of calculating temperature through use of complex equations. The control of concrete temperature is very important. In all weather conditions, a concrete temperature significantly higher than the ambient temperature can produce detrimental evaporation rates. Furthermore, Neville [28] writes that high concrete temperatures cause increase in water demand, accelerated slump loss which means less workability, more rapid hydration which tends to lower long-term compressive strengths, rapid evaporation causing great risk of plastic shrinkage cracking, and introduction of higher tensile stresses upon cooling.

4.2 Temperature Rise in Fresh Concrete

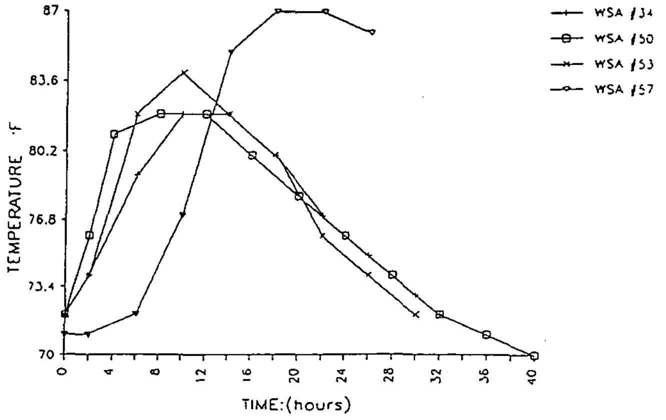
The chemical reaction between cement and water, hydration, is an exothermic reaction, i.e., a reaction which releases heat. If the mass of the concrete placement is large, a significant rise in the concrete temperature can occur. Although this is of greater concern when dealing with massive placements with a high volume-to- surface ratio such as concrete dams, the core of a bridge deck can experience a significant rise in temperature, especially with the use of stay-in-place forms. Fig. 4.1a-c illustrates the rise of temperature in concrete lab specimens due to heat of hydration. The data from these plots was produced in a study for the Pennsylvania Department of Transportation (Penn DOT) conducted



(a) Effect of Aggregates



b) Effect of Cement Type/Source



c) Effect of Mixture Design

Fig. 4.1. Heat of Hydration vs. Time Curves for Laboratory Specimens [15]

by Wilbur Smith and Associates [15]. In Fig. 4.1a, effect of aggregates on temperature rise due to heat of hydration is shown. To isolate the effect of aggregates, each mixture contained the same Type I cement. For all of the mixtures, the maximum temperature was reached in 8-10 hours after mixing. The temperature began to decrease at 14-16 hours. According to this data, aggregate type has little effect on the temperature gain due to hydration. Fig. 4. lb displays how heat gain changes with different cement types. Two of the Type I mixtures reached their maximum temperature at 10 hours and their temperature decreased at 12-14 hours. At 18 hours, the Lonestar Type I reached a significantly higher temperature than the other Type I mixtures and temperature decreased at 22-24 hours. Temperature for a Type H cement, a moderate heat cement, peaked at 22 hours and decreased soon afterward. Obviously, cement type has a considerable impact on the magnitude of temperature rise and the initial rate of temperature increase. Fig. 4. 1 c is a plot of temperature rise vs. time for actual in-place bridge deck mixtures on Penn DOT projects. All of the mixtures were made with Type I cement and WSA #57 was made with Lonestar Type 1. All of the mixtures except WSA #57 reached the maximum temperature at 8-10 hours and began to decrease around 12 hours. The Lonestar mixture exhibited similar temperature rise and decrease as shown in Fig. 4. 1 b, reaching a higher temperature at 18 hours.

From the data of Fig. 4. 1 a-c, it is evident that choice of cement in bridge deck construction is very important. Lower heat of hydration cements can reduce the magnitude of temperature rise of the concrete and slow the rate of temperature rise, two desirable factors in bridge deck construction. As the concrete temperature rises, evaporation rate of the surface increases at the time when the concrete is most vulnerable to plastic and early drying shrinkage. A higher magnitude of temperature increase would induce greater tensile stresses upon cooling by creating a large temperature differential between the deck concrete and the surrounding environment.

4.3 Calculation of Concrete Temperature

Calculation of freshly mixed concrete temperature depends mainly upon the temperature of the mixture ingredients. An equation is provided by ACI 305 [7] for calculation of temperature of freshly mixed concrete, T, and is as follows:

$$T = \frac{0.22(T_aW_a+T_cW_c)+T_wW_w+T_aW_{wa}}{0.22(W_a+W_c)+W_w+W_{wa}} \tag{4.1}$$

T_a=Temperature. of Agg.
T_c=Temperature. of Cement
T_w=Temperature of Water

W_a=Dry Agg. Weight
W_c=Weight of Cement
W_w=Weight of Water

W_{wa}=Weight of Free and Absorbed Moisture in Aggregate

The preceding equation is valid for calculation with US or Sl units. A similar equation can be used to calculate the temperature of freshly mixed concrete when using ice as a replacement by weight for some of the mixing water. This technique is often used in hot weather concreting to lower the temperature of the concrete. A different equation is needed depending upon which standards system is used and uses the same nomenclature as the preceding ACI equation and each are provided below:

$$T = \frac{0.22(T_aW_a+T_cW_c)T_wW_w}{0.22(W_a+W_c)+W_w+W_i+W_{wa}} + \frac{T_aW_{wa}-W_i(79.6-0.5T_i)}{0.22(W_a+W_c)+W_w+W_i+W_{wa}} \quad (SI) \tag{4.2a}$$

$$T = \frac{0.22(T_aW_a+T_cW_c)T_wW_w}{0.22(W_a+W_c)+W_w+W_i+W_{wa}} + \frac{T_aW_{wa}-W_i(128-0.5T_i)}{0.22(W_a+W_c)+W_w+W_i+W_{wa}} \quad (US) \tag{4.2b}$$

T_i=Temperature of Ice

W_i=Weight of Ice

FIP [19] provides a simplified equation to calculate the temperature of freshly mixed concrete and is as follows:

$$T = \frac{T_c+AT_a+5WT_w}{1+A+5W} \tag{4.3}$$

T_c=Temperature of Cement
T_a=Temperature of Aggregate

T_w=Temperature of Water
A=Aggregate /Cement Ratio

W=Water/ Cement Ratio

Fig. 4.2 is a nomograph developed from the FIP equation to calculate temperature of freshly mixed concrete. Another nomograph is provided by Kosmatka and Panarese [22] and is shown in Fig. 4.3.

All of the above methods produce the temperature of freshly mixed concrete whose value is directly related to the temperature of the mixture constituents. Neville [28] states that temperature of the concrete at placement will be higher due to the mechanical work of the mixer and due to heat of hydration.

4.4 Empirical Concrete Temperature Relationships

In this study, field measurements of concrete temperature and ambient temperature were obtained in order to determine the relationship between concrete and ambient temperature. This is a good way to estimate concrete temperature because the mixture ingredients will be at some temperature which relates to ambient temperature and it is very easy to measure the ambient air temperature as opposed to accurately measuring the temperature of every mixture ingredient. Three data sets were acquired and analyzed. One of the data sets consisted of measurements of concrete temperature and corresponding ambient temperature extracted from actual ALDOT bridge deck construction reports on three different projects by the authors. The other sets contained the same measurements at jobsites in the Atlanta area for 4000 psi concrete and were extracted and provided by Blue Circle Cement Company. All three sets included measurements from throughout the year and are presented in Appendix B.

Each data set was plotted and a linear regression performed to develop an equation to calculate concrete temperature from ambient temperature. These plots with superimposed regression lines and equations are shown in Fig. 4.4-4.7. Fig. 4.8 is a plot of all three equations developed from linear regression of the data sets for comparative purposes. Above 70 °F, the equations are in fairly close agreement. Concrete temperatures used for calculation of evaporation rates in Chapter 5 were obtained from use of the ALDOT Eqn. 4.4 (see Table 4. 1). This equation was chosen because this study is concerned with evaporation rates when using the present ALDOT mixture for bridge deck concrete. Also, the close proximity of Eqn. 4.4 to the equations from the Blue Circle data provides confidence in the use

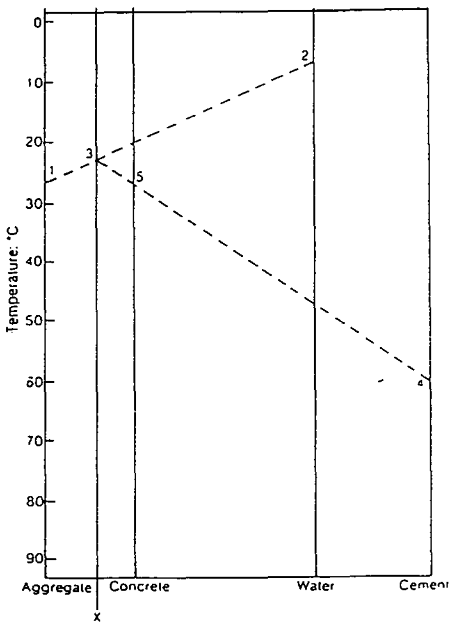


Fig. 4.2. Nomograph for Determining Approximate Temperature of Fresh Concrete [19]

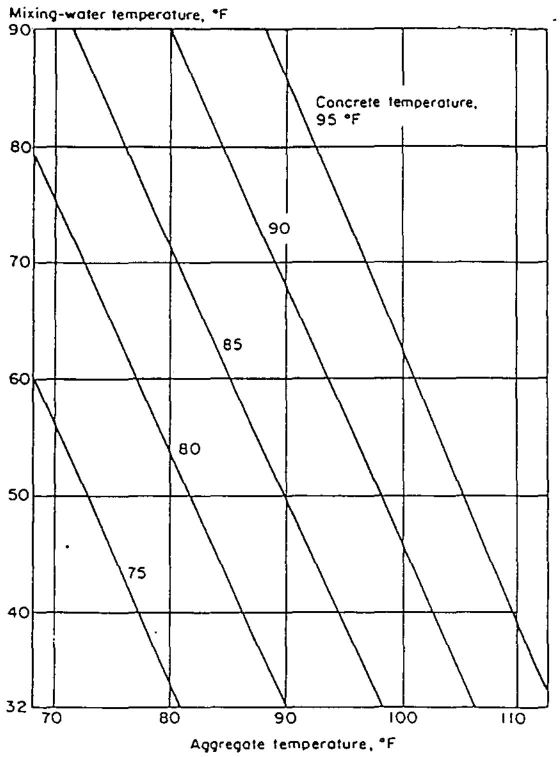


Fig. 4.3. Temperature of Freshly Mixed Concrete as Affected by IngredientTemperature[22]

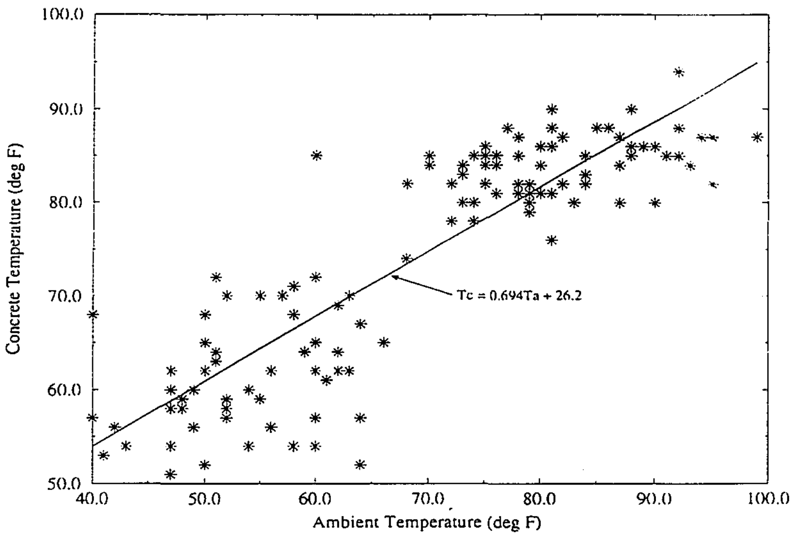


Fig. 4.4. ALDOT Concrete - Ambient Temperature Data ($r^2 = 0.767$)

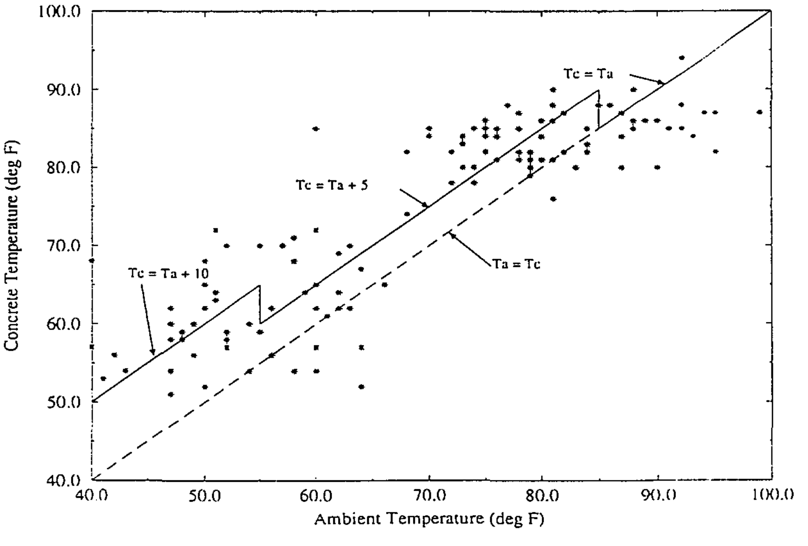


Fig. 4.5. Approximate Concrete - Ambient Temperature Relationship Developed from ALDOT Data

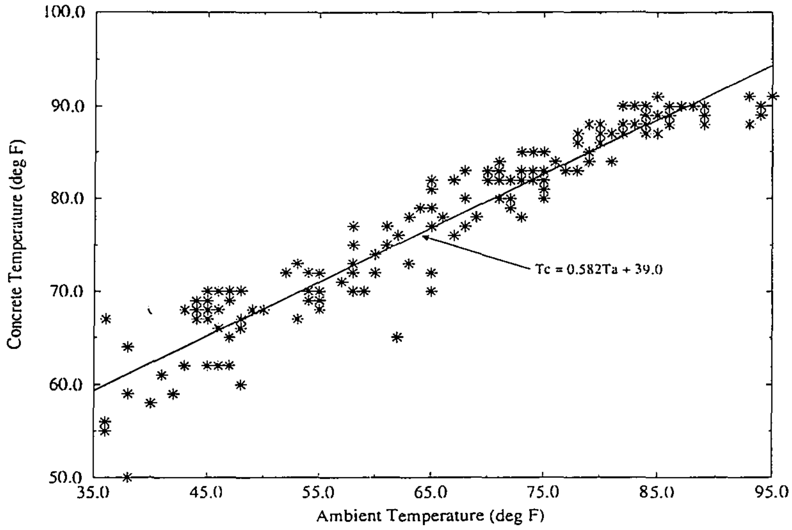


Fig. 4.6. Blue Circle Cement Concrete - Ambient Temperature Data Set #1($r^2 = 0.918$)

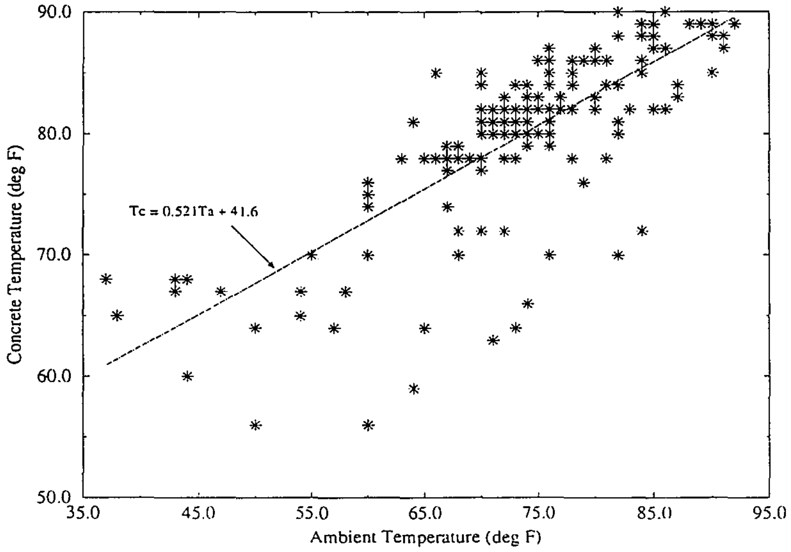


Fig. 4.7. Blue Circle Cement Concrete - Ambient Temperature Data Set #2 ($r^2 = 0.576$)

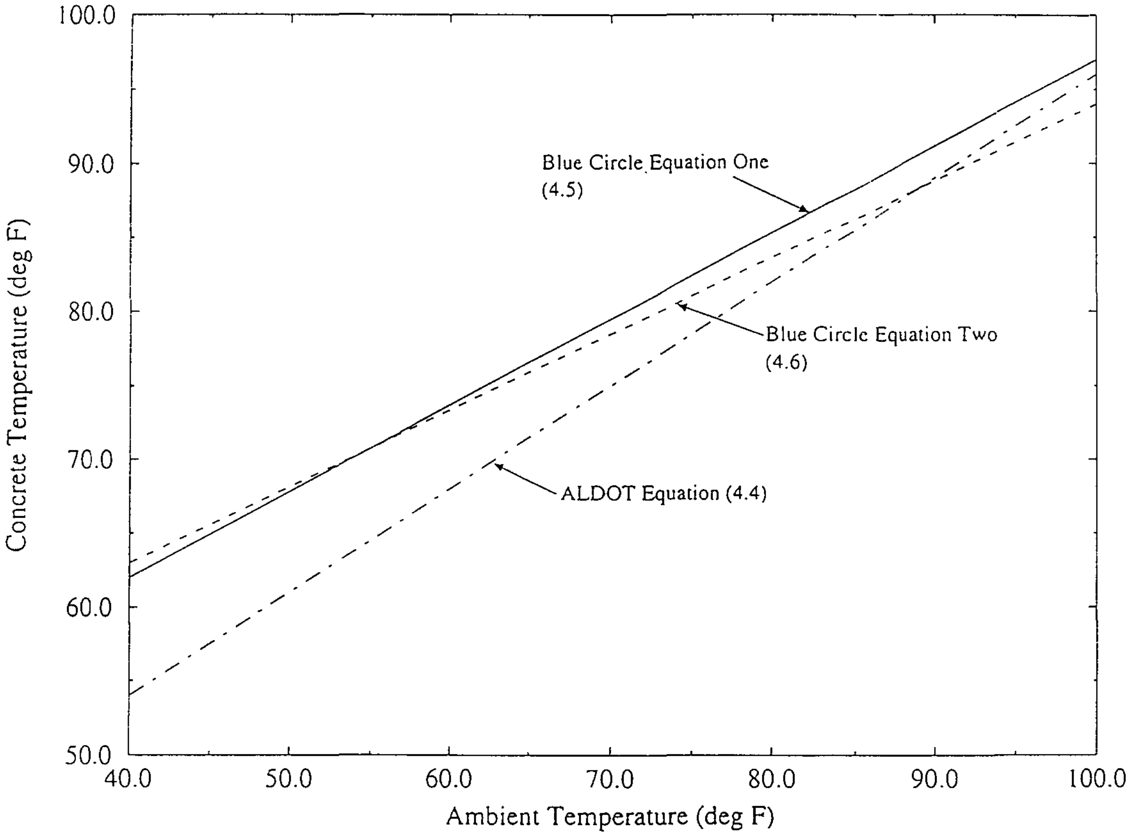


Fig. 4.8. Plot of Linear Regression Curves Developed from Concrete - Ambient Temperature Data Sets

of the equation. Table 4.1 summarizes the above empirical equations along with some other approximate relationships between concrete and ambient temperature obtained from Nawy [27] and from discussions with personnel of the ALDOT.

4.5 Control of Concrete Temperature

There are many opportunities in concrete batching and placement to minimize the increase of concrete temperature above ambient temperature. ACI 305 [7] lists several factors which are helpful in controlling concrete temperature. One problem is the high temperature of cement for the mixture. Cement may be delivered from the plant hot or stored in a way to produce much higher temperatures than ambient conditions. Although only 10-15% of the mixture weight is cement, a significant increase in concrete temperature can occur, a 1°F increase in concrete temperature for an 8°F increase in cement temperature. It is prudent to place a limit of 170°F on the temperature of the cement as it enters the mixer. Also, the use of chilled mixing water or ice as a replacement of mixing water can be an effective means of reducing concrete temperature. Fig. 4.9 illustrates the reduction in temperature of freshly mixed concrete by using chilled water or ice. Another productive measure is to reduce the temperature of the aggregates, because the aggregate makes up the largest portion of the concrete mixture. Simple, efficient ways to cool aggregates are shading of coarse and fine aggregates and sprinkling or fog spraying of coarse aggregates. ACI reminds that setting up the means for cooling sizeable amounts of concrete production requires planning well in advance of placement and may require specialized equipment.

Neville [29] states that cooling the mixing water with ice is a highly efficient way to reduce concrete temperature because 2.2 lb of ice absorbs 317 Btu when melting at 32°F. This is a quantity of heat four times greater than cooling mixing water by 36°F. It is important, however, that all of the ice has melted at the end of mixing. Also, cooling of aggregate can be achieved by spraying coarse aggregate with chilled water or blowing air, preferably chilled, over coarse and fine aggregates.

Krauss and Rogalla [23] provide some recommendations to control concrete temperature. These steps include: use low heat of hydration portland cement and pozzolans; specify bridge deck concrete

Table 4. 1. Empirical Relations Between T_c and T_a*

Eqn. No.	Relationship	Source/Comments
4.4	$T_c = 0.69T_a + 26.2°F$	Relationships estimated from ALDOT data set
4.4a	$T_c = T_a + 10°F (40° \leq T_a < 55°)$ $T_c = T_a + 5°F (55° \leq T_a < 85°)$ $T_c = T_a (85° \leq T_a \leq 95°)$	Alternate approximate relationships from ALDOT data set. See Fig. 4.4.
4.5	$T_c = 0.58\ T_a + 39°F$	Relationships estimated from first Blue Circle data set.
4.6	$T_c = 0.52\ T_a + 41.6°F$	Relationship estimated from second Blue Circle data set.
4.7	$T_c = T_a + 10°F$	Approximate relationship used by Nawy [27]
4.8	$T_c = T_a + 8°F$	Approximate relationship expressed by ALDOT Materials and Tests Bureau personnel.

*T_c = Concrete Temperature
T_a = Ambient Temperature

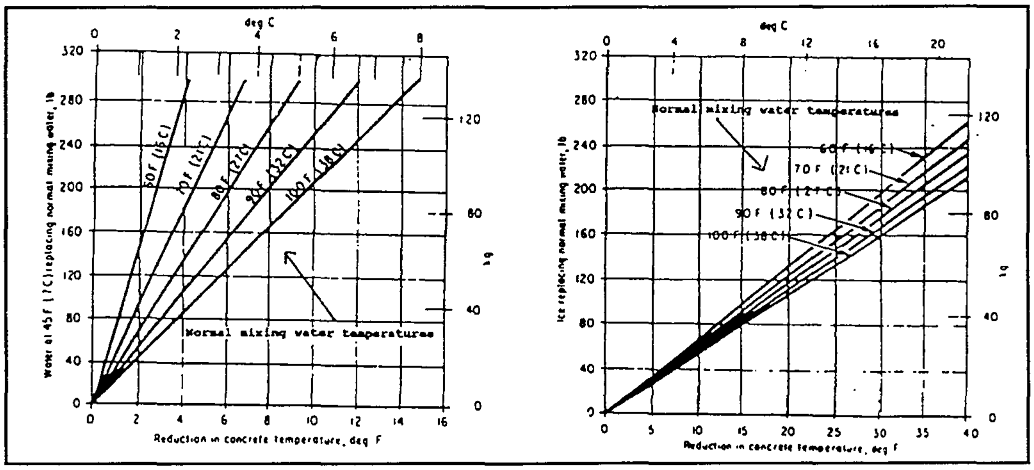


Fig. 4.9. Reducing Concrete Temperature for Hot Weather Concreting [7].

based upon 56- or 90-day compressive strengths to allow cementitious concrete systems with pozzolans to be used; avoid placement over 80°F ; use ice to cool mixing water; minimize solar radiation effects on bridge deck concrete when cooling; and avoid castings in the morning and early afternoon and use late afternoon or evening castings. When a bridge deck is placed between morning and late afternoon, warm air temperatures and solar radiation typically heat the concrete at setting, adding to the temperature increase of the concrete.

5. EVAPORATION RATE PARAMETER SENSITIVITY ANALYSIS

5.1 General

Plastic shrinkage cracking of concrete bridge decks occurs when the water evaporation rate (E_r) at the surface exceeds the bleeding rate of the freshly placed concrete. Also, the rate of drying shrinkage after the concrete hardens is related to water evaporation rate due to environmental conditions over a prolonged period of time (3-12 months). Thus, evaporation rate values are of great interest when placing bridge decks.

The mean ambient weather conditions of air temperature, relative humidity, and wind speed for Alabama presented in Chapter 3, along with concrete temperature prediction equations discussed in Chapter 4, and the ACI 305 Surface Evaporation Chart shown in Fig. 5. 1, allows the development of daily E_r curves for any time of the day, season of the year, or geographical location in Alabama. These curves were developed by the authors and are presented in this chapter. The daily E_r curves were synthesized into one "best estimate" E_r versus month of the year curve for Alabama. All of these curves can be used in conjunction with limiting values of evaporation rate as a construction QA/QC tool by bridge contractors and inspectors to help mitigate plastic shrinkage cracking and early drying shrinkage cracking.

5.2 Limiting Values of Evaporation Rate

In order to make use of predicted values of E_r for a bridge deck condition, limit values of E_r must be known or established. However, this rate, which must exceed the concrete bleeding rate for plastic cracking, is strongly dependent on the concrete ingredients and the mixture design. In general,

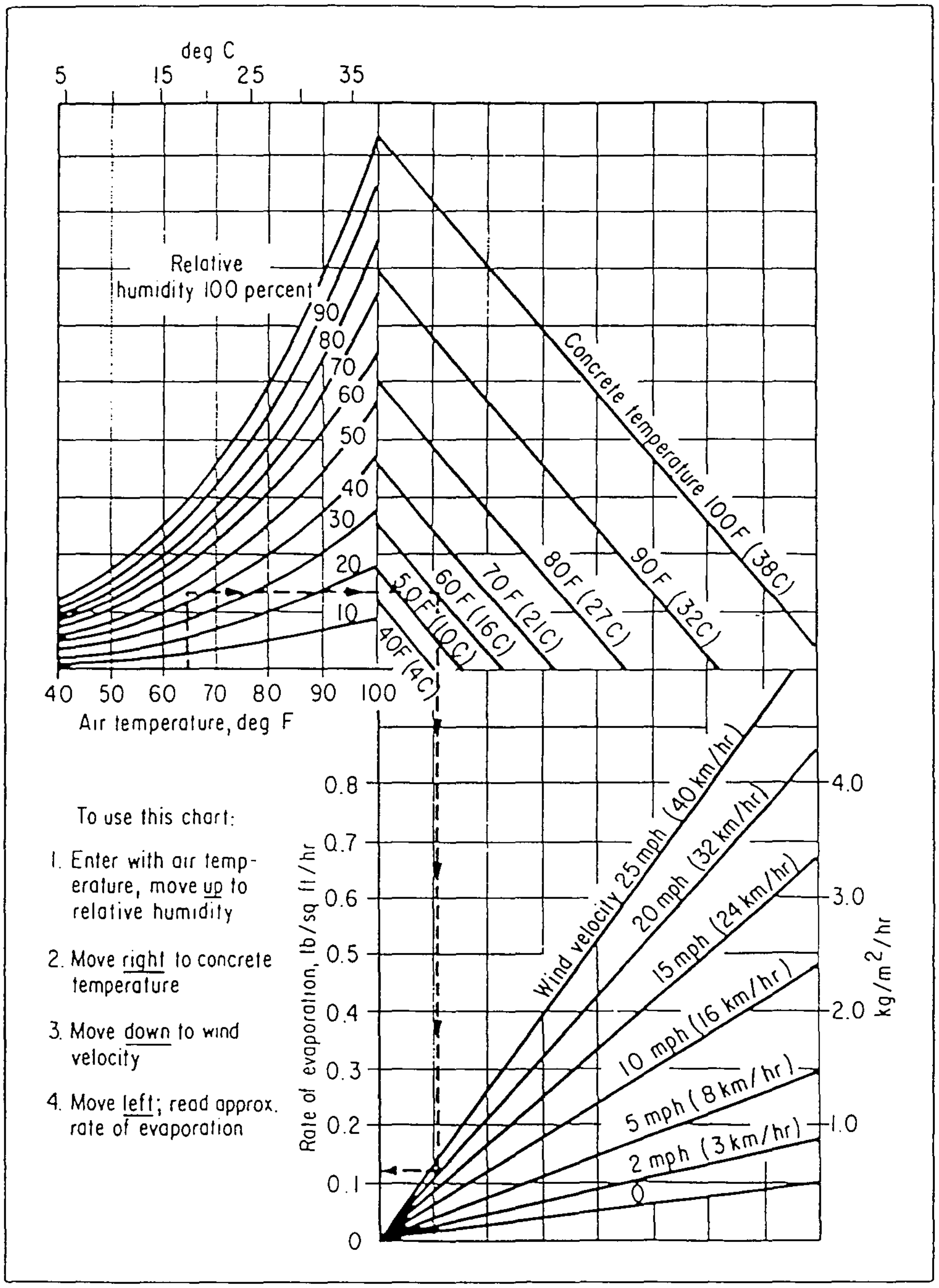


Fig. 5.1. ACI 305 Surface Evaporation Chart [7]

the higher the water content of the mixture, the higher the bleeding rate, and, thus, the higher the allowable evaporation rate. Also, as indicated earlier. when ambient conditions are such that E_r is large, the early (6 hrs-60 days) drying conditions are favorable for cracking and extra care in deck curing may be warranted.

Various agencies use maximum acceptable values of E_r from 0. 10 lb/ft^2 /hr to 0.25 lb/ft^2 /hr as indicated in Table 5. 1. It should be noted that the value of 0. 10 lb/ft^2 /hr used by the Ohio Turnpike Commission is for bridge decks made of shrinkage-compensating concrete (SCC) which is a very cohesive concrete which exhibits a low bleeding rate. The high value of E_r of 0.25 lb/ft^2 /hr in Table 5.1 recommended by the Portland Cement Association (PCA) is for a typical concrete mixture with an assumed generous water content. The ALDOT deck concrete has a maximum w/c = 0.44 and could probably tolerate an E_r = 0.20 lb/ft^2 /hr. However, to allow for adverse changes in ambient conditions and less than desirable early curing application habits of contractors, a limiting value of 0. 15 lb/ft^2 /hr is recommended for bridge deck placement in Alabama. This is shown in Table 5.1 as are the limitations on concrete and ambient temperature at the time of concrete placement. Note that the comment column in Table 5.1 provides measures to be taken to reduce E_r when it exceeds the limiting value.

5.3 Evaporation Rate Parameter Sensitivity

Lerch [25] performed a parameter sensitivity analysis via use of the ACI 305 Surface Evaporation Chart to determine the sensitivity of evaporation rate to the various weather parameters. The results of his analysis are presented in Table 5.2 which contains eight groups of parameter variations, with each group showing how evaporation rate changes with change of one parameter. Group 1 displays the effects of wind velocity. With air temperature and concrete temperature at 70°F and relative humidity at 70%, the wind is increased by 5 mph increments. E_r, increases linearly with each incremental increase of wind velocity. In Group 2, concrete and air temperature are held again at

Table 5.1. Some Temperature and Evaporation Rate Limitations for Bridge Deck Concrete

Agency	Limitations at Placement			Comments
	Temperature of Concrete (T_c) (°F)	Ambient Temperature (T_a) (°F)	Evaporation Rate (E_r) ($lb/ft^2/hr$)	
ALDOT	$50^\circ \le T_c \le 90^\circ$	$35^\circ \le T_a \le$ none given	none given	Current Specs
ALDOT/AU QA/QC Project Recommendations	$50^\circ \le T_c \le 90^\circ$	$40^\circ \le T_a \le 90^\circ$	$E_r \le 0.10$	If $E_r > 0.10$ reduce E_r by • Windbreakers • Fog Spray to increase RH • Ice to reduce T_c • Ponding of water
PCA	$55^\circ \le T_c \le (75^\circ\text{-}100^\circ)$	none given	0.25	
ACI	$55^\circ \le T_c \le (75^\circ\text{-}100^\circ)$*	none given	0.20	Recommendations of ACI Committee 305.
OTC	$60^\circ \le T_c \le 90^\circ$	$45^\circ \le T_a \le 80^\circ$	0.10	For SCC decks
NYTA**	$- \le T_c \le 90^\circ$	$- \le T_a \le 80^\circ$	none given	For SCC decks
Ohio DOT**	-	$- \le T_a \le 80^\circ$	0.20	For SCC decks
FLDOT	none given $\le T_c \le 85^\circ$ $85^\circ < T_c < 100^\circ$	$40^\circ \le T_a \le$ none given	none given	Current Specs Allowed under special conditions
This Thesis Recommendations	$50^\circ \le T_c \le 90^\circ$	$40^\circ \le T_a \le 90^\circ$	$E_r \le 0.15$	If $E_r > 0.15$ reduce E_r by • Early application of evaporation reducer • Wind breakers • Fog spray to increase RH • Add ice to reduce T_c • Ponding of water

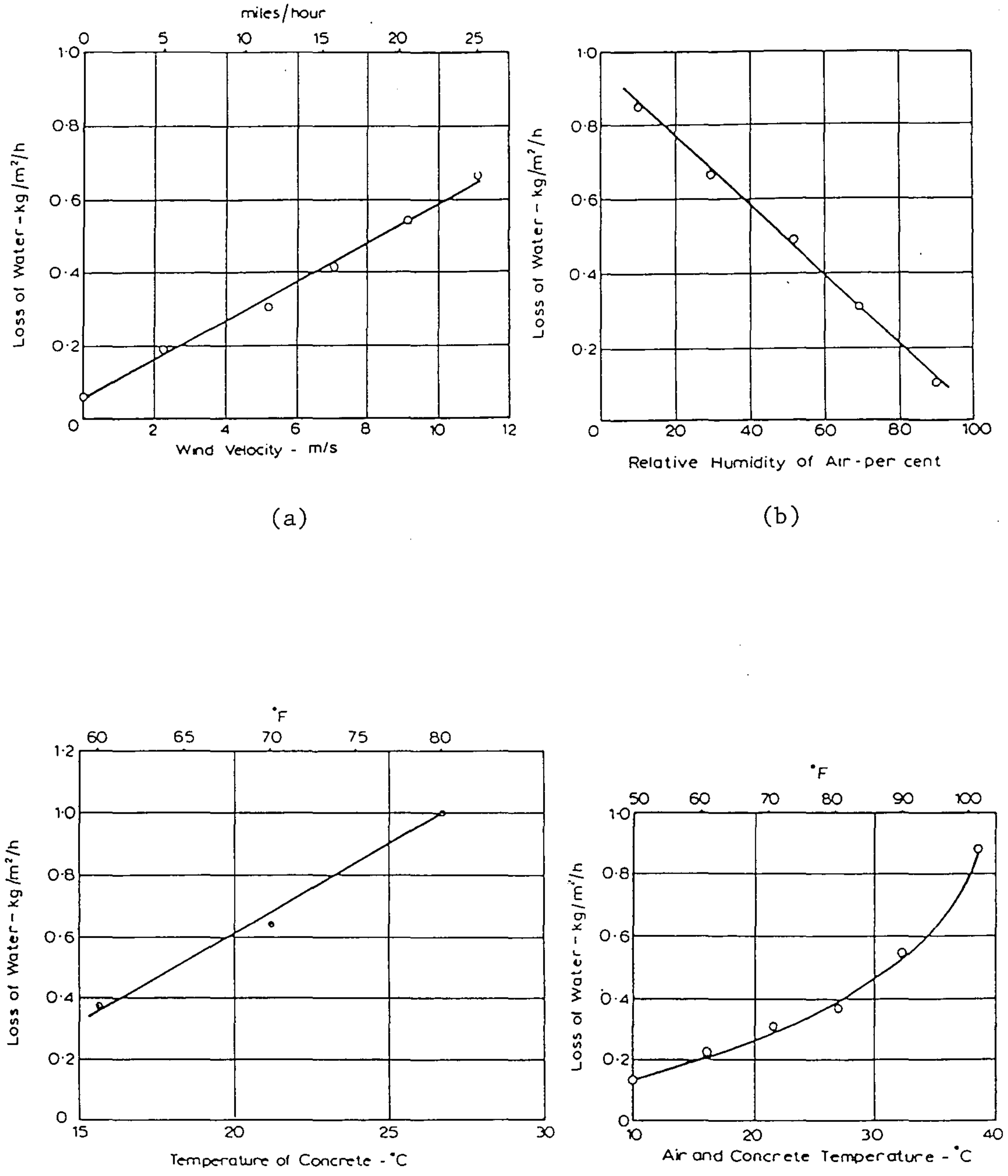
*ACI recommends $T_{cMAX} = 90^\circ$F for SCC.
**Have stopped using SCC decks.

Table 5.2 Effect of Variations in Evaporation Rate Parameters [25]

Group	Concrete Temperature (°F)	Air Temperature (°F)	Relative Humidity (%)	Wind Velocity (mph)	E_r (lb/ft^2/hr)
Group 1 - Increase in Wind Velocity	70	70	70	0	0.015
	70	70	70	5	0.038
	70	70	70	10	0.062
	70	70	70	15	0.085
	70	70	70	20	0.110
	70	70	70	25	0.135
Group 2 - Decrease in Relative Humidity	70	70	90	10	0.02
	70	70	70	10	0.062
	70	70	50	10	0.100
	70	70	30	10	0.135
	70	70	10	10	0.175
Group 3 - Increase in Concrete and Air Temperatures	50	50	70	10	0.026
	60	60	70	10	0.043
	70	70	70	10	0.062
	80	80	70	10	0.077
	90	90	70	10	0.110
	100	100	70	10	0.180
Group 4 - Concrete at 70°F: Decrease in Air Temperature	70	80	70	10	0.000
	70	70	70	10	0.062
	70	50	70	10	0.125
	70	30	70	10	0.165
Group 5 - Concrete at High Temperature: Air at 40°F: 100% Relative Humidity	80	40	100	10	0.205
	70	40	100	10	0.130
	60	40	100	10	0.075
Group 6 - Concrete at High Temperature: Air at 40°F: Variable Wind	70	40	50	0	0.035
	70	40	50	10	0.162
	70	40	50	25	0.357
Group 7 - Decrease in Concrete Temperature: Air at 70°F	80	70	50	10	0.175
	70	70	50	10	0.100
	60	70	50	10	0.045
Group 8 - Concrete and Air at High Temperature: Relative Humidity at 10%: Variable Wind	90	90	10	0	0.070
	90	90	10	10	0.336
	90	90	10	25	0.740

70°F, wind velocity held constant at 10 mph, and relative humidity is incrementally decreased by 20%. As humidity drops, evaporation rate increases and it appears that a 20% decrease in relative humidity enhances evaporative conditions more than a 5 mph increase in wind velocity. Concrete and air temperature are increased in Group 3 by increments of 10°F with relative humidity at 70% and wind velocity at 10 mph. The effect of the increase in concrete and air temperature appears to be less significant as decrease in humidity or increase in wind speed as long as the temperature is below 80°F. Above 80°F, the increase of 10°F results in a large increase in evaporation rate. Group 4 illustrates the detrimental effects of allowing concrete temperature to increase over ambient air temperature. A differential of 20°F in air temperature and concrete temperature can double the evaporation rate. Group 5 shows how large differential in concrete and air temperature in cold weather can create evaporative conditions even at 100% humidity. In northern climates due to the frequency of cold temperatures and construction schedules, concrete must often be placed in cold weather and the concrete is heated. This would most likely not be a concern in a warm climate such as Alabama's but is important to consider. For Group 6, concrete temperature is 70°F, air temperature is 40°F, relative humidity held at 50%, and wind is varied. With a large concrete-air temperature differential at the low air temperature, excessive winds result in excessive evaporation rate. The beneficial effect of reducing concrete temperature is shown in Group 7. Finally, Group 8 combines high air and concrete temperature, 90°F, extremely low relative humidity, 10%, and variable wind. Any significant winds, i.e., wind speeds greater than 10 mph, produce E_r well above the 0.20 lb/ft^2 /hr limit set forth by ACI 305.

Neville [28] plotted some of the results of Table 5.2 to provide graphical displays of the parameter sensitivities. These are shown in Fig. 5.2 and reflect approximate linear relationships within the bounds of typical and/or acceptable parameter values. Fig. 5.2 also reflects a great sensitivity of E_r to all of the parameters shown.



(a)

(b)

(c)

(d)

Fig. 5.2. Sensitivity to E_s to Temperature and Weather Conditions [28].

Table 5.3. Evaporation Rate Parameter Sensitivity in Hot Weather.

Air Temperature (°F)	**Concrete Temp. (°F)**	**Relative Humidity (%)**	**Wind Speed (mph)**	**E_r (lb/ft^2/hr)**
90	90	60	10	0.15
90	95	60	10	0.20
90	100	60	10	0.28
95	100	60	10	0.24
90	95	50	10	0.25
90	95	50	15	0.35
90	95	50	20	0.44

An important condition not addressed by Table 5.2 and Fig. 5.2 is concrete-air temperature differential at high air temperature. During the hot months of late spring and summer, temperatures above 90 °F are very common throughout Alabama. Table 5.3 contains evaporation rates for hot weather conditions which could be expected for locations in Alabama. A relative humidity of 60% reflects a typical value of relative humidity at peak temperature conditions for a summer day. At 90°F with no temperature differential and a 10 mph wind, the evaporation rate is 0. 15 lb/ft^2 /hr. If the concrete temperature reaches 95 °F at the same conditions, the evaporation rate increases to 0.2 lb/ft^2 /hr. Concrete which reaches 100 °F will cause an extremely high evaporation rate of 0.28 lb/ft^2/hr. With air temperature at 95 °F and concrete temperature at 100 °F, the evaporation rate is a critical 0.24 lb/ft^2 /hr. The remaining data display the effects of decreased relative humidity and higher wind speed. With high air temperature and 5 °F higher concrete temperature, the combined effects of reduced relative humidity and increased wind speed produce extremely high evaporation rates.

Observation of Tables 5.2 and 5.3 and Fig. 5.2 demonstrate the importance of controlling concrete temperature. The data of Table 5.3 supports the fact that it is imperative to keep concrete temperatures low in extreme hot weather conditions. The 5-10 °F temperature differentials given in Table 5.3 could be expected as the concrete was delivered. After placement in forms on a hot sunny day, heat of hydration and solar radiation could cause the concrete temperature to increase further, therefore, increasing evaporation rate while the concrete is still plastic. On hot days (temperature greater than 90 °F), it would be advisable to use one or more of the methods described in Chapter 4 to reduce concrete temperature which would in turn reduce evaporation rate and, hence, the possibility of plastic shrinkage cracking.

5.4 Monthly Evaporation Rate Curves for Alabama

A first step toward developing geographical and seasonal "planning" evaporation rate curves for Alabama was to plot daily evaporation rate cycles for the four major cities for each month of the year. Thus, E_r curves were developed using temperature and relative humidity from the mean weather curves of Appendix A, and concrete temperature was calculated from Eqn. 4.4. At every six hours and the peak hour of the day, relative humidity and temperature were read from the mean weather curves. Using these readings and the calculated concrete temperature, daily E_r curves were developed from use of the ACI 305 Surface Evaporation Chart for every 5 mph increment of wind speed from 0-20 mph. These curves were developed for each month of the year for each major city, and are shown in Figs. 5.3-5.6.

From observation of the daily E_r curves of Figs. 5.3-5.6, the nature of variation of evaporation rate over the course of a day is evident. No matter which month or city, the evaporation rate is lowest around 6 a.m. and/or 12 a.m. (midnight) and peaks in early to mid-afternoon. The magnitudes of the curves increase with increase in wind speed, and for a higher wind speed, the change in evaporation rate from morning to afternoon is greater. It appears that in order to expose fresh or green hardened concrete to the lowest amount of evaporation, placement of bridge deck concrete should occur after 6 p.m. In doing so, the fresh concrete would experience low and decreasing evaporation rate, and the concrete would not be exposed to higher evaporation rates until it was over 12 hours old and had probably gained adequate strength to resist early cracking with proper curing in place.

5.5 "Planning" Evaporation Rate Curves for Alabama

The daily E_r curves for each month of the year and the four locations in Alabama were analyzed in an effort to develop appropriate "planning" E_r curves for Alabama. Appropriate "planning" curves would allow bridge construction planners, i.e., State DOT managers, construction inspectors, and contractors, to estimate evaporation rate for any time of day, time of year, and location in Alabama. This, in turn, would allow them to finalize their deck placement and curing plans. It should be understood that the use of these curves is for planning only. On the day of deck placement, the actual E_r value(s) should be determined, and the appropriate procedures for deck placement and curing followed.

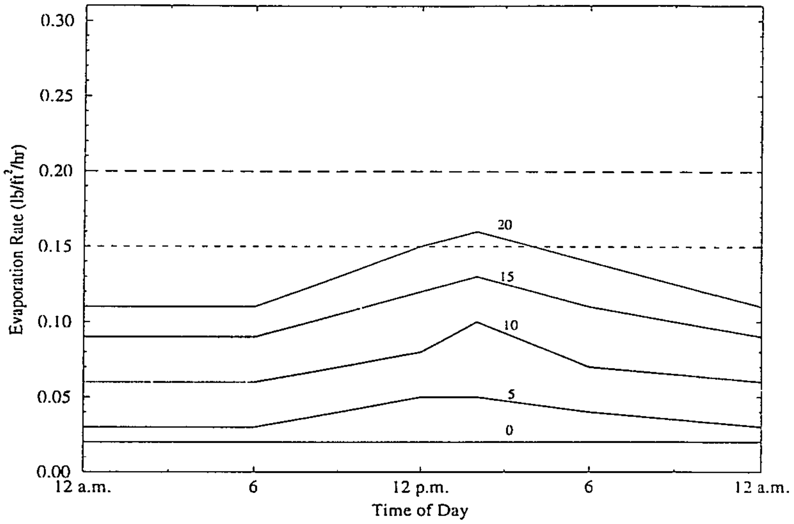


Fig. 5.3a. Daily E_r Curve for January - Mobile

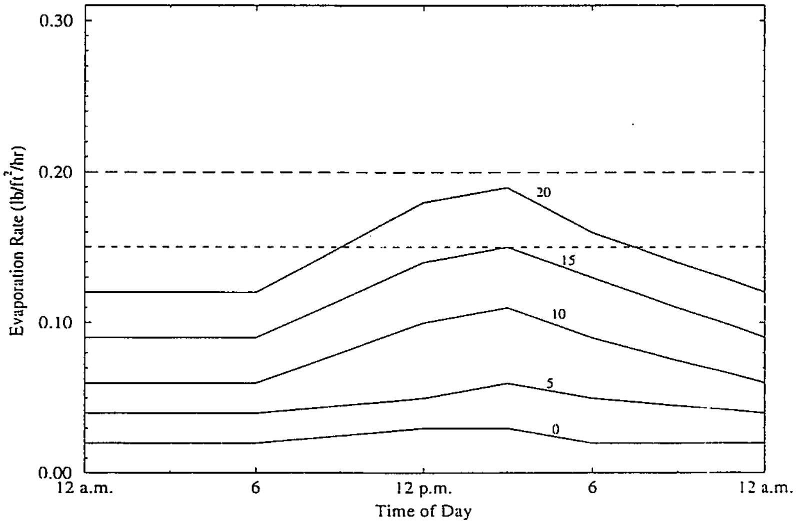


Fig. 5.3b. Daily E_r Curve for February - Mobile

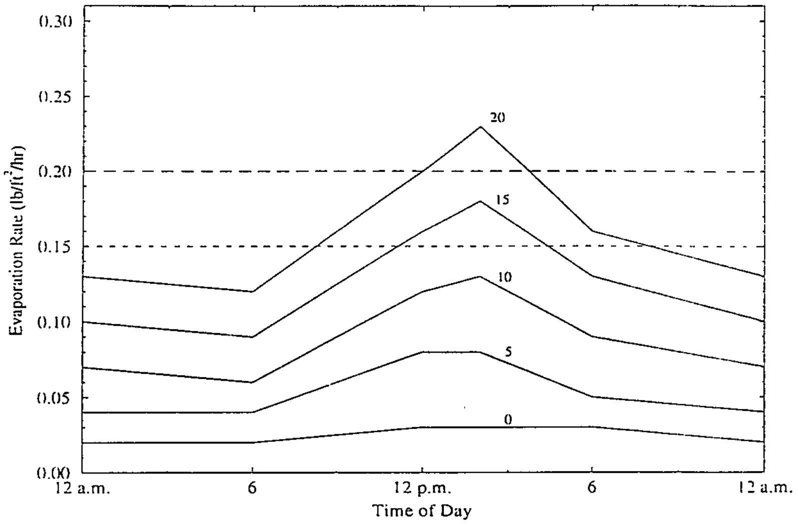


Fig. 5.3c. Daily E_r Curve for March - Mobile

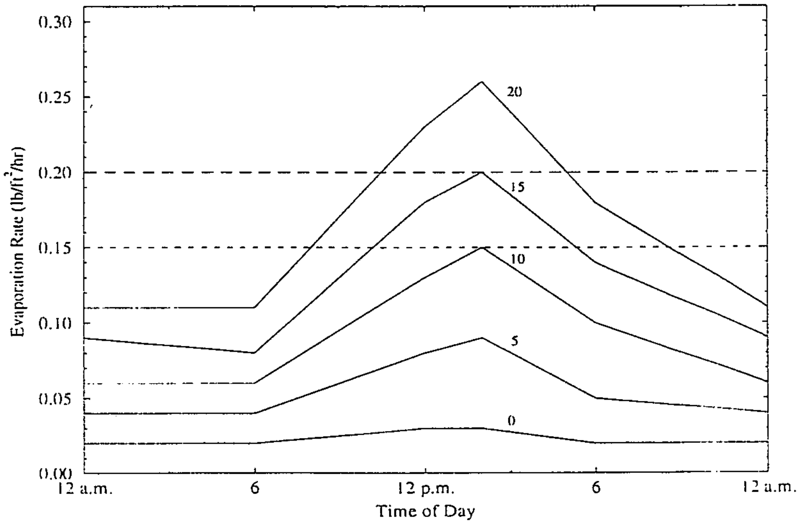


Fig. 5.3d. Daily E_r Curve for April - Mobile

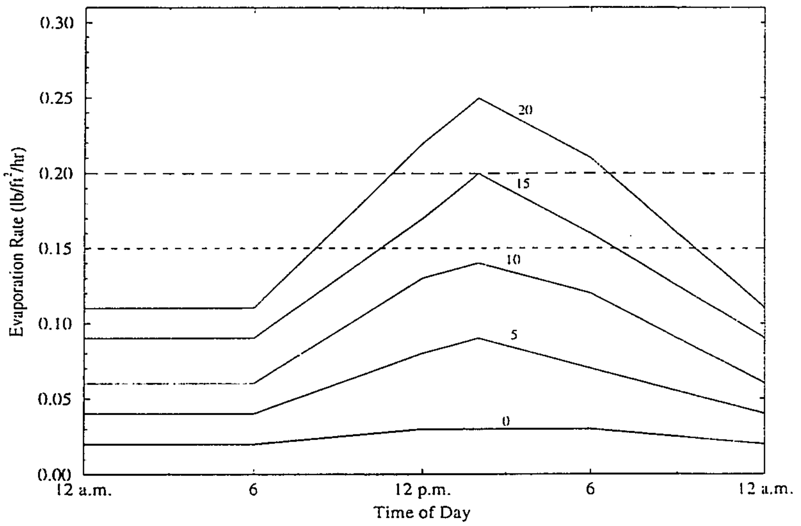


Fig. 5.3e. Daily E_r Curve for May - Mobile

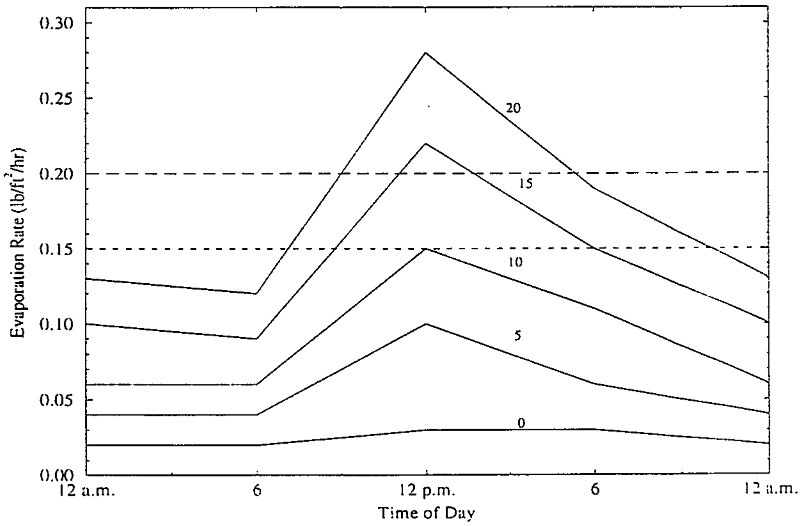


Fig. 5.3f. Daily E_r Curve for June - Mobile

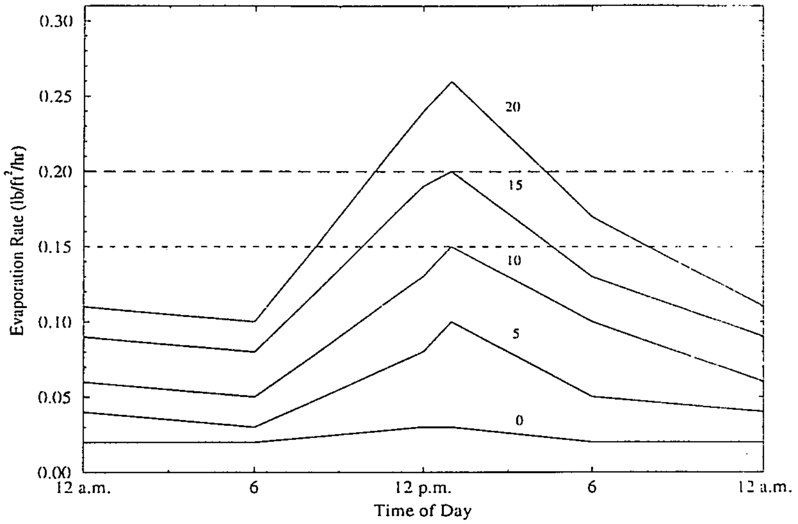


Fig. 5.3g. Daily E_r Curve for July - Mobile

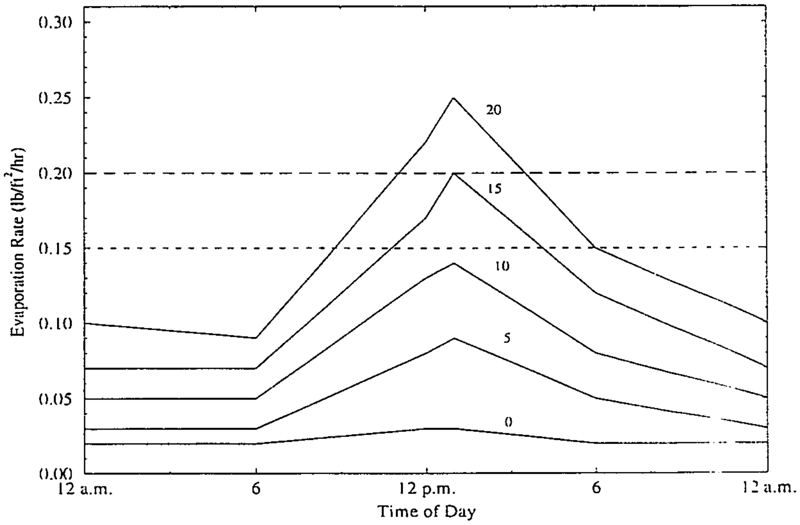


Fig. 5.3h. Daily E_r Curve for August - Mobile

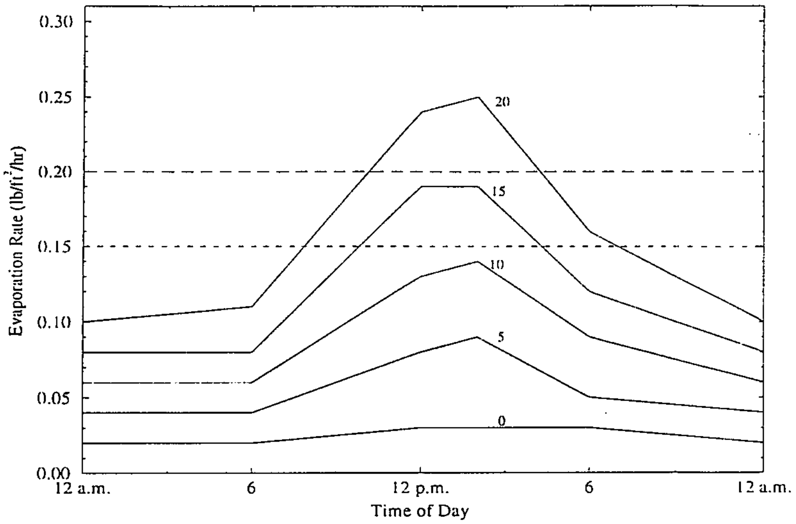


Fig. 5.3i. Daily E_r Curve for September - Mobile

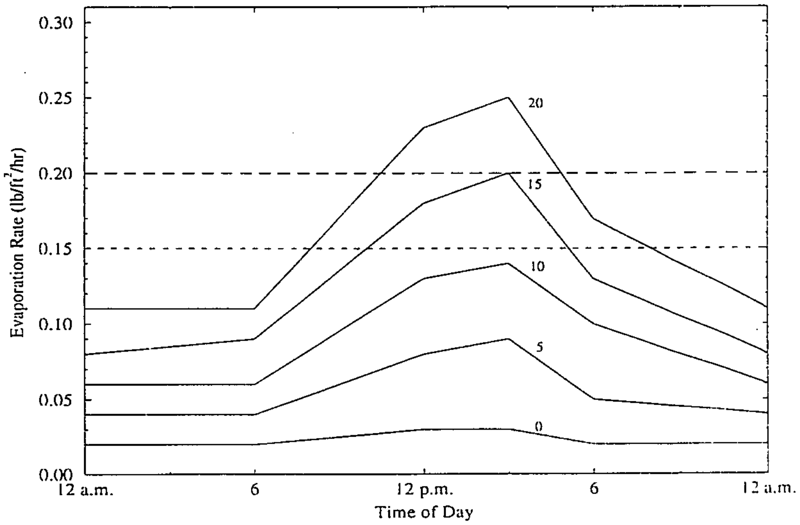


Fig. 5.3j. Daily E_r Curve for October - Mobile

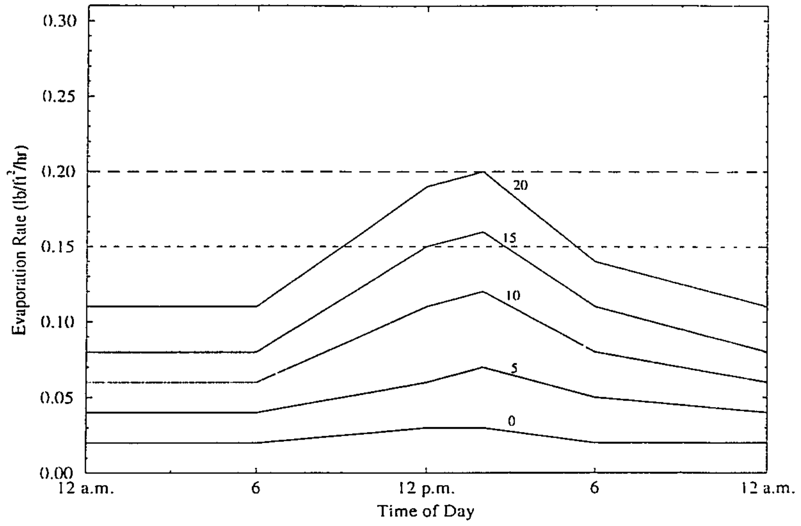


Fig. 5.3k. Daily E_r Curve for November - Mobile

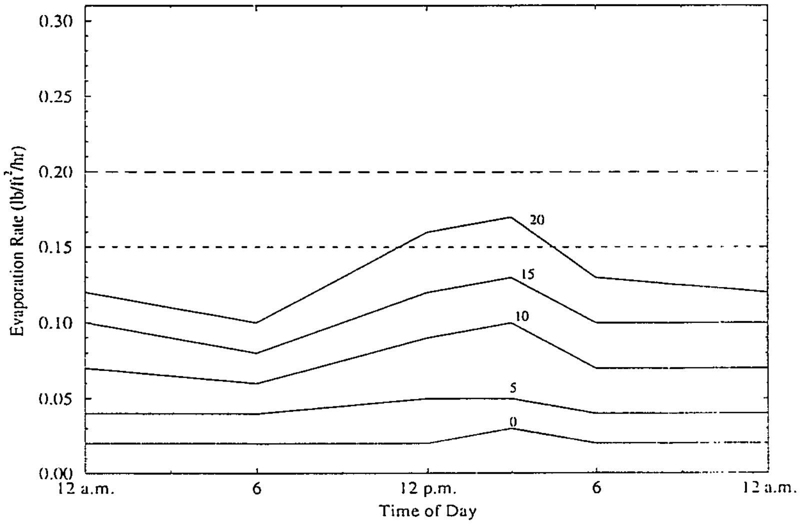


Fig. 5.3l. Daily E_r Curve for December - Mobile

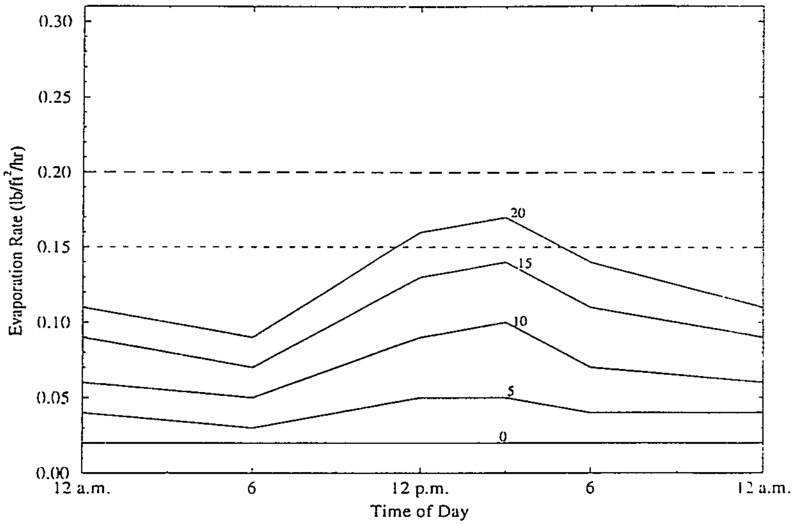


Fig. 5.4a. Daily E_r Curve for January - Montgomery

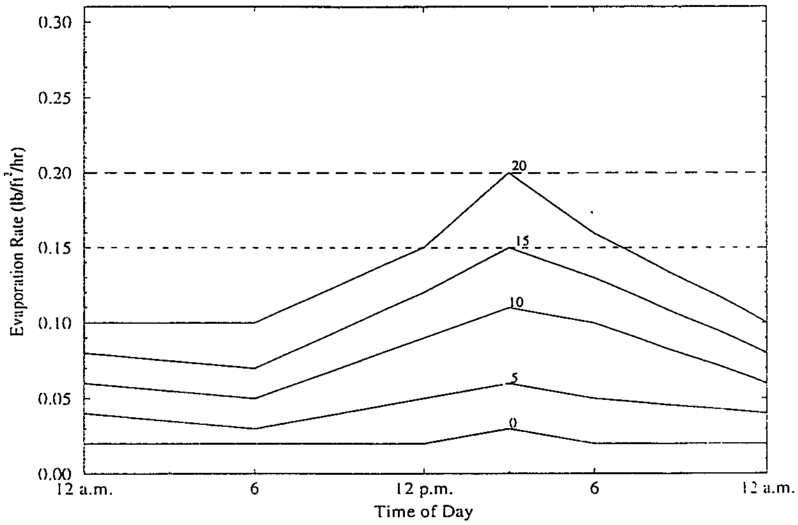


Fig. 5.4b. Daily E_r Curve for February - Montgomery

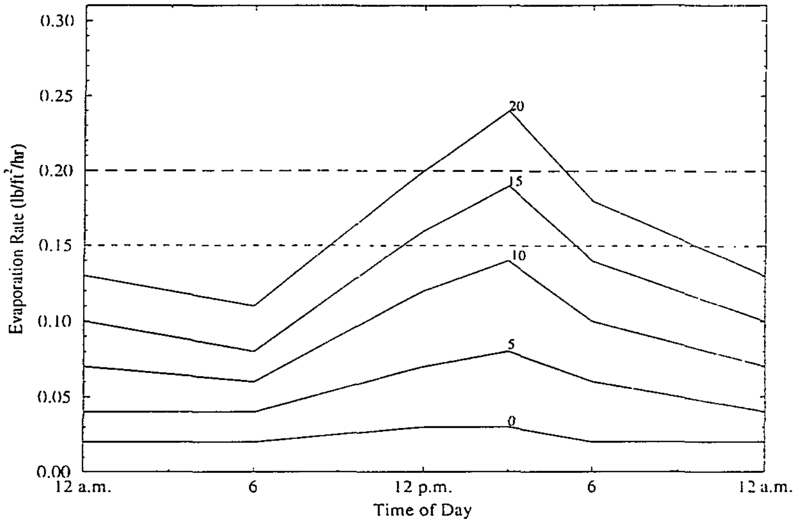


Fig 5.4c. Daily E_r Curve for March - Montgomery

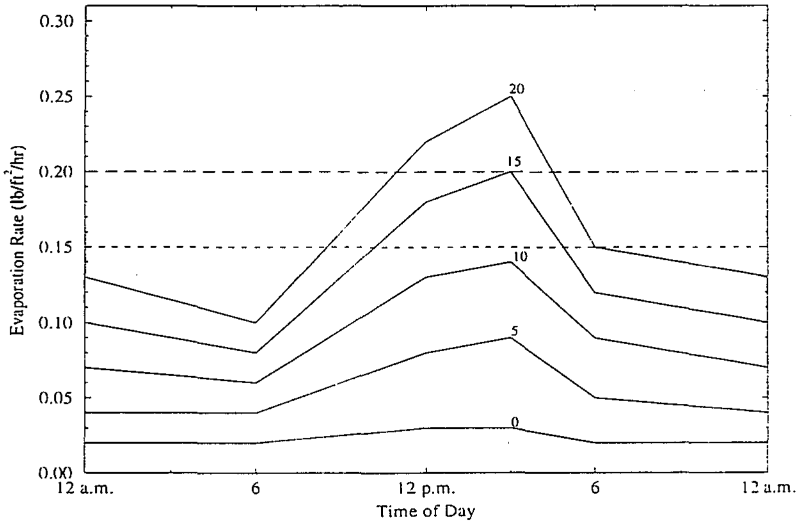


Fig. 5.4d. Daily E_r Curve for April - Montgomery

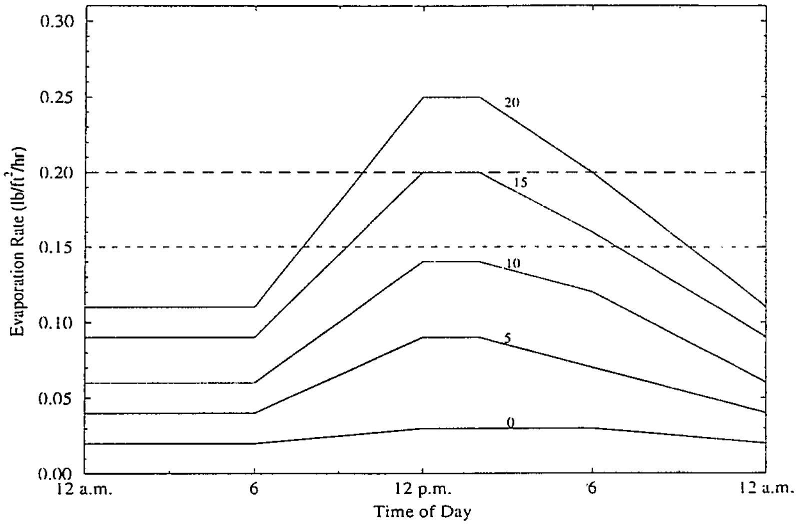


Fig. 5.4e. Daily E_r Curve for May - Montgomery

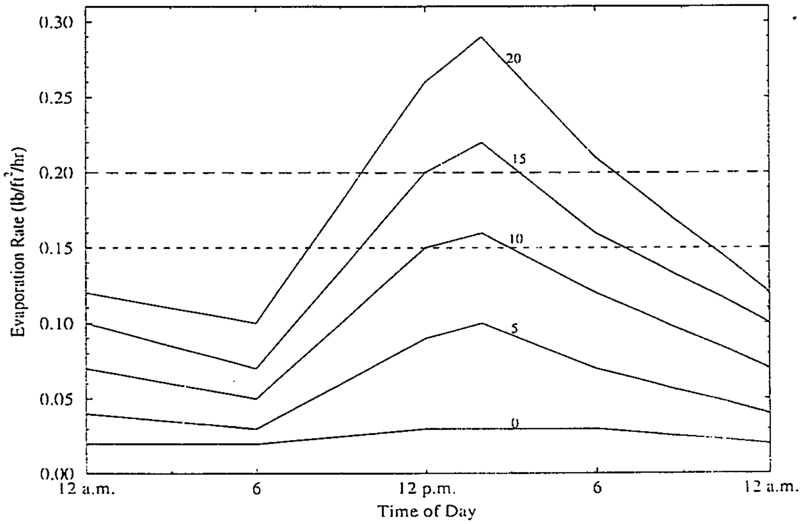


Fig. 5.4f. Daily E_r Curve for June - Montgomery

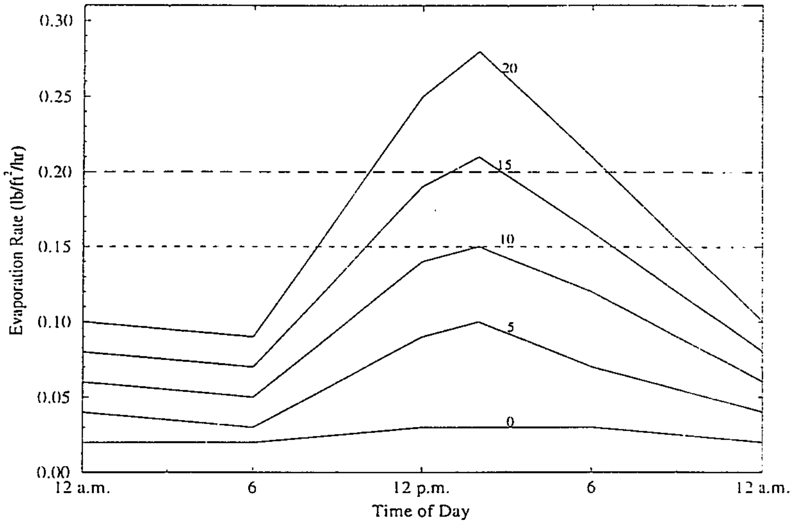


Fig. 5.4g. Daily E_r Curve for July - Montgomery

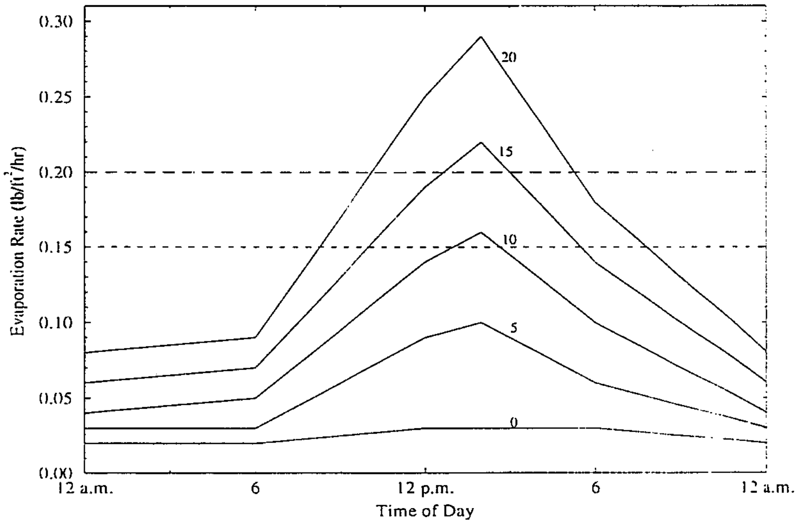


Fig. 5.4h. Daily E_r Curve for August - Montgomery

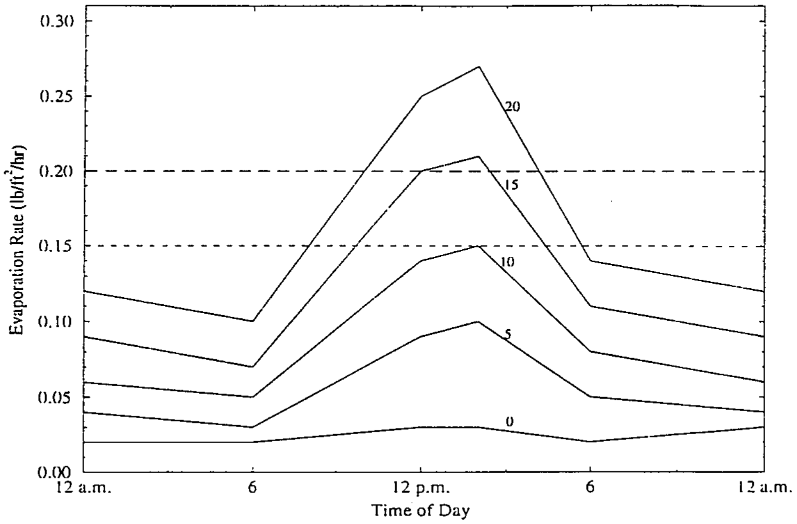


Fig. 5.4i. Daily E_r Curve for September - Montgomery

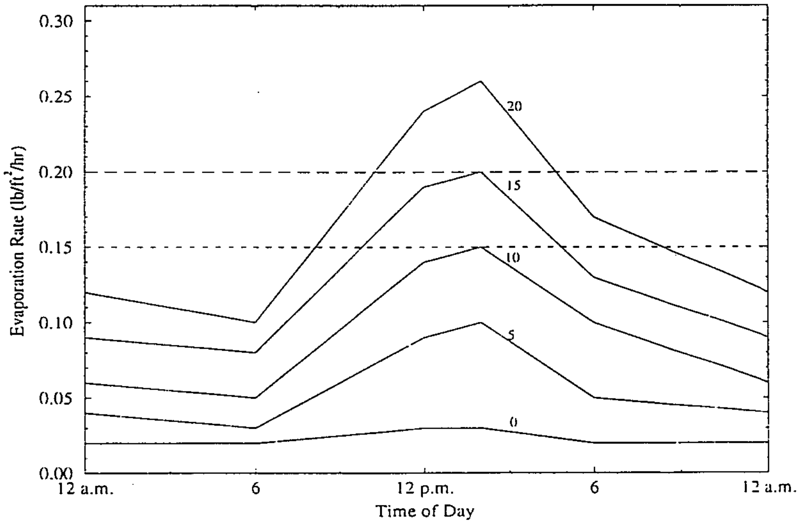


Fig. 5.4j. Daily E_r Curve for October - Montgomery

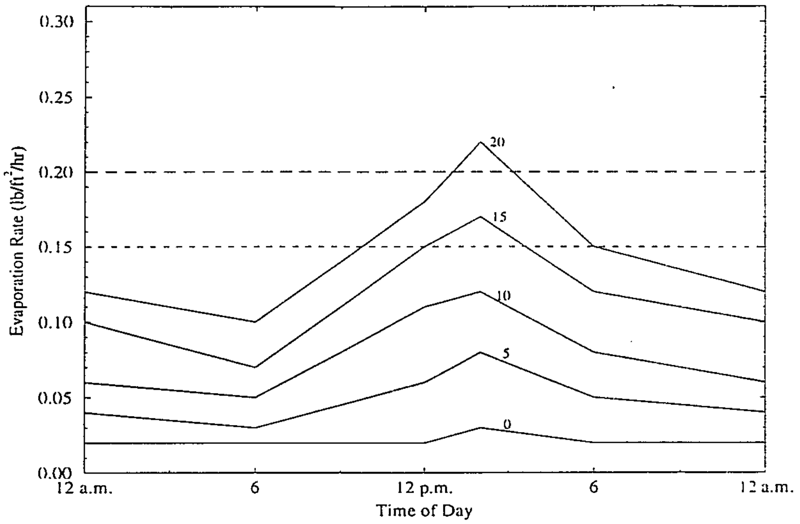


Fig. 5.4k. Daily E_r Curve for November - Montgomery

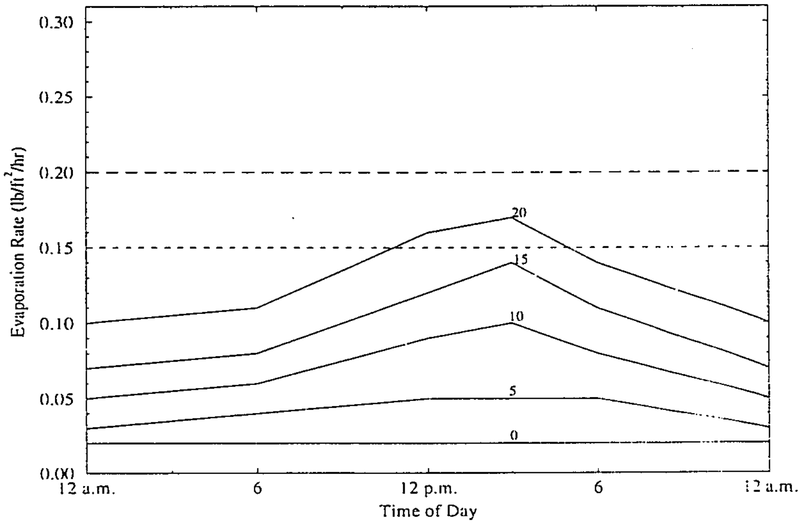


Fig. 5.4l. Daily E_r Curve for December - Montgomery

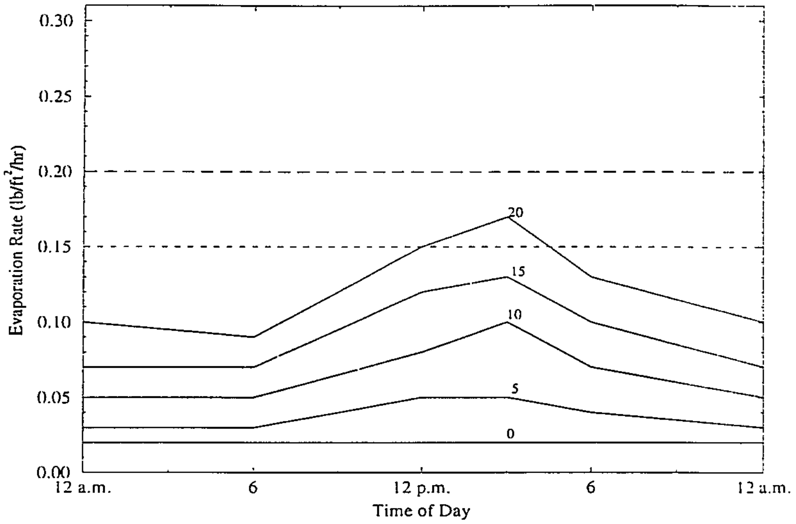


Fig. 5.5a. Daily E_r Curve for January - Birmingham

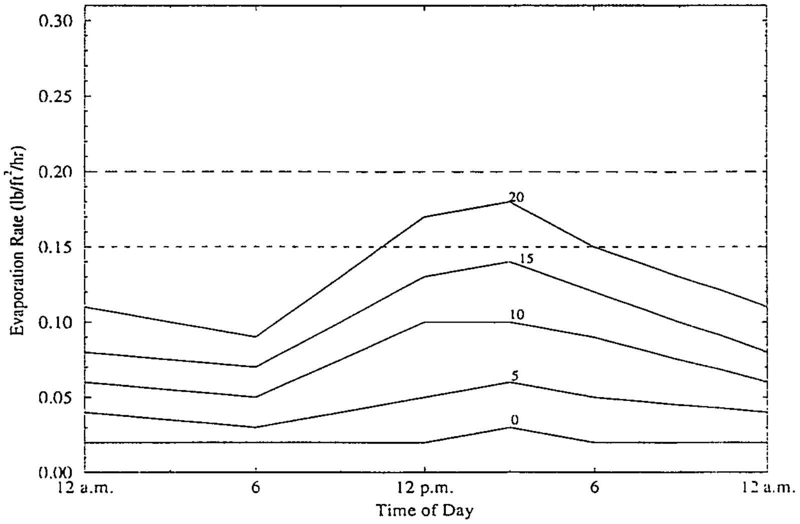


Fig 5.5b. Daily E_r Curve for February - Birmingham

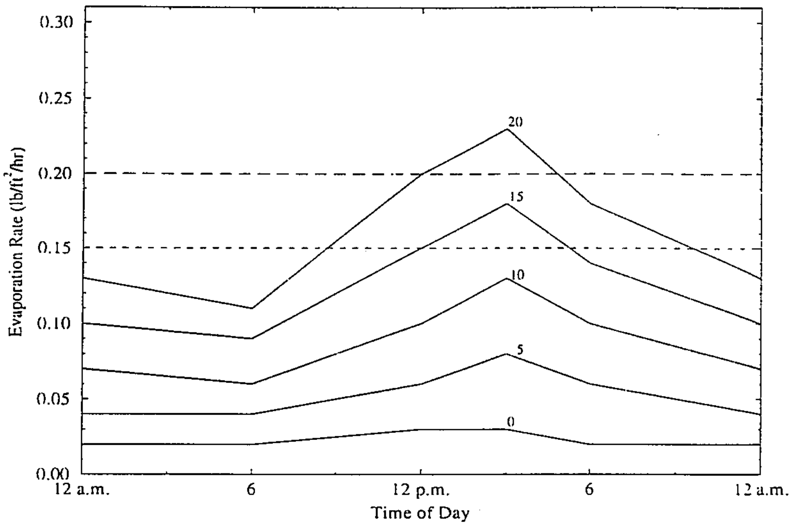


Fig. 5.5c. Daily E_r Curve for March - Birmingham

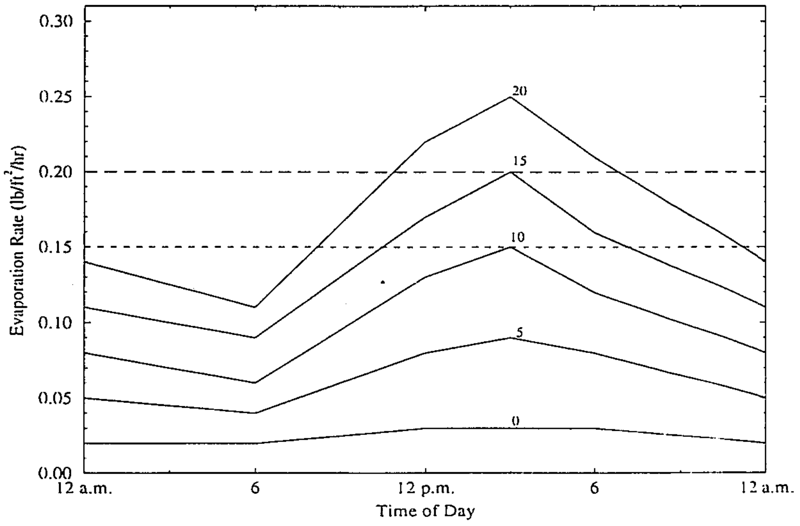


Fig. 5.5d. Daily E_r Curve for April - Birmingham

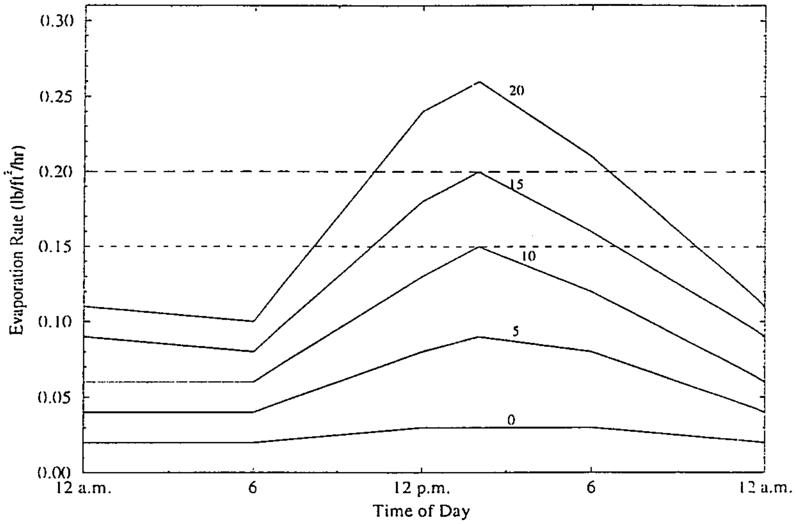


Fig. 5.5e. Daily E_r Curve for May - Birmingham

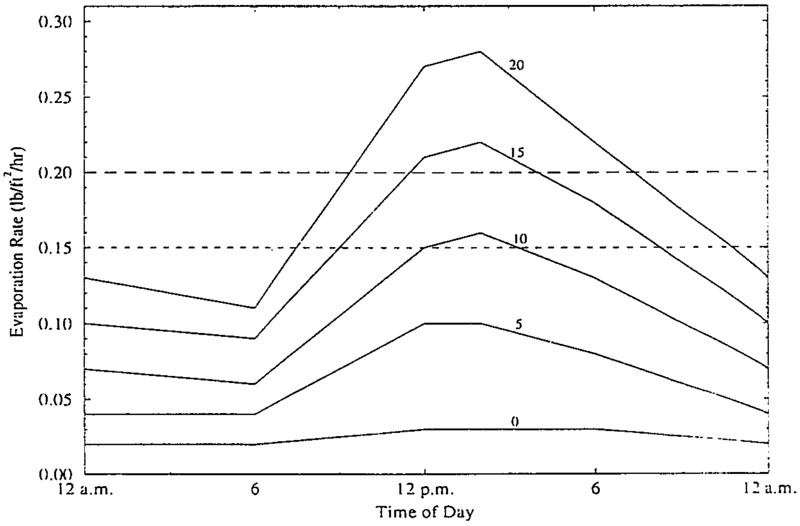


Fig. 5.5f. Daily E_r Curve for June - Birmingham

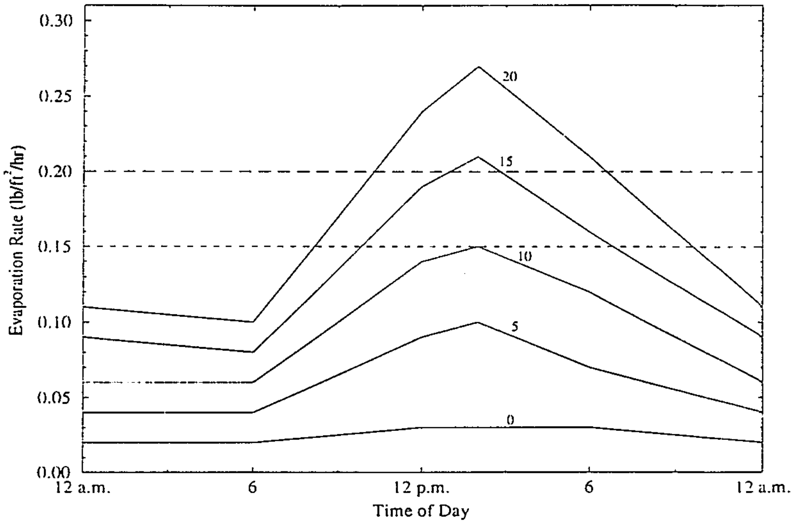


Fig. 5.5g. Daily E_r Curve for July - Birmingham

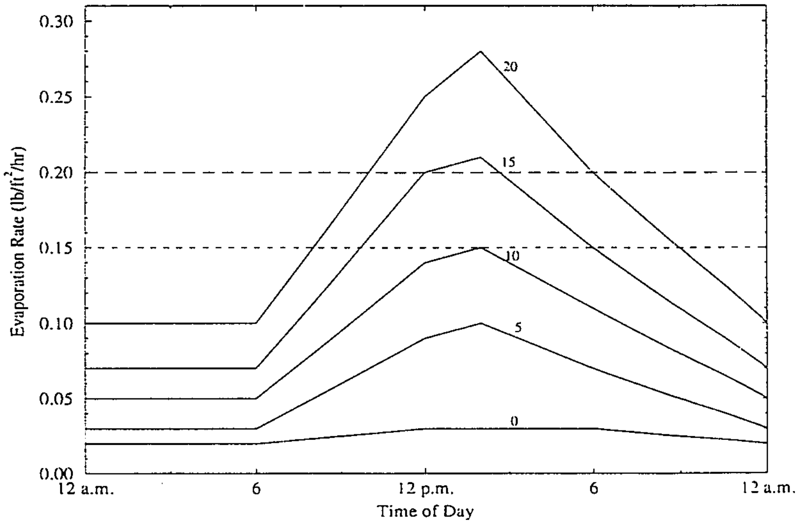


Fig. 5.5h. Daily E_r Curve for August - Birmingham

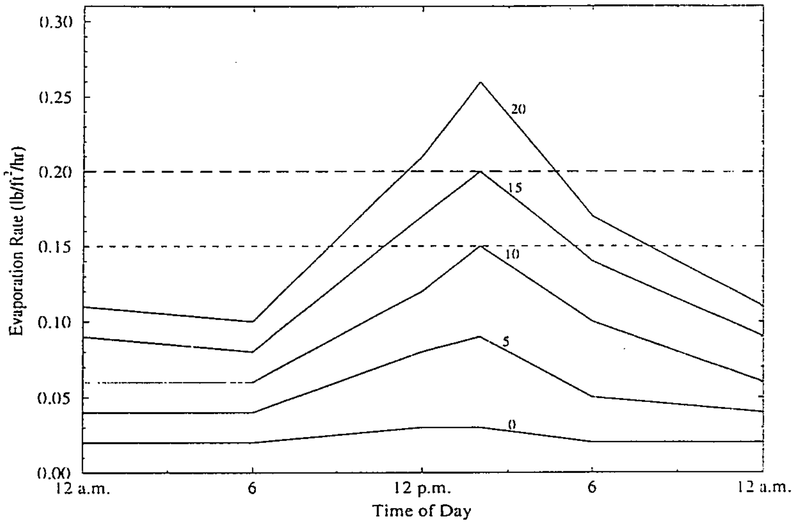


Fig. 5.5i. Daily E_r Curve for September - Birmingham

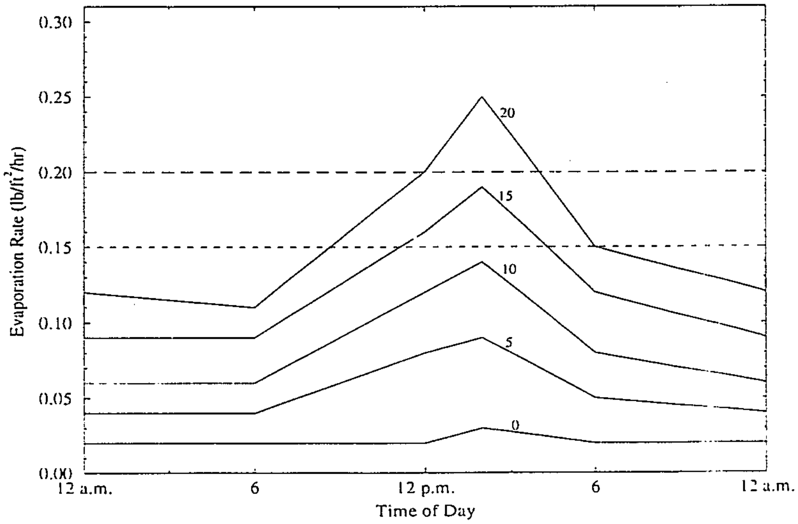


Fig. 5.5j. Daily E_r Curve for October - Birmingham

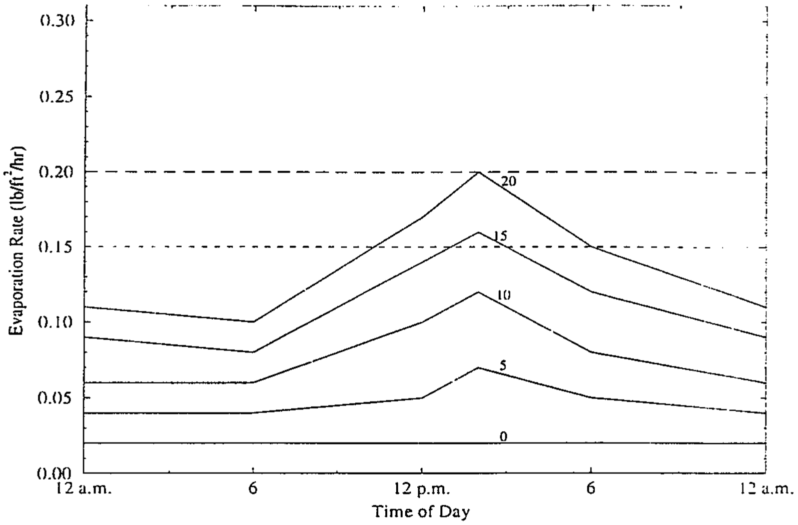


Fig. 5.5k. Daily E_r Curve for November - Birmingham

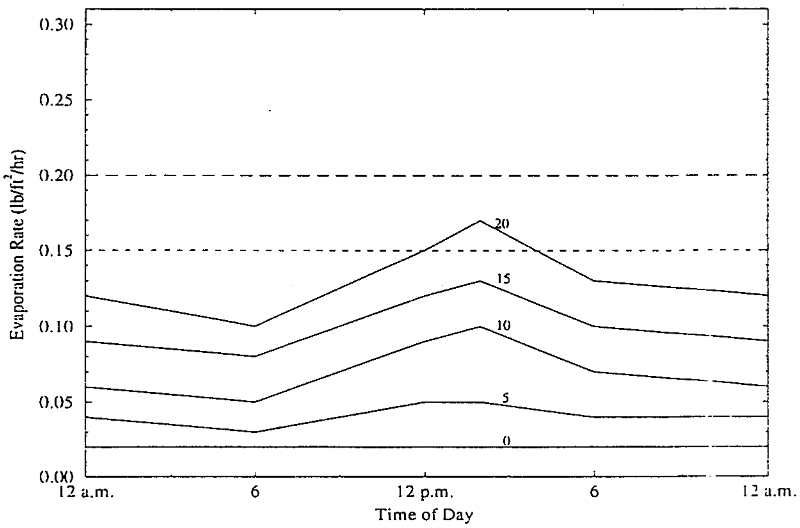


Fig 5.5l. Daily E_r Curve for December - Birmingham

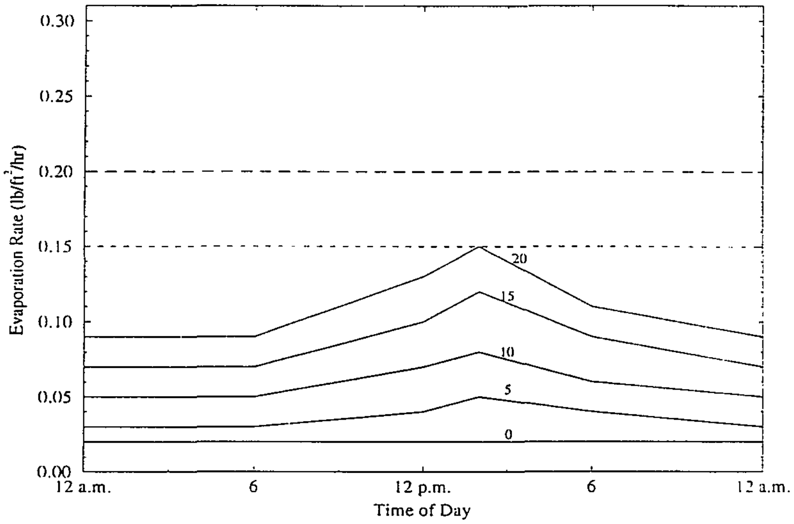


Fig. 5.6a. Daily E_r Curve for January - Huntsville

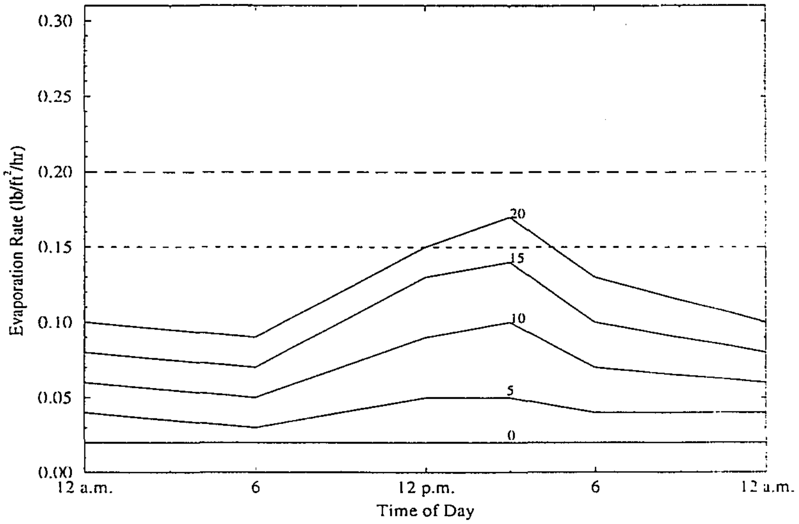


Fig. 5.6b. Daily E_r Curve for February - Huntsville

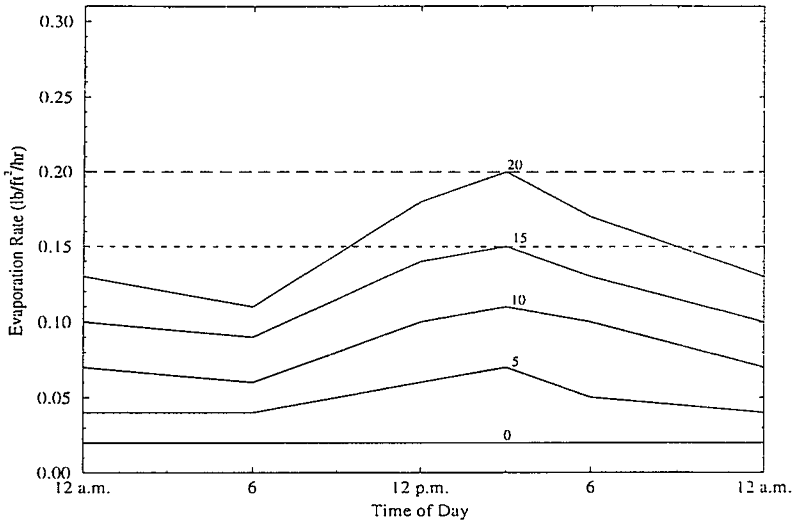


Fig. 5.6c. Daily E_r Curve for March - Huntsville

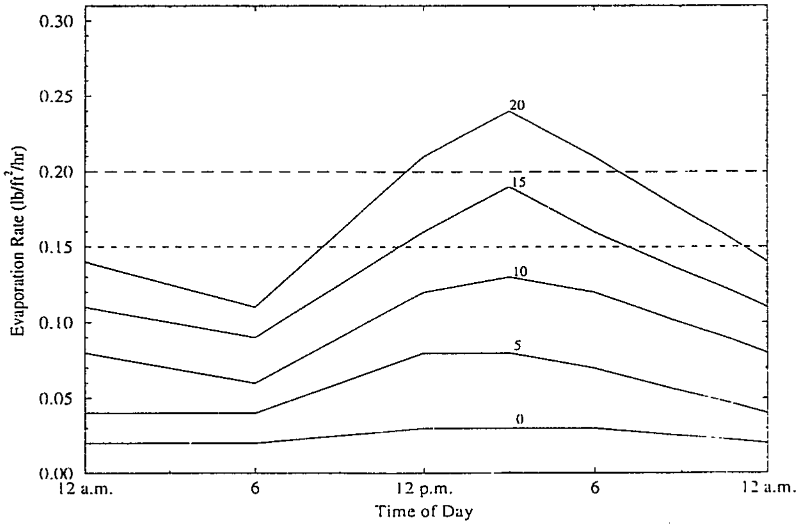


Fig. 5.6d. Daily E_r Curve for April - Huntsville

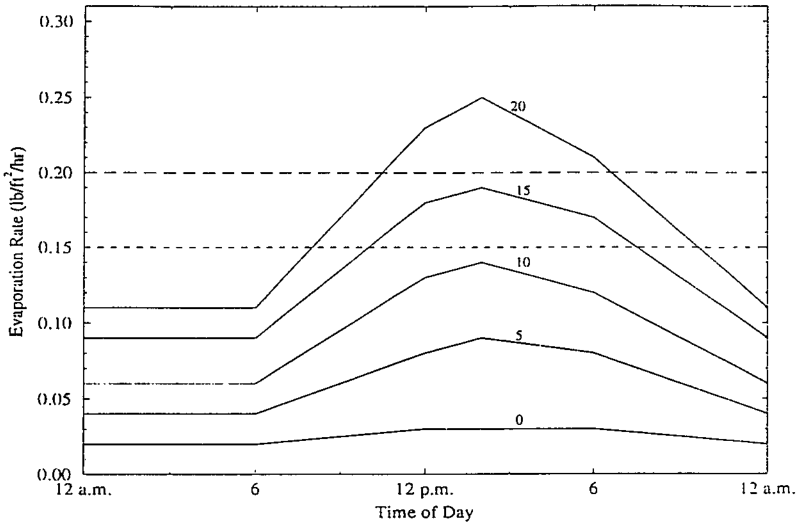


Fig. 5.6e. Daily E_r Curve for May - Huntsville

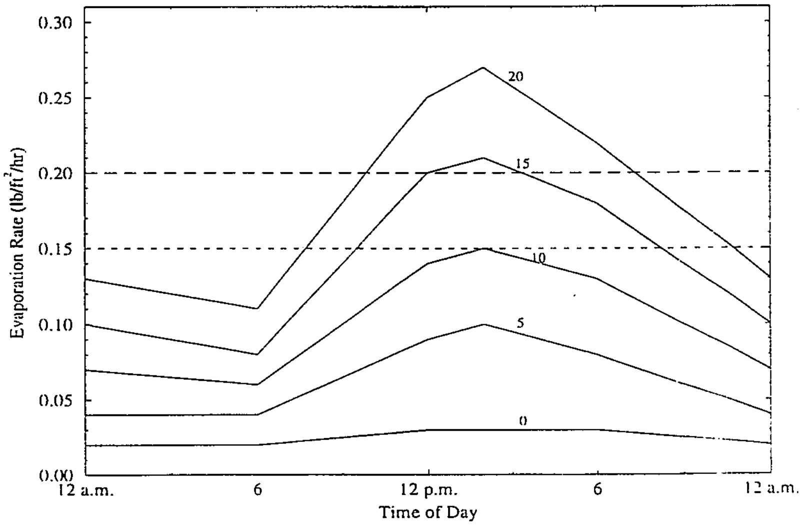


Fig. 5.6f. Daily E_r Curve for June - Huntsville

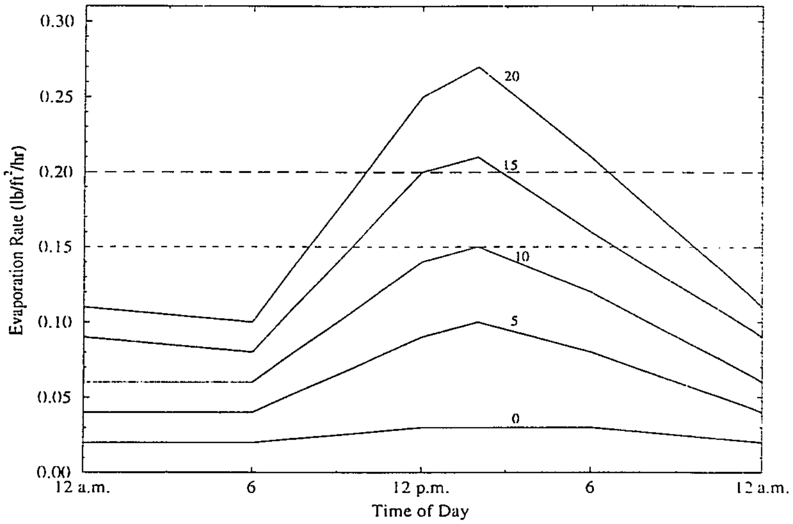


Fig. 5.6g. Daily E_r Curve for July - Huntsville

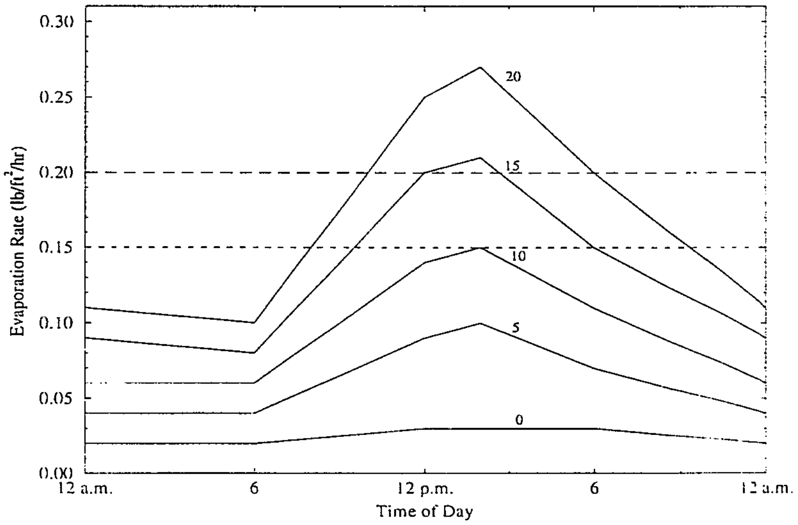


Fig. 5.6h. Daily E_r Curve for August - Huntsville

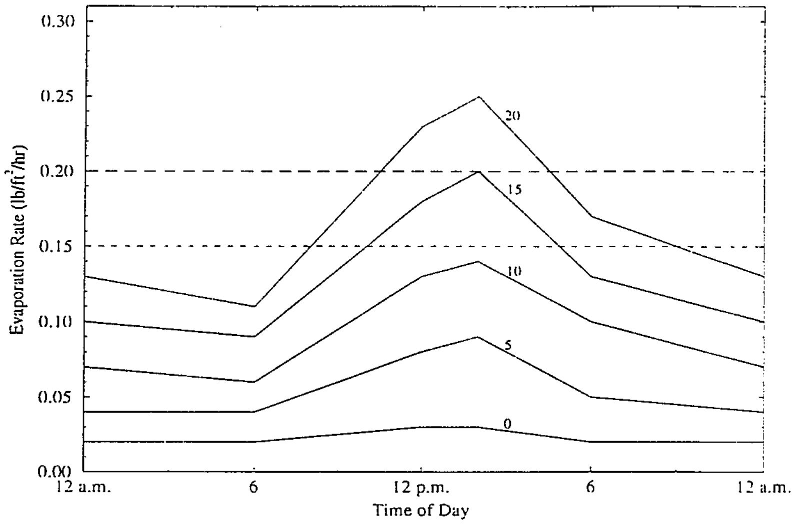


Fig. 5.6i. Daily E_r Curve for September - Huntsville

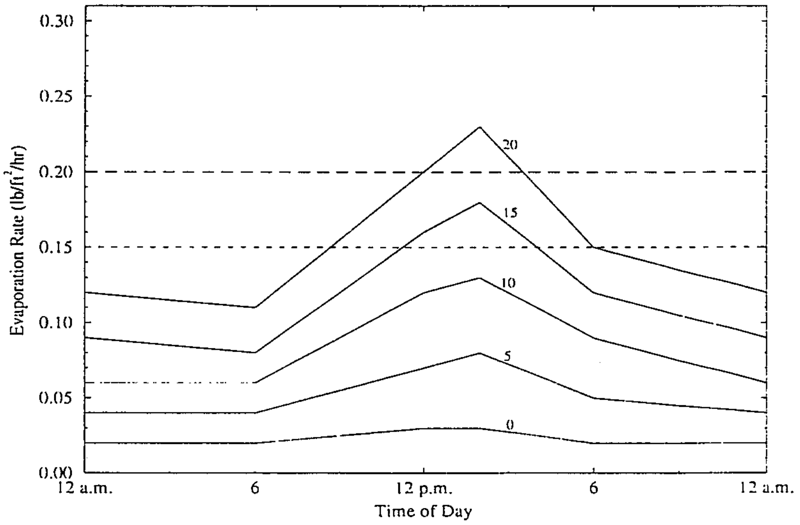


Fig. 5.6j. Daily E_r Curve for October - Huntsville

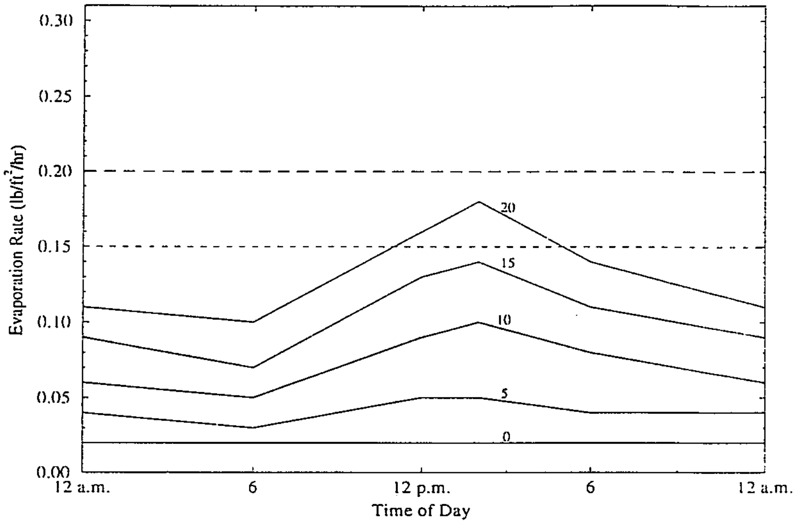


Fig. 5.6k. Daily E_r Curve for November - Huntsville

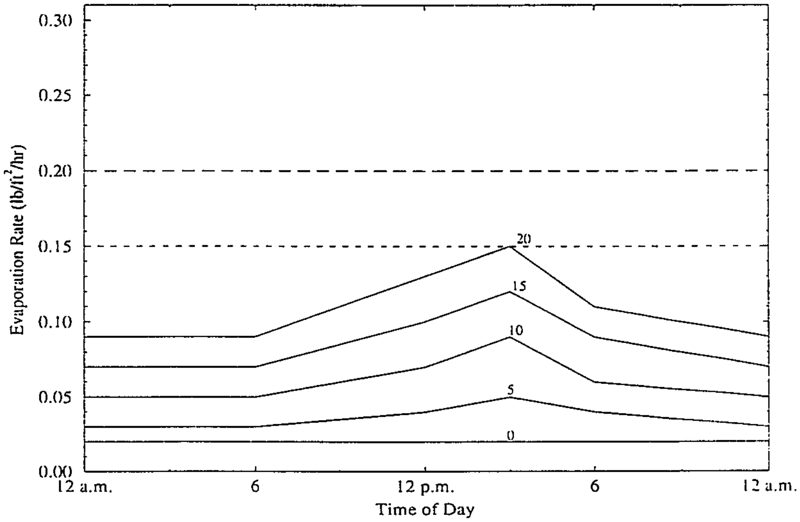


Fig. 5.6l. Daily E_r Curve for December - Huntsville

In studying the curves of Figs. 5.3-5.6, the daily trends are evident as discussed in the previous section. Because of these strong daily trends, it was viewed that "planning" curves should be of the form of those in Figs. 5.3-5.6, i.e., they should show E_r versus Hour of Day. Also, in studying the figures, it was evident that there was little difference between the evaporation rate curves developed for each city. Thus, evaporation rate categorizations for "planning" curves based on geographical locations within Alabama could not be made, i.e., all of Alabama should be considered as one geographical region.

Seasonally, the magnitudes of evaporation rate curves are lower for the winter months December, January, and February. Even with winds at 15-20 mph, evaporation rates do not exceed the ACI limit of 0.20 lb/ft^2/hr, and with winds below 15 mph, evaporation rate will typically not exceed 0.15 lb/ft^2/hr. March and November show a significant increase in magnitude of evaporation rate curves over the winter months. From April to October, the curves are virtually the same with slight increase from June to August. Figure 5.7 is a plot of the peak evaporation rate for the 20 mph curve for each city for each month. The plot was constructed to more conveniently compare the magnitude of E_r curves for each month to see if seasonal variation of evaporation rate was evident. This figure reflects that the peak evaporation rates are lowest for December through February, higher for March and November, higher again for April and May which coincide with September and October, and maximum for the three summer months of June, July, and August.

Figure 5.7 leaves out an important factor, i.e., from analysis of the weather data in Chapter 3, higher wind speeds are more common in certain months which, in turn, could affect the typical value of evaporation rate. Fig. 5.8 is a plot of typical peak evaporation rates for each month for each city. The evaporation rates were again calculated using the ACI 305 Surface Evaporation Chart with peak temperature, relative humidity, and wind speed obtained from the mean weather curves of Appendix A. The evaporation rate obtained can be considered a mean maximum evaporation rate for a day in each month for each city. From Fig. 5.8. the lowest evaporation rates are again in December and

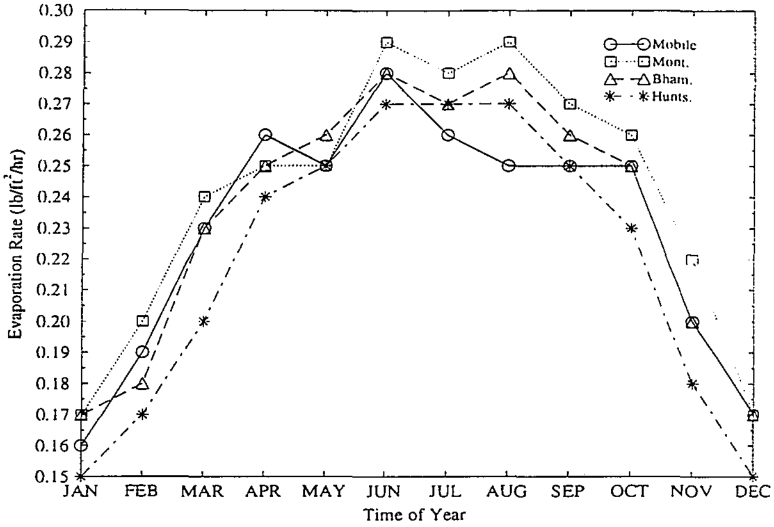


Fig. 5.7. Peak Evaporation Rates at 20 mph

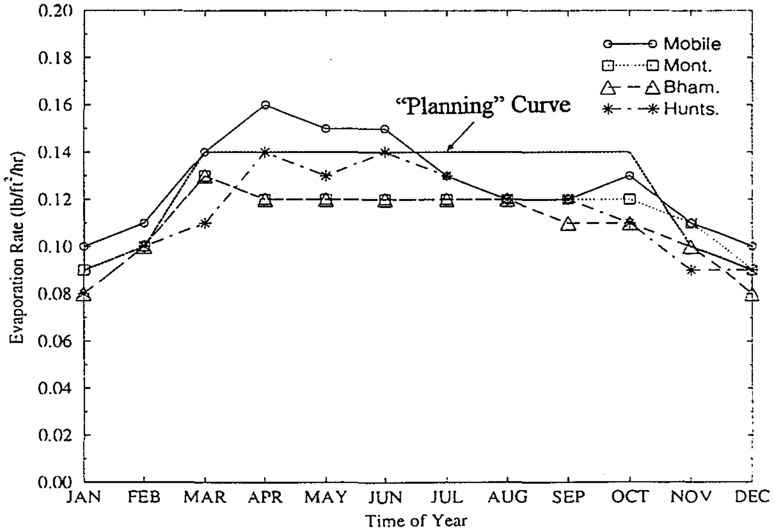


Fig. 5.8. Mean Peak Evaporation Rates

January with February and November next. There is little difference in the months from March to October except for spring in Mobile, which is higher. Evidently, the windy conditions closer to the coast increase the possibility of higher evaporative conditions. This is also the only time and place the mean maximum evaporation rate is equal to or grater than 0.15 lb/ft^2/hr.

From analysis of the evaporation rate data, it is difficult to develop distinct seasonal categories for evaporation rate. The only distinct category is that November through February is a period for which low evaporation rate can be expected. Also, the period of March through October reflects very little difference in evaporation rate. Since Fig. 5.8 integrates mean wind conditions into evaluating the mean maximum evaporation rate for each month, the curves of that figure should provide the expected or most probable maximum daily (around 1-2 p.m.) evaporation rate value for each month. Thus a recommended "planning" E_r curve for Alabama would be as indicated in Fig. 5.8. This "planning" curve is shown alone in Fig. 5.9 along with a modification factor (MF) to be employed if concrete placement is in the early evening (around 6 p.m.) or at night. As an alternative to using Fig. 5.9, the evaporation rate curves for the month of placement and the city closest to the jobsite can be used with the time of day of placement to provide a good estimate of the E_r value.

5.6. Closure

There are some important recommendations which can be drawn from the data presented in this chapter. It is evident that concrete should not be placed in hot or cold weather conditions when the wind speed is 20 mph or greater. From March to November, concrete should not be placed when the wind speed is greater than 15 mph. If the construction schedule makes placement imperative, windbreaks should be erected to slow the wind velocity, or fogging should be conducted to keep the surface humidity as high as possible. These preventative measures should also be taken if wind speed is above 10 mph with temperature and humidity typical for months between March and November.

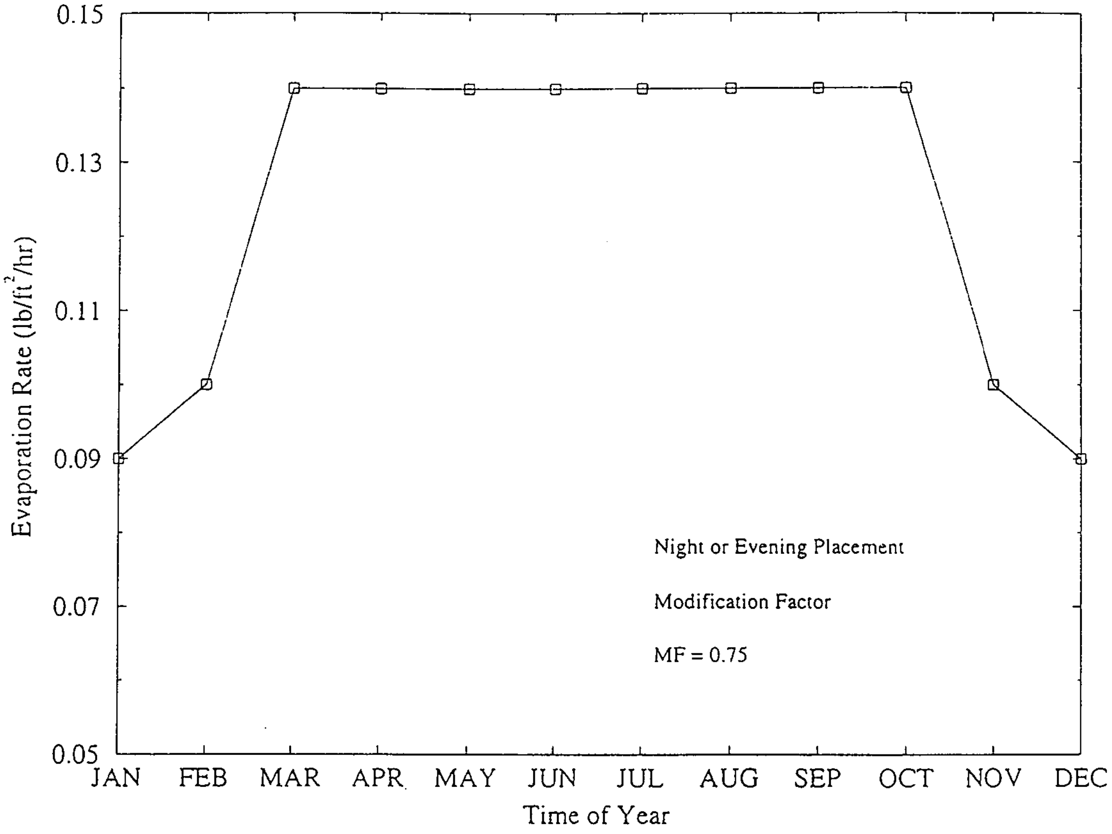


Fig. 5.9. Annual "Planning"/Best Estimate Evaporation Curve for Alabama.

Also, particular care should be taken for summertime placements. Concrete-air temperature differentials at high ambient temperature can cause high evaporation rates and any drop in humidity or increase in wind speed can create extremely high evaporation rates. An effective solution for windy or hot conditions is to move placement time from midday to late in the evening. Usually the wind speed is lower in the evening and the evaporation rate is falling.

It is important to not that all the curves of this chapter are for planning only. The curves are based upon mean weather conditions, and weather conditions can be highly variable at any time of the year. Thus, on the day before a bridge deck placement, the expected evaporation rate should be calculated/verified using the ACI 305 Surface Evaporation Chart and weather data obtained from a local forecasting center. On the day of placement, current weather data should be used with ACI 305 Evaporation Chart to determine the existing value. Concrete and curing methods as appropriate should then be taken based upon the E_r value.

6. CONCLUSIONS AND RECOMMENDATIONS

6.1 Conclusions

Although some of the steps of the work plan for this research did not provide the results anticipated, the research presents much useful information toward developing a design/construction tool to reduce early cracking in concrete bridge decks for the state of Alabama. The first information of note is the geographical and seasonal breakdowns of the weather parameters affecting water evaporation rate. Geographically, little difference was found between regions in Alabama concerning weather parameters and, likewise, the evaporation rate curves developed using these parameters. Therefore, Alabama can be considered as one region likely to exhibit similar evaporation rates throughout the region.

Seasonally, weather conditions and, accordingly, evaporation rates vary considerably. From the E_r curves developed in Chapter 5, November - February is typically a time of low evaporation rates due, in most part, to low ambient temperature. Hence, this is a period in which plastic shrinkage and early drying shrinkage cracking are less likely to occur, so rapid application of curing materials is not as critical. March - October appear to exhibit similar mean evaporative conditions which are more extreme than November - February. During this period, delays in implementation of curing materials must be minimized because typical daytime peak evaporation rates are close to the recommended limit of 0.15 $lb/ft^2/hr$ as stated in Chapter 5. Also, during this period (especially June - August), extremely high ambient temperature is common. In times of hot weather ($T_a > 90°F$), failure to keep concrete temperature low, which can be difficult, can result in detrimental evaporation rates causing plastic shrinkage cracking and increasing the likelihood of thermal cracking due to high stresses induced upon cooling.

The key to preventing plastic shrinkage cracking is proper planning and good construction practices. Using the E_r curves of Chapter 5, typical evaporation rates for the date and location of placement can be closely estimated. On the day of placement, evaporation rate for the time of day for placement can be accurately calculated using forecast information from a local weather center, and the empirical temperature of concrete equations given in Chapter 4. Wind speed should be monitored at regular intervals at the construction site.

The weather data in Chapter 3 provide bridge contractors and inspectors excellent summaries of temperature, relative humidity, and wind speed weather conditions to expect during any month of the year or time of day. Likewise, the evaporation rate vs. time of day curves for each month of the year in Chapter 5 provide expected values for the important evaporation rate parameter. This is the main parameter in planning very early (before hardening of the concrete) curing requirements to prevent plastic shrinkage cracking, and after hardening (4 hr - 7 days) curing requirements to mitigate drying shrinkage cracking.

6.2 Recommendations

From the information developed and collected in this study, several recommendations can be made concerning construction practices. Concrete for bridge decks should not be placed if the evaporation rate exceeds 0.15 $lb/ft^2/hr$. If placement at the time is imperative, windbreaks to reduce the wind velocity should be erected and/or fogging of the immediate area conducted to increase the relative humidity of the concrete surface. If winds above 15 mph occur, windbreaks should be erected. The most effective way to reduce evaporation rate, along with thermal stresses, is to reduce concrete temperature. Mixture ingredients should be as cool as possible, forms and rebar cooled before placement, and transportation coordinated as to avoid significant increase in concrete temperature. Another effective measure is to move time of placement to late evening or early night. Evaporation rates are lower due to the lower ambient temperature, higher relative humidity, and, most likely, lower wind speed. Evening placement is beneficial not only for the immediate time of placement, but for the green concrete as well, which is exposed to more favorable conditions during the first twelve hours after placement.

It is also recommended that curing of concrete bridge decks should be implemented as soon as possible. In Alabama, typical evaporation rates are below 0. 15 lb/ft^2/hr. Therefore, proper curing placed immediately after finishing should prevent plastic shrinkage cracking and early drying shrinkage cracking. The most effective form of curing is wet curing, which prevents evaporation from the concrete surface and also reduces the temperature of the concrete surface. During periods of extreme evaporative conditions (March - October), wet curing should be used for curing bridge deck concrete. During the cooler months (November - February), water retention curing using liquid membrane curing compounds and polyethylene sheeting would probably be adequate. However, wet curing should enhance the top surface quality and durability.

Based on the weather and evaporation rate data collected and generated in this study, rational and reasonable curing categories and requirements for Alabama conditions are shown in Tables 6.1 and 6.2 The time of year is related to the average evaporation rate and, in turn, to early drying shrinkage (4 hr - 7 days), and the evaporation rate at time of placement is related to the plastic shrinkage cracking. This is reflected in Table 6.1. The specific curing requirements indicated in Table 6.2 are felt to be reasonable and cost-effective. However, research should be conducted to verify and refine the curing requirements in Table 6.2 for curing categories A, B, C, and D in Table 6.1

Actual tests of the factors discussed in this study were not conducted by the authors. A follow-up study to this report should be conducted to experimentally evaluate the effects of evaporation rate, drying shrinkage, and thermal stress on concrete bridge decks. The study should not be conducted on unrestrained laboratory specimens, but on specimens which accurately model bridge decks or on actual bridge decks. Tests in the follow-up study should accurately record evaporation rates at time of placement, drying shrinkage strains over an extended period, i.e., one year, and temperature change

Table 6.1. Curing Categories[1,2]

Month/Season of Year	**E_r (lb/ft^2/hr at time of placement)[3,4]**	
	0 - 0.10	**0.10 - 0.15**
JAN, FEB, NOV, DEC	D	C
MAR - OCT	B	A

[1] When $E_r \geq 0.20$ or $V > 20$ mph, deck concrete cannot be placed.

[2] When $0.15 \leq E_r \leq 0.20$ and $V \leq 20$ mph, actions should be taken to reduce the wind speed to a level such that $E_r \leq 0.15$ in order to place deck concrete.

[3] E_r value and curing requirements indicated (A, B, C, D) are based on ALDOT's current Type I cement concrete mixture design.

[4] E_r values for evening or night placements are typically 75% (MF = 0.75) of those around midday.

Table 6.2. Tentative Curing Requirements

Curing Requirement Category	Time Period (after placement)	Requirements
A	0.5 hr - 4 hr	Fogging or Evaporation Retarder (200 ft^2/gal)
	4 hr - 8 hr	Double layer of wet burlap
	8 hr - 7 days	Soaker hose on wet burlap and covered with layer of white polyethylene
	7 days	Spray-on liquid curing compound (200 ft^2/gal)
B	0.5 hr - 4 hr	none
	4 hr - 8 hr	Double layer of wet burlap
	8 hr - 7 days	Soaker hose on wet burlap and covered with layer of white polyethylene
	7 days	Spray-on liquid curing compound (200 ft^2/gal)
C	0.5 hr - 4 hr	Fogging or Evaporation Retarder (200 ft^2/gal)
	4 hr - 8 hr	Spray-on liquid curing compound (200 ft^2/gal)
	8 hr - 7 days	Cover with layer of white polyethylene
	7 days	none
D	0.5 hr - 4 hr	none
	4 hr - 8 hr	Spray-on liquid curing compound (200 ft^2/gal)
	8 hr - 7 days	Cover with layer of white polyethylene
	7 days	none

throughout the depth of the deck over the same period as monitoring of drying shrinkage. Incidence of cracking should be monitored and recorded. Recording of this data on decks wet cured and water retention cured should indicate the appropriate curing method. Such data could provide the answer to reducing and, possibly, eliminating early deck cracking.

Another study should be performed on small laboratory specimens concerning the effectiveness of curing compounds. If economic necessity requires their use over wet curing, only compounds exhibiting exceptional qualities to retain moisture should be used. Also the possibility of using curing compound in conjunction with wet curing could be considered. Application of curing compound at the end of a wet curing period could produce the best possible curing due to longer retention of moisture in the concrete which could reduce drying shrinkage.

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APPENDIX A

Weather Data Curves and Tables

Table A.1a. Normals, Means, and Extremes for Mobile, AL

LATITUDE: 30° 41' N LONGITUDE: 88° 15' W ELEVATION: FT. GRND 211 BARO 226 TIME ZONE: CENTRAL WBAN: 13894

	(a)	JAN	FEB	MAR	APR	MAY	JUN	JUL	AUG	SEP	OCT	NOV	DEC	YEAR
TEMPERATURE °F														
Normals														
-Daily Maximum		59.7	63.6	70.9	78.5	84.6	90.0	91.3	90.5	86.9	79.5	70.3	62.9	77.4
-Daily Minimum		40.0	42.7	50.1	57.1	64.4	70.7	73.2	72.9	68.7	57.3	49.1	43.1	57.4
-Monthly		49.9	53.2	60.5	67.8	74.5	80.4	82.3	81.8	77.9	68.4	59.8	53.0	67.5
Extremes														
-Record Highest	53	84	82	90	94	100	102	104	102	99	93	87	81	104
-Year		1949	1989	1946	1987	1953	1952	1952	1968	1990	1963	1971	1974	JUL 1952
-Record Lowest	53	3	11	21	32	43	49	60	59	42	30	22	8	3
-Year		1985	1951	1993	1987	1960	1984	1947	1956	1967	1993	1950	1983	JAN 1985
NORMAL DEGREE DAYS:														
Heating (base 65 °F)		492	344	177	48	0	0	0	0	0	52	196	393	1702
Cooling (base 65 °F)		24	14	38	132	295	462	536	521	387	157	40	21	2627
% OF POSSIBLE SUNSHINE														
MEAN SKY COVER(tenths)														
Sunrise - Sunset	46	6.6	6.3	6.1	5.7	5.8	5.8	6.5	6.0	5.7	4.5	5.4	6.3	5.9
MEAN NUMBER OF DAYS:														
Sunrise to Sunset														
-Clear	46	7.8	7.6	8.8	9.2	8.7	6.9	4.1	6.2	8.9	14.3	11.0	8.8	102.4
-Partly Cloudy	46	6.3	6.6	7.8	8.7	11.2	13.8	15.0	14.8	10.1	7.7	7.2	6.4	115.5
-Cloudy	46	17.0	14.0	14.4	12.1	11.1	9.3	11.9	10.0	11.0	9.0	11.8	15.8	147.4
Precipitation														
.01 inches or more	53	10.8	9.6	10.3	7.5	8.5	11.4	16.2	13.8	10.2	5.7	7.8	10.1	122.1
Snow,Ice Pellets,Hail														
1.0 inches or more	53	0.*	0.1	0.*	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.*	0.2
Thunderstorms	53	2.0	2.3	4.9	4.9	7.2	12.0	18.0	14.3	7.5	2.1	2.3	2.2	79.6
Heavy Fog Visibility														
1/4 mile or less	53	6.1	4.6	5.3	4.6	2.7	0.9	1.0	1.3	1.9	2.6	4.3	4.9	40.2
Temperature °F														
-Maximum														
90° and above	32	0.0	0.0	0.0	0.3	3.6	16.8	22.1	20.6	10.3	0.9	0.0	0.0	74.6
32° and below	32	0.2	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.1	0.3
-Minimum														
32° and below	32	8.2	5.3	1.2	0.*	0.0	0.0	0.0	0.0	0.0	0.*	1.4	5.5	21.6
0° and below	32	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
AV. STATION PRES.(mb)	22	1012.9	1011.6	1009.3	1008.8	1007.5	1007.9	1009.3	1008.9	1008.5	1010.4	1011.6	1013.0	1010.0
RELATIVE HUMIDITY (%)														
Hour 00	32	79	78	81	83	85	86	87	88	86	83	83	81	83
Hour 06 (Local Time)	32	82	82	85	88	88	88	90	91	89	86	86	84	87
Hour 12	32	61	56	55	53	54	56	60	61	59	53	57	61	57
Hour 18	32	69	63	63	63	63	67	72	74	72	68	71	72	68
PRECIPITATION (ins):														
Water Equivalent														
-Normal		4.76	5.46	6.41	4.48	5.74	5.04	6.85	6.96	5.91	2.94	4.10	5.31	63.96
-Maximum Monthly	53	16.07	11.89	15.58	17.69	15.08	13.07	19.29	15.19	14.04	13.20	13.65	11.38	19.29
-Year		1991	1983	1946	1955	1980	1961	1949	1984	1988	1985	1948	1953	JUL 1949
-Minimum Monthly	53	0.98	1.31	0.59	0.48	0.45	1.19	1.72	1.46	0.58	T	0.25	1.29	T
-Year		1968	1948	1967	1954	1962	1966	1983	1990	1963	1978	1960	1980	OCT 1978
-Maximum in 24 hrs	53	8.34	5.37	10.57	13.36	8.00	7.38	5.34	6.62	8.55	5.65	7.02	5.50	13.36
-Year		1965	1981	1990	1955	1981	1961	1975	1969	1979	1985	1975	1968	APR 1955
Snow,Ice Pellets,Hail														
-Maximum Monthly	53	3.5	3.6	2.7	T	T	0.0	T	0.0	0.0	0.0	T	3.0	3.6
-Year		1955	1973	1993	1988	1991		1992				1966	1963	FEB 1973
-Maximum in 24 hrs	53	3.5	3.6	2.7	T	T	0.0	T	0.0	0.0	0.0	T	3.0	3.6
-Year		1955	1973	1993	1988	1991		1992				1966	1963	FEB 1973
WIND:														
Mean Speed (mph)	46	10.3	10.6	10.8	10.2	8.8	7.7	6.9	6.7	7.8	8.2	9.3	9.9	8.9
Prevailing Direction through 1963		N	N	N	S	S	S	S	NE	NE	N	N	N	N
Fastest Obs. 1 Min.														
-Direction (!!)	36	18	23	10	01	32	22	21	14	09	36	36	32	09
-Speed (mph)		44	46	40	44	51	44	60	63	63	46	37	38	63
-Year		1959	1960	1985	1964	1963	1989	1992	1969	1979	1964	1959	1959	SEP 1979
Peak Gust														
-Direction (!!)	11	W	S	SW	SE	SW	SW	SW	E	SE	S	NW	NW	SW
-Speed (mph)	11	45	61	55	46	62	60	64	53	60	52	48	43	64
-Date		1993	1987	1991	1993	1985	1989	1992	1991	1985	1985	1988	1990	JUL 1992

Table A.1b. Normals, Means, and Extremes for Montgomery, AL

LATITUDE: 32° 18' N LONGITUDE: 86° 24' W ELEVATION: FT. GRND 192 BARO 210 TIME ZONE CENTRAL WBAN: 13895

	(a)	JAN	FEB	MAR	APR	MAY	JUN	JUL	AUG	SEP	OCT	NOV	DEC	YEAR
TEMPERATURE °F														
Normals														
-Daily Maximum		56.3	60.8	68.6	76.4	82.9	89.4	91.1	90.4	87.0	78.2	68.7	60.2	75.8
-Daily Minimum		35.8	38.8	45.7	52.9	60.8	67.9	71.5	70.8	66.1	53.3	44.6	38.7	53.9
-Monthly		46.1	49.8	57.2	64.7	71.9	78.7	81.3	80.6	76.5	65.8	56.6	49.5	64.9
Extremes														
-Record Highest	50	83	85	89	91	98	105	105	104	101	100	87	85	105
-Year		1949	1962	1954	1988	1953	1954	1952	1983	1980	1954	1986	1982	JUN 1954
-Record Lowest	50	0	10	17	28	40	49	59	56	39	26	13	5	0
-Year		1985	1951	1993	1987	1971	1984	1947	1992	1967	1952	1950	1983	JAN 1985
NORMAL DEGREE DAYS:														
Heating (base 65 °F)		594	426	263	78	6	0	0	0	0	91	274	492	2224
Cooling (base 65 °F)		8	0	21	69	220	411	505	484	345	116	22	11	2212
% OF POSSIBLE SUNSHINE	44	47	53	59	65	63	62	61	63	62	64	55	49	59
MEAN SKY COVER(tenths)														
Sunrise - Sunset	50	6.6	6.3	6.2	5.6	5.8	5.7	6.2	5.6	5.5	4.8	5.5	6.3	5.8
MEAN NUMBER OF DAYS:														
Sunrise to Sunset														
-Clear	50	7.4	7.8	8.1	9.6	9.0	8.2	5.5	8.0	9.8	13.7	10.9	9.0	107.1
-Partly Cloudy	50	6.3	6.1	7.8	8.5	9.9	11.6	14.1	13.9	9.4	7.4	6.3	5.9	107.3
-Cloudy	50	17.3	14.3	15.0	11.9	12.1	10.2	11.4	9.1	10.8	9.9	12.8	16.0	150.8
Precipitation														
.01 inches or more	50	10.8	9.2	10.0	8.2	8.6	9.2	12.0	9.0	7.7	5.7	7.7	10.1	108.0
Snow,Ice Pellets,Hail														
1.0 inches or more	50	0.1	0.*	0.*	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.*	0.2
Thunderstorms	50	1.7	2.3	4.7	5.2	6.3	8.9	11.9	8.7	4.0	1.4	2.0	1.6	58.6
Heavy Fog Visibility														
1/4 mile or less	50	3.4	1.9	1.6	1.1	1.2	0.7	1.0	1.0	1.6	2.0	2.9	3.3	21.7
Temperature °F														
-Maximum														
90° and above	31	0.0	0.0	0.0	0.2	3.3	17.0	21.5	20.6	12.4	1.3	0.0	0.0	76.4
32° and below	31	0.4	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.2	0.6
-Minimum														
32° and below	31	13.3	8.7	2.5	0.1	0.0	0.0	0.0	0.0	0.0	0.3	4.1	9.8	38.9
0° and below	31	0.*	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	*
AV. STATION PRES.(mb)	22	1014.0	1012.7	1010.2	1009.6	1008.5	1008.8	1010.0	1010.0	1010.0	1011.8	1012.9	1014.2	1011.1
RELATIVE HUMIDITY (%)														
Hour 00	31	77	74	74	78	83	84	88	88	86	85	82	79	82
Hour 06 (Local Time)	31	82	81	83	86	88	88	91	92	90	89	87	83	87
Hour 12	31	60	55	52	51	54	55	60	59	56	52	54	59	56
Hour 18	31	64	58	55	55	60	60	67	68	67	66	66	67	63
PRECIPITATION (ins):														
Water Equivalent														
-Normal		4.68	5.48	6.26	4.49	3.92	3.90	5.19	3.69	4.09	2.45	4.08	5.20	53.43
-Maximum Monthly	50	10.16	13.38	12.40	15.64	12.01	14.44	9.99	10.43	10.62	9.06	21.32	11.35	21.32
-Year		1990	1961	1990	1964	1978	1989	1988	1984	1953	1959	1948	1961	NOV 1948
-Minimum Monthly	50	0.72	1.47	1.93	0.52	1.14	0.33	1.58	0.78	0.44	0.01	0.32	1.36	0.01
-Year		1954	1947	1985	1986	1962	1979	1952	1958	1954	1978	1949	1955	OCT 1978
-Maximum in 24 hrs	50	4.73	5.95	8.62	4.59	6.36	6.99	4.52	5.68	8.81	4.25	8.17	4.89	8.81
-Year		1965	1982	1990	1957	1978	1946	1970	1984	1953	1964	1948	1992	SEP 1953
Snow,Ice Pellets,Hail														
-Maximum Monthly	50	6.0	3.1	3.8	0.8	0.0	0.0	0.0	0.0	0.0	T	T	1.0	6.0
-Year		1977	1973	1993	1987						1993	1971	1993	JAN 1977
-Maximum in 24 hrs	50	3.0	3.1	3.8	0.8	T	0.0	0.0	0.0	0.0	T	T	1.0	3.8
-Year		1977	1973	1993	1987	1990					1993	1971	1993	MAR 1993
WIND:														
Mean Speed (mph)	50	7.7	8.2	8.4	7.3	6.1	5.8	5.7	5.2	5.9	5.7	6.5	7.1	6.6
Prevailing Direction through 1963		NW	S	NW	S	S	S	SW	ENE	NE	NE	NW	NW	S
Fastest Obs. 1 Min.														
-Direction (!!)	9	25	26	24	32	30	29	26	22	28	23	23	30	29
-Speed (mph)		29	38	35	39	35	44	35	26	25	31	30	33	44
-Year		1994	1990	1992	1990	1991	1985	1994	1994	1994	1990	1989	1990	JUN 1985
Peak Gust														
-Direction (!!)	11	S	SW	NW	NW	NW	N	N	NE	NW	SW	SW	W	SW
-Speed (mph)	11	43	66	54	60	60	60	55	44	41	37	56	48	66
-Date		1994	1990	1993	1985	1991	1992	1993	1987	1989	1990	1991	1993	FEB 1990

Table A.1c. Normals, Means, and Extremes for Birmingham, AL

LATITUDE: 33° 34' N LONGITUDE: 86° 45' W ELEVATION: FT. GRND 620 BARO 622 TIME ZONE: CENTRAL WBAN: 13876

	(a)	JAN	FEB	MAR	APR	MAY	JUN	JUL	AUG	SEP	OCT	NOV	DEC	YEAR
TEMPERATURE °F														
Normals														
-Daily Maximum		51.7	56.9	66.1	74.6	81.0	87.4	89.9	89.1	83.9	74.7	64.6	55.7	73.0
-Daily Minimum		31.3	34.5	42.3	49.2	57.7	65.2	69.5	68.8	62.9	50.2	41.6	34.8	50.7
-Monthly		41.5	45.7	54.2	62.0	69.4	76.3	79.8	79.0	73.4	62.5	53.1	45.2	61.8
Extremes														
-Record Highest	51	81	83	89	92	99	102	106	103	100	94	84	80	106
-Year		1949	1962	1982	1987	1962	1954	1980	1990	1990	1954	1961	1951	JUL 1980
-Record Lowest	51	-6	3	2	26	35	42	51	51	37	27	5	1	-6
-Year		1985	1958	1993	1973	1944	1966	1967	1946	1967	1956	1950	1989	JAN 1985
NORMAL DEGREE DAYS:														
Heating (base 65 °F)		729	540	350	135	31	0	0	0	7	148	364	614	2918
Cooling (base 65 °F)		0	0	15	45	168	339	459	434	259	71	7	0	1797
% OF POSSIBLE SUNSHINE	34	42	50	55	63	66	65	59	63	61	66	55	46	58
MEAN SKY COVER (tenths)														
Sunrise - Sunset	37	6 9	6.5	6 5	5.8	6.0	5.9	6.4	5.8	5.6	4.6	5.7	6.4	6.0
MEAN NUMBER OF DAYS:														
Sunrise to Sunset														
-Clear	37	6.9	7.2	7.4	8.8	8.0	7.1	4.7	6.8	9.5	14.0	10.2	8.4	98.8
-Partly Cloudy	37	6.2	6.4	7.9	8.0	10.9	12.6	14.4	14.5	9.3	7.6	6.8	6.6	111.2
-Cloudy	37	17.9	14.8	15.8	13.2	12.2	10.4	12.0	9.7	11.2	9.4	13.0	15.9	155.3
Precipitation														
.01 inches or more	51	11.1	10.2	11.0	9.1	9.7	9.7	12.5	9.6	7.9	6.4	9.0	10 7	116 9
Snow,Ice Pellets,Hail														
1.0 inches or more	51	0.3	0.1	0.1	0.*	0.0	0.0	0.0	0 0	0.0	0.0	0.*	0.1	0 5
Thunderstorms	51	1.5	2.3	4.5	5.1	6.9	8.5	11.5	8.8	4.3	1.2	1.9	1.2	57 7
Heavy Fog Visibility														
1/4 mile or less	51	1.3	0.6	0.6	0.3	0.3	0.7	0.5	0.5	0 5	0.7	1.0	1.2	8.2
Temperature °F														
-Maximum														
90° and above	31	0.0	0.0	0.0	0.1	1.7	10.9	17.1	15.2	6 1	0.1	0.0	0.0	51.1
32° and below	31	1.5	0.4	0.1	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.*	0.5	2 5
-Minimum														
32° and below	31	17.1	13.1	6.0	1.2	0.0	0.0	0.0	0.0	0.0	0.5	6.7	13.9	58.5
0° and below	31	0.2	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.2
AV. STATION PRES.(mb)	22	998.4	997.1	994.6	994.3	993.4	993.9	995.1	995.2	995.4	997.0	997.6	998.5	995.9
RELATIVE HUMIDITY (%)														
Hour 00	31	76	73	72	77	84	85	86	86	85	84	80	77	80
Hour 06 (Local Time)	31	80	79	79	84	86	86	89	90	88	87	84	81	84 ← Hor
Hour 12	31	61	56	52	51	55	56	60	59	59	54	57	60	57 ← La
Hour 18	31	65	57	52	52	59	61	65	66	69	71	69	69	63
PRECIPITATION (ins):														
Water Equivalent														
-Normal		5.10	4.72	6.19	4.96	4.85	3.73	5.25	3.59	3.93	2.81	4.33	5.12	54.58
-Maximum Monthly	51	11.00	17.67	15.80	13.75	11.10	8.44	13.70	10.85	10.43	7.52	15.25	13.98	17.67
-Year		1949	1961	1980	1979	1969	1963	1950	1967	1977	1977	1948	1961	FEB 1961
-Minimum Monthly	51	1.09	1.20	1.71	0.42	1.15	0.67	0.30	0.38	T	0.07	0.42	0.81	T
-Year		1981	1968	1985	1986	1951	1968	1983	1989	1955	1991	1949	1980	SEP 1955
-Maximum in 24 hrs	45	5.81	6.57	7.05	5.08	4.63	3.85	5.47	5.13	5.03	3.75	4.87	5.29	7.05
-Year		1949	1961	1970	1966	1969	1957	1985	1952	1977	1977	1948	1961	MAR 1970
Snow,Ice Pellets,Hail														
-Maximum Monthly	51	6.6	2.3	13.0	5.0	T	T	T	0.0	T	T	1.4	8.0	13.0
-Year		1982	1960	1993	1987	1993	1992	1994		1992	1993	1950	1963	MAR 1993
-Maximum in 24 hrs	45	4.5	2.3	13.0	5.0	T	T	T	0.0	T	T	1.4	8.4	13.0
-Year		1948	1960	1993	1987	1993	1992	1994		1992	1993	1950	1963	MAR 1993
WIND:														
Mean Speed (mph)	51	8.1	8.7	9.1	8.3	6.8	6.1	5.7	5.4	6.3	6.2	7.2	7.7	7.1
Prevailing Direction through 1963		S	N	S	S	S	SSW	SSW	NE	ENE	ENE	N	NNW	S
Fastest Mile														
-Direction (!!)	34	W	SE	SW	SW	NW	SW	SW	NW	SE	W	N	SE	SW
-Speed (mph)	34	49	59	65	56	65	56	57	50	50	43	52	41	65
-Year		1975	1960	1955	1956	1951	1957	1960	1956	1951	1955	1944	1954	MAR 1955
Peak Gust														
-Direction (!!)														
-Speed (mph)														
-Date														

Table A.1d. Normals, Means, and Extremes for Huntsville, AL

LATITUDE: 34° 39' N LONGITUDE: 86° 46' W ELEVATION: FT. GRND 624 BARO 631 TIME ZONE: CENTRAL WBAN: 03856

	(a)	JAN	FEB	MAR	APR	MAY	JUN	JUL	AUG	SEP	OCT	NOV	DEC	YEAR
TEMPERATURE °F														
Normals														
-Daily Maximum		48.2	53.5	62.8	72.5	79.3	86.6	89.0	88.8	82.8	73.0	62.4	52.6	71.0
-Daily Minimum		29.2	32.6	40.9	49.0	57.3	64.9	68.9	67.9	61.6	49.3	40.5	33.1	49.6
-Monthly		38.8	43.1	51.9	60.8	68.4	75.8	79.0	78.3	72.2	61.2	51.5	42.9	60.3
Extremes														
-Record Highest	27	76	79	84	90	93	101	104	103	101	90	83	77	104
-Year		1972	1989	1991	1989	1986	1988	1993	1990	1990	1986	1982	1978	JUL 1993
-Record Lowest	27	-11	6	6	26	36	45	54	52	40	29	15	-3	-11
-Year		1985	1981	1980	1992	1971	1972	1972	1992	1981	1993	1976	1989	JAN 1985
NORMAL DEGREE DAYS:														
Heating (base 65 °F)		812	613	417	158	41	0	0	0	13	173	411	685	3323
Cooling (base 65 °F)		0	0	11	32	147	324	434	412	229	56	6	0	1651
% OF POSSIBLE SUNSHINE														
MEAN SKY COVER(tenths)														
Sunrise - Sunset	27	6.9	6.7	6.7	6.0	6.2	5.8	5.9	5.5	5.7	5.2	6.1	6.7	6.1
MEAN NUMBER OF DAYS:														
Sunrise to Sunset														
-Clear	27	7.1	6.9	6.9	9.0	7.7	8.0	7.1	8.9	9.3	12.4	9.0	7.6	99.9
-Partly Cloudy	27	5.9	5.8	7.6	7.4	9.8	10.7	12.9	12.6	9.0	7.0	6.5	5.8	101.0
-Cloudy	27	18.0	15.5	16.5	13.6	13.6	11.4	10.9	9.5	11.8	11.7	14.5	17.6	164.4
Precipitation														
.01 inches or more	27	11.4	9.6	11.7	9.4	10.5	9.3	10.4	8.6	8.6	7.5	9.5	10.9	117.5
Snow,Ice Pellets,Hail														
1.0 inches or more	27	0.4	0.4	0.1	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.1	1.1
Thunderstorms	27	1.1	2.1	4.3	4.7	7.1	8.5	10.3	8.2	4.9	2.1	2.3	1.1	56.9
Heavy Fog Visibility														
1/4 mile or less	27	2.6	1.4	1.2	0.8	1.1	1.3	1.6	1.9	2.1	2.4	1.8	1.3	19.6
Temperature °F														
-Maximum														
90° and above	27	0.0	0.0	0.0	0.1	0.7	9.3	16.5	14.4	4.7	0.*	0.0	0.0	45.9
32° and below	27	3.0	1.0	0.1	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.1	1.1	5.3
-Minimum														
32° and below	27	18.9	14.1	6.7	0.9	0.0	0.0	0.0	0.0	0.0	0.5	7.7	15.5	64.2
0° and below	27	0.2	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.1	0.3
AV. STATION PRES.(mb)	22	996.2	996.5	993.8	993.5	992.8	993.2	994.3	994.6	995.0	996.4	996.8	997.8	995.1
RELATIVE HUMIDITY (%)														
Hour 00	27	78	75	73	75	83	85	87	87	87	83	79	78	81
Hour 06 (Local Time)	27	82	81	81	83	87	88	90	91	91	87	84	82	86
Hour 12	27	64	59	56	52	56	56	59	58	59	55	58	63	58
Hour 18	27	68	61	57	52	60	61	65	66	68	65	65	69	63
PRECIPITATION (ins):														
Water Equivalent														
-Normal		5.17	4.87	6.62	4.93	5.08	4.13	4.85	3.47	4.08	3.25	4.86	5.87	57.18
-Maximum Monthly	27	10.92	10.14	17.00	10.29	11.88	14.99	9.44	9.81	9.78	12.06	11.53	18.68	18.68
-Year		1982	1994	1980	1991	1983	1989	1973	1986	1980	1975	1977	1990	DEC 1990
-Minimum Monthly	27	1.32	0.59	2.70	0.42	1.99	0.17	0.79	0.93	0.55	0.77	1.82	0.91	0.17
-Year		1986	1978	1982	1986	1988	1988	1983	1973	1982	1971	1971	1980	JUN 1988
-Maximum in 24 hrs	27	4.90	5.55	7.70	3.85	5.90	4.81	4.47	4.89	3.99	6.04	3.33	10.22	10.22
-Year		1982	1994	1973	1983	1983	1992	1975	1986	1980	1975	1973	1990	DEC 1990
Snow,Ice Pellets,Hail														
-Maximum Monthly	27	9.6	4.2	7.3	T	T	T	0.0	T	0.0	T	0.8	1.0	9.6
-Year		1988	1985	1993	1993	1993	1994		1990		1993	1974	1974	JAN 1988
-Maximum in 24 hrs	27	9.6	3.6	7.3	T	T	T	0.0	T	0.0	T	0.8	1.0	9.6
-Year		1988	1985	1993	1993	1993	1994		1990		1993	1974	1974	JAN 1988
WIND:														
Mean Speed (mph)	27	9.3	9.7	10.1	9.3	8.1	7.0	6.3	5.9	6.8	7.5	8.6	9.3	8.2
Prevailing Direction														
Fastest Obs. 1 Min.														
-Direction (!!)	27	26	08	12	18	24	25	27	02	23	33	27	30	02
-Speed (mph)		44	43	46	44	46	44	43	63	43	32	40	40	63
-Year		1978	1987	1969	1970	1993	1989	1969	1990	1968	1972	1989	1988	AUG 1990
Peak Gust														
-Direction (!!)	11	SW	E	W	SW	NW	NW	SW	N	S	W	W	NW	W
-Speed (mph)	11	48	58	70	58	69	67	62	55	48	47	51	53	70
-Date		1992	1987	1991	1985	1990	1994	1985	1986	1987	1990	1989	1993	MAR 1991

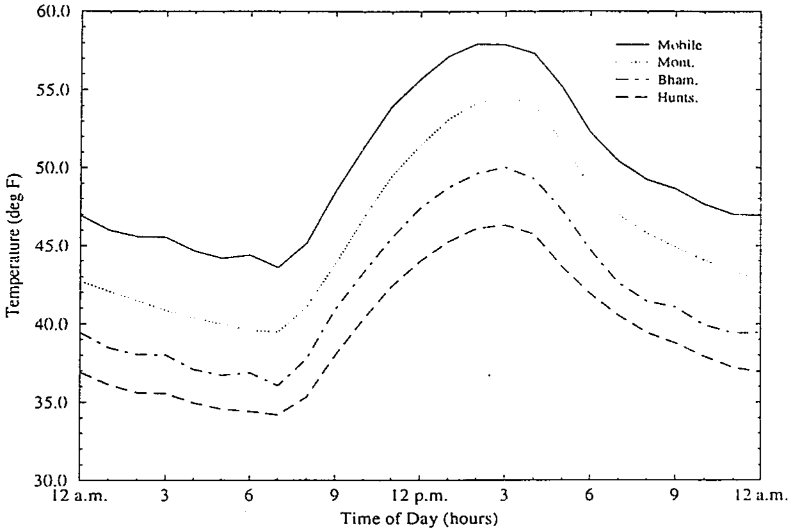

Fig. A.1. Mean Daily Temperature Cycle - January

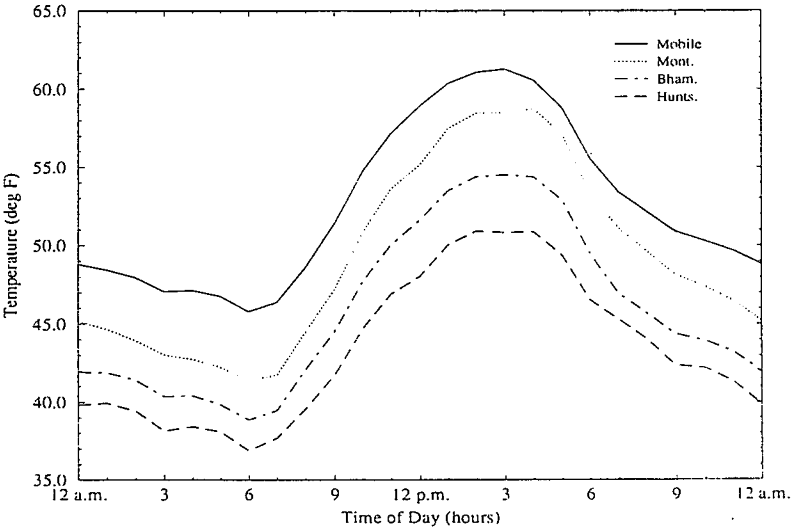

Fig. A.2. Mean Daily Temperature Cycle - February

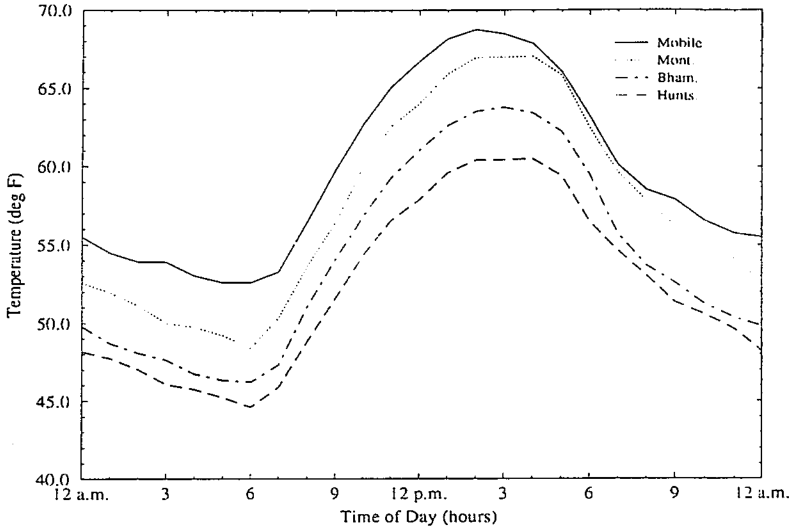

Fig. A.3. Mean Daily Temperature Cycle - March

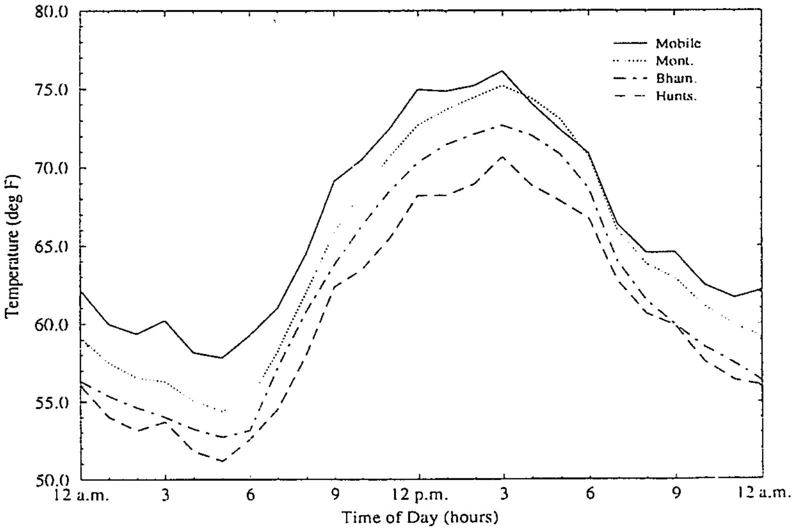

Fig. A.4. Mean Daily Temperature Cycle - April

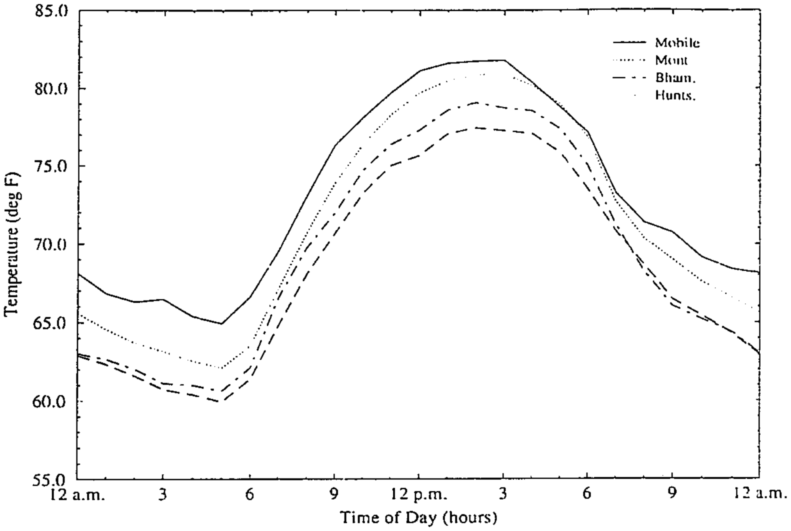

Fig. A.5. Mean Daily Temperature Cycle - May

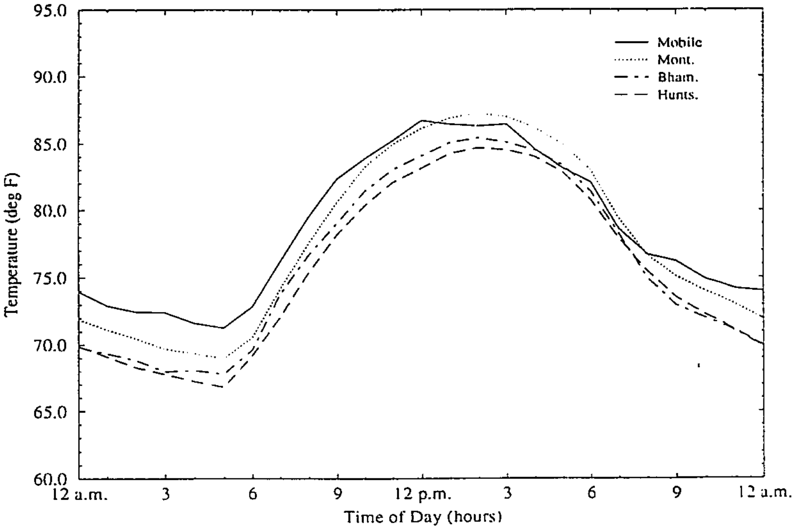

Fig. A.6. Mean Daily Temperature Cycle - June

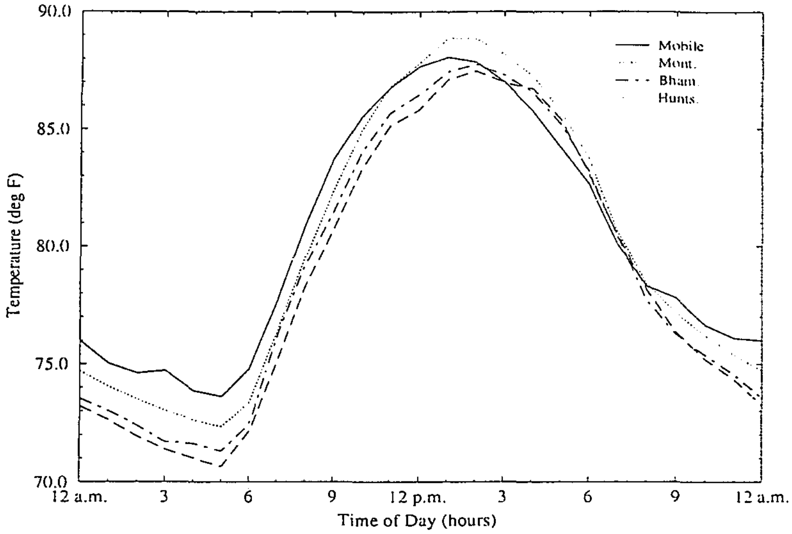

Fig. A.7. Mean Daily Temperature Cycle - July

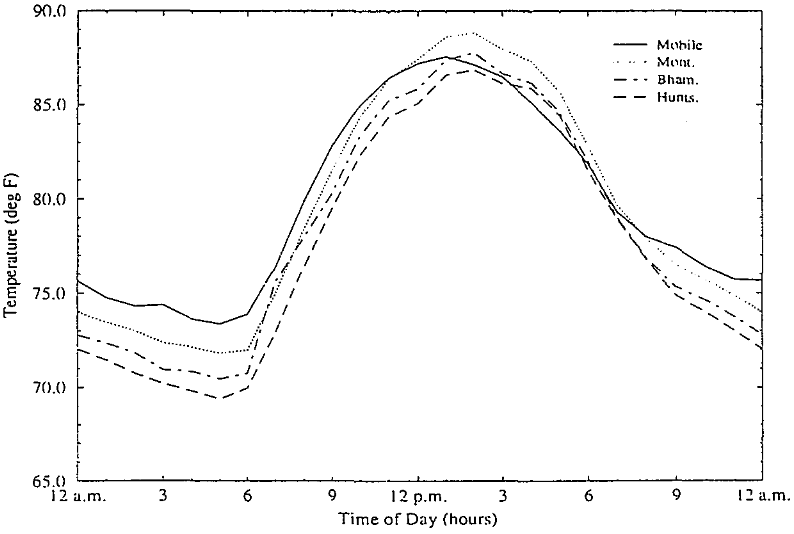

Fig. A.8. Mean Daily Temperature Cycle - August

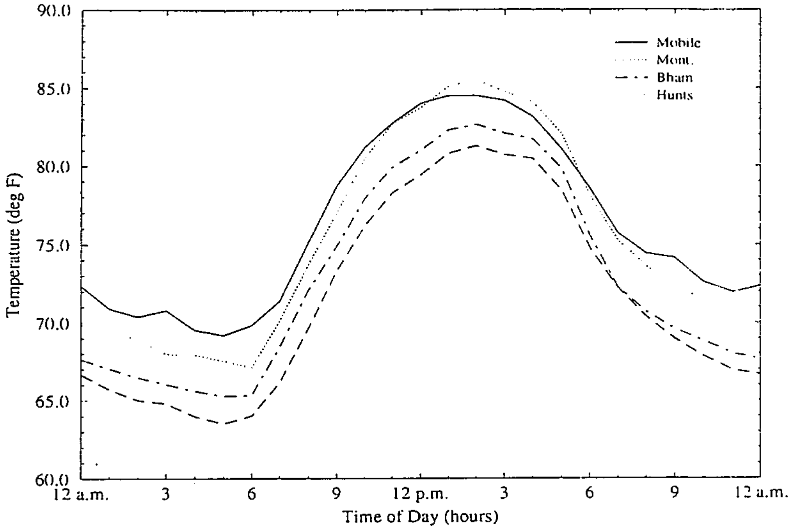

Fig. A.9. Mean Daily Temperature Cycle - September

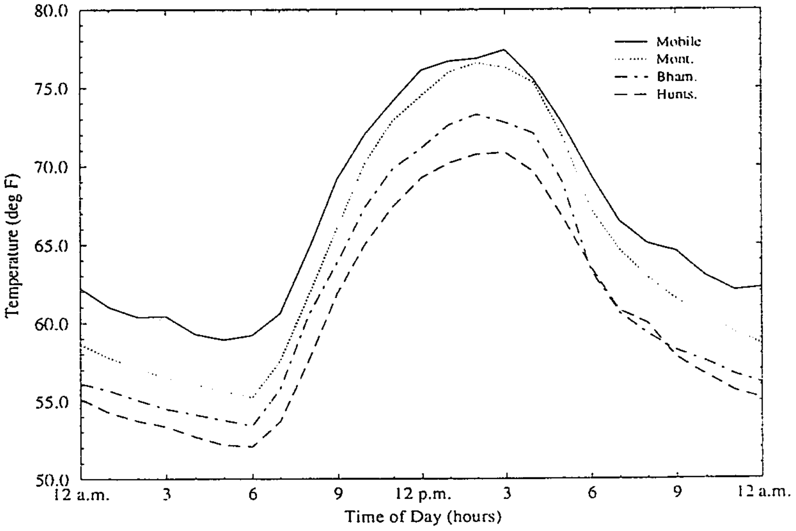

Fig. A.10. Mean Daily Temperature Cycle - October

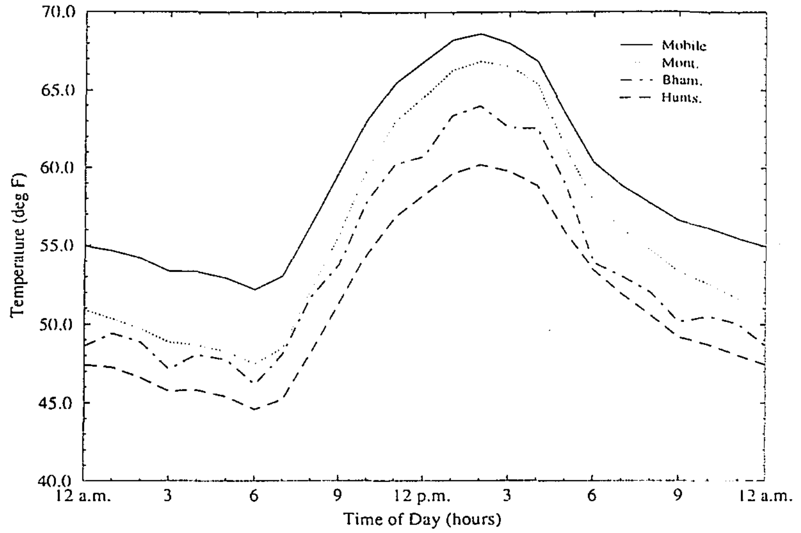

Fig. A.11. Mean Daily Temperature Cycle - November

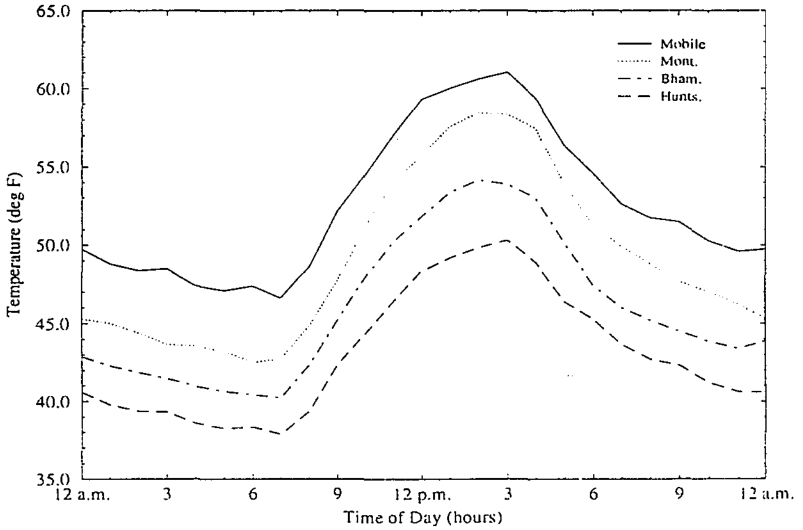

Fig. A.12. Mean Daily Temperature Cycle - December

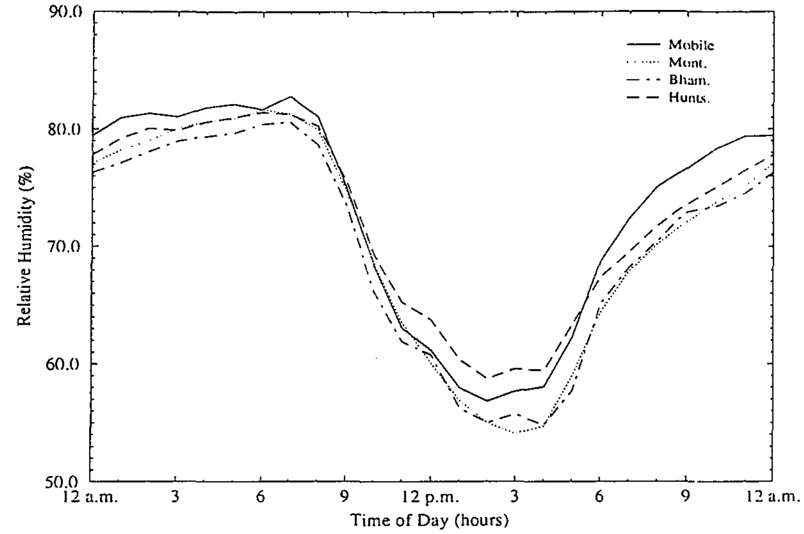

Fig. A.13. Mean Daily Relative Humidity Cycle - January

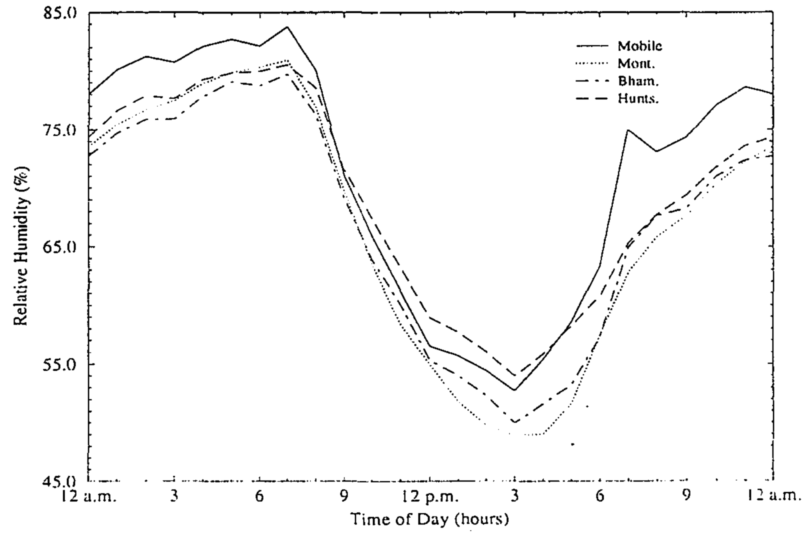

Fig. A14. Mean Daily Relative Humidity Cycle - February

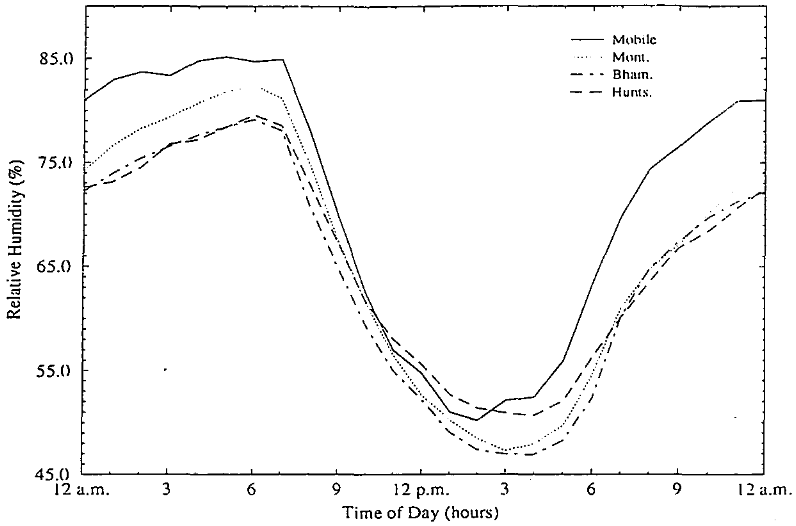

Fig. A.15. Mean Daily Relative Humidity Cycle - March

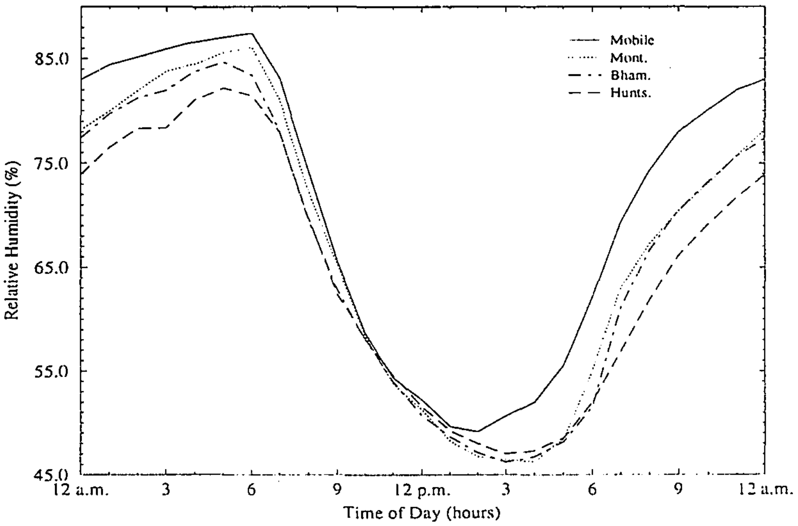

Fig. A16. Mean Daily Relative Humidity Cycle - April

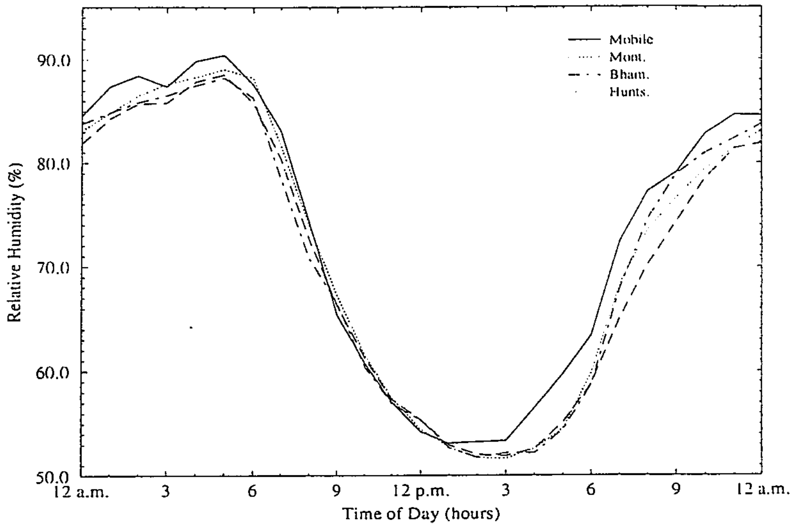

Fig. A.17. Mean Daily Relative Humidity Cycle - May

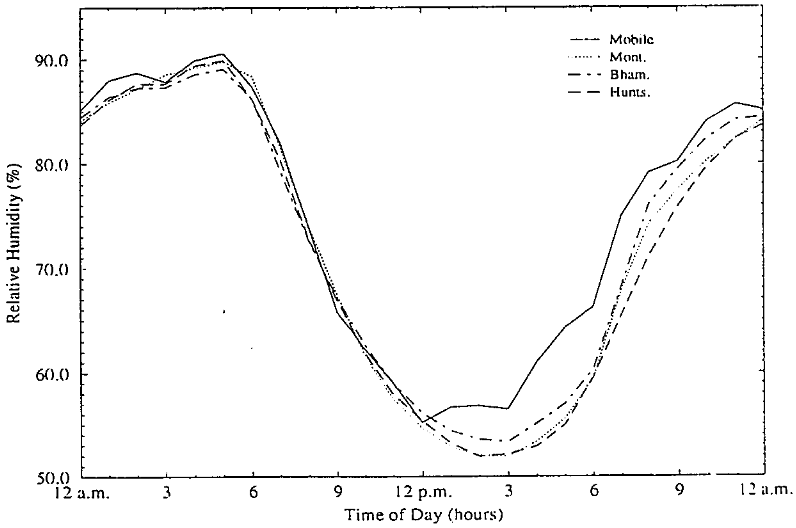

Fig. A.18. Mean Daily Relative Humidity Cycle - June

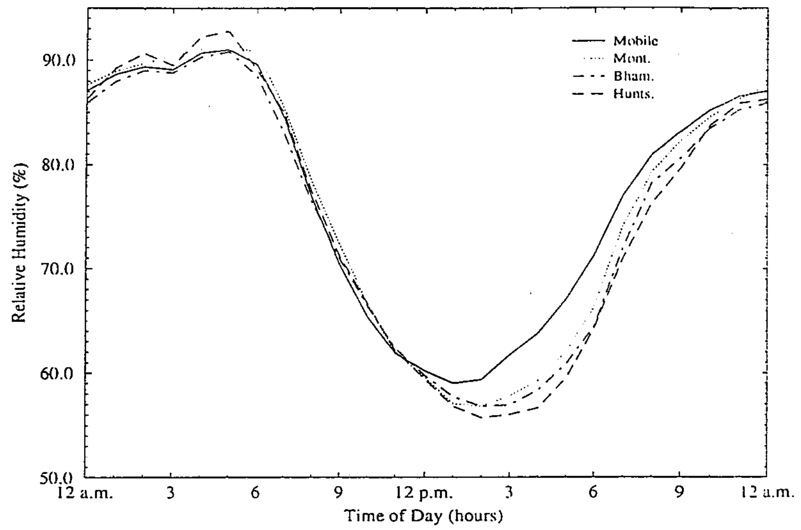

Fig. A.19. Mean Daily Relative Humidity Cycle - July

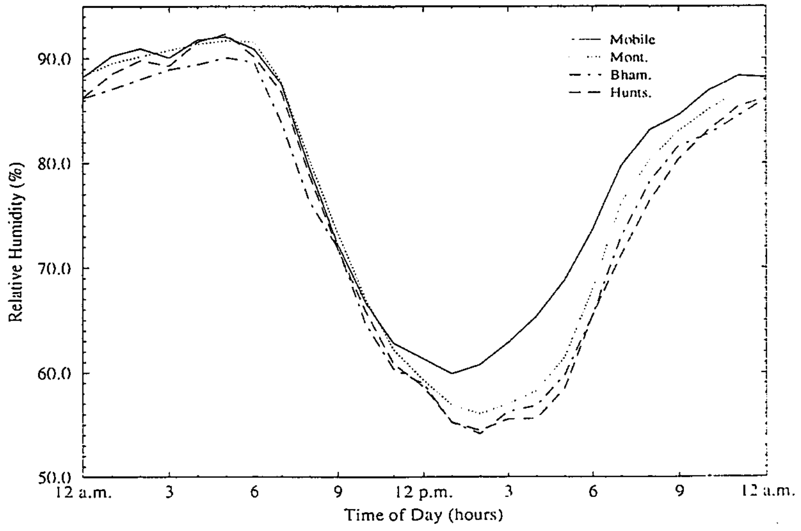

Fig. A.20. Mean Daily Relative Humidity Cycle - August

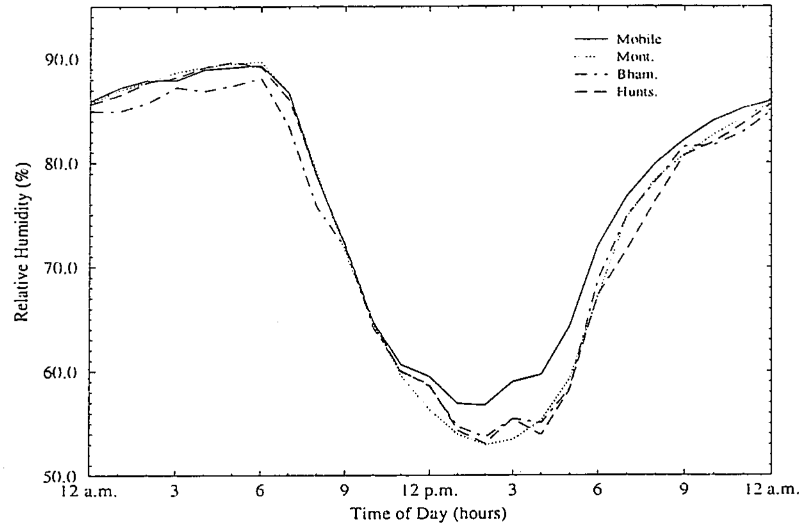

Fig. A.21. Mean Daily Relative Humidity Cycle - September

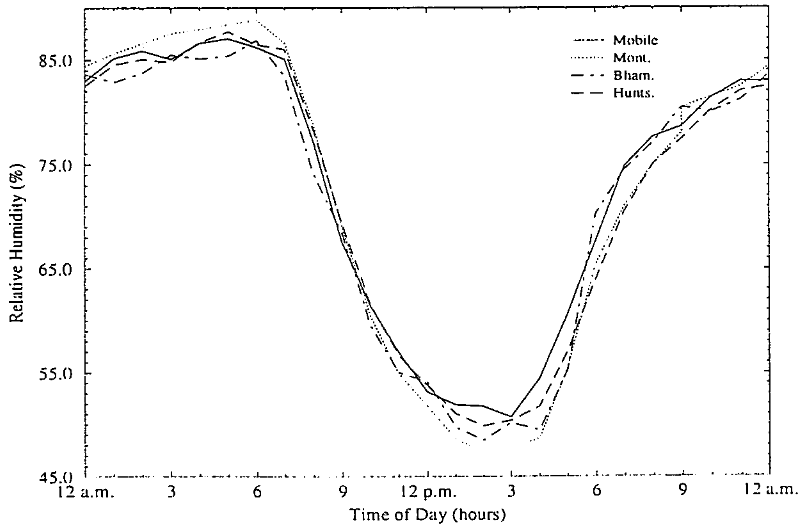

Fig. A.22. Mean Daily Relative Humidity Cycle - October

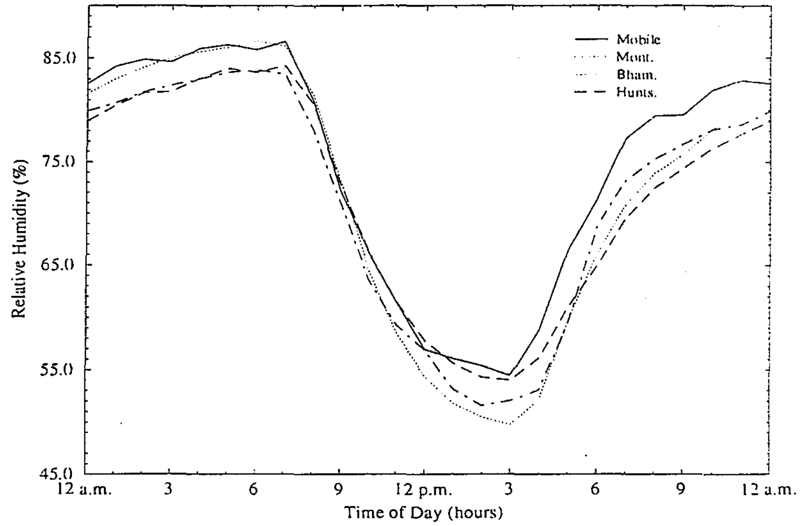

Fig. A.23. Mean Daily Relative Humidity Cycle - November

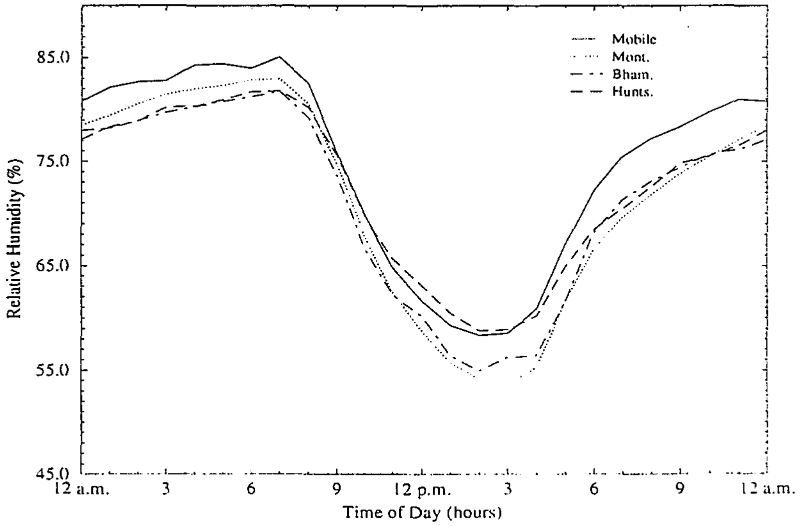

Fig. A.24. Mean Daily Relative Humidity Cycle - December

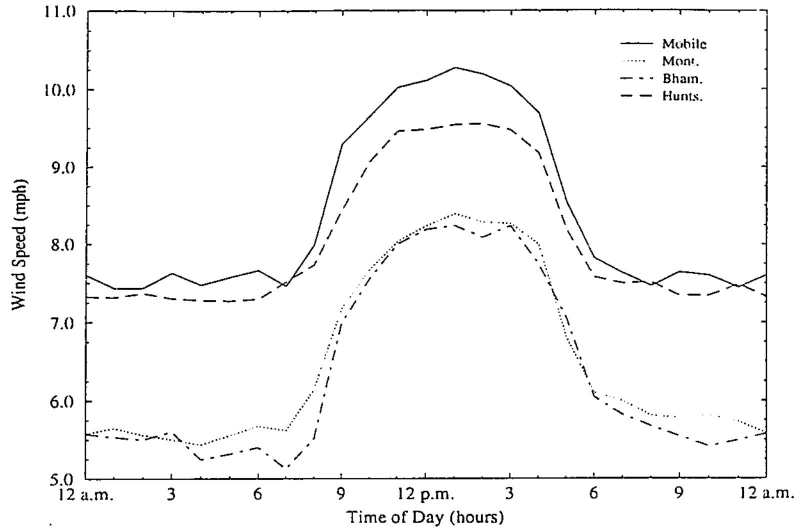

Fig. A.25. Mean Daily Wind Speed Cycle - January

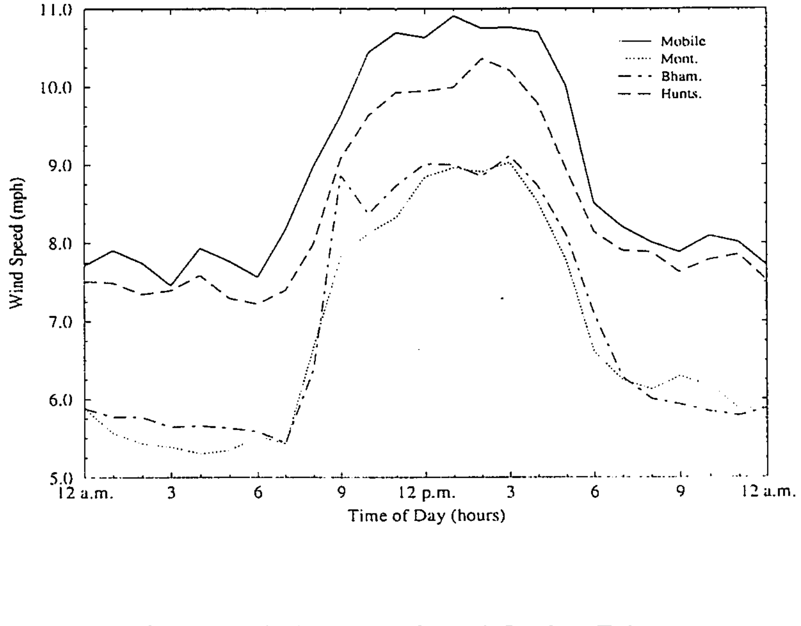

Fig. A.26. Mean Daily Wind Speed Cycle - February

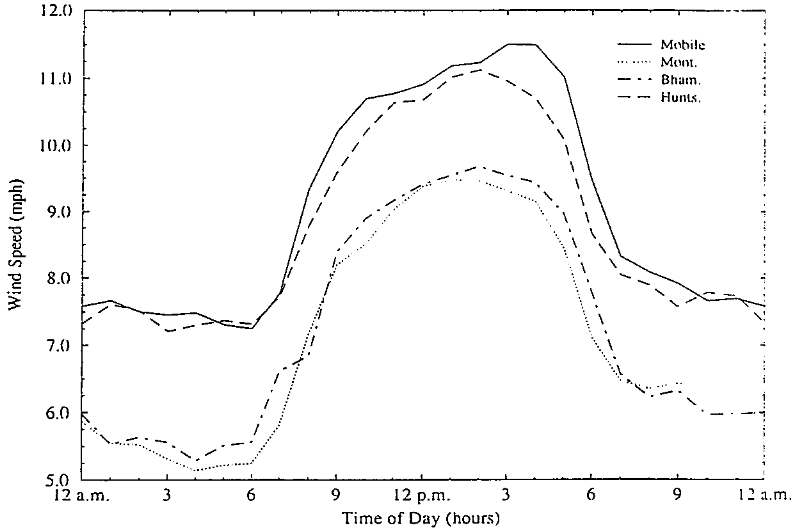

Fig. A.27. Mean Daily Wind Speed Cycle - March

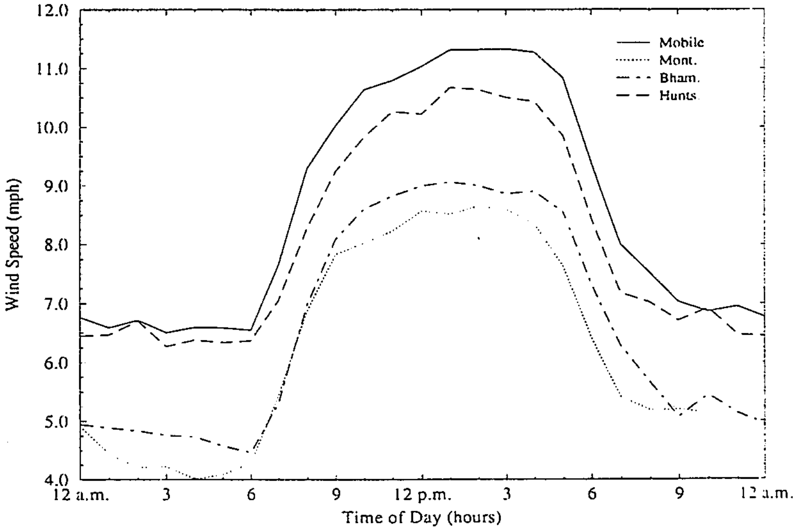

Fig. A.28. Mean Daily Wind Speed Cycle - April

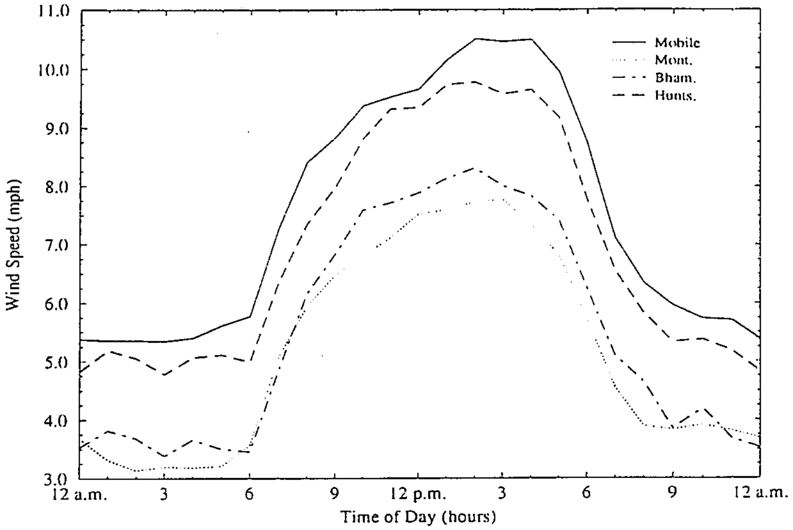

Fig. A.29. Mean Daily Wind Speed Cycle - May

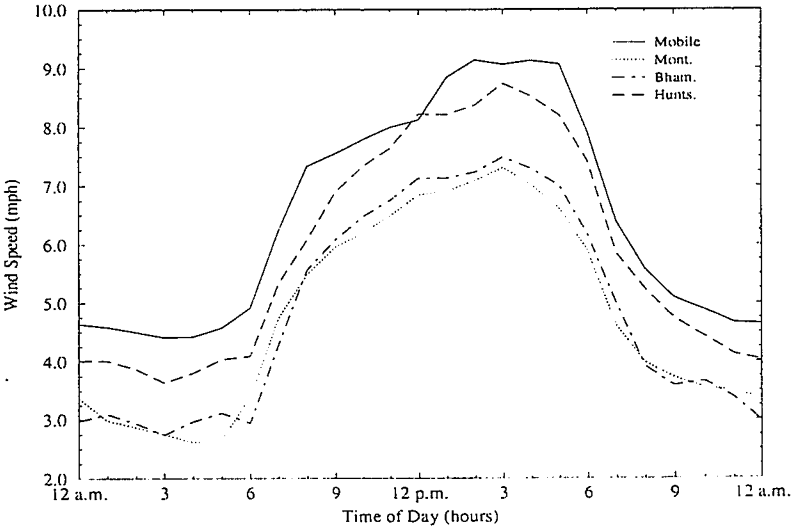

Fig. A.30. Mean Daily Wind Speed Cycle - June

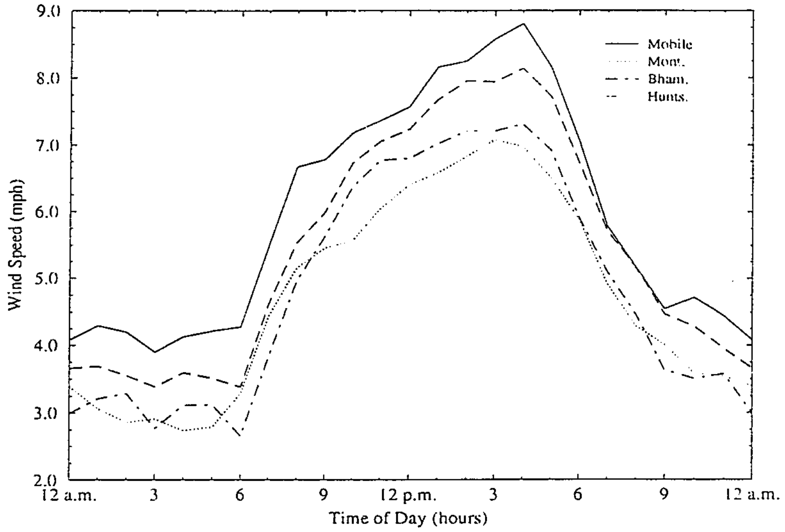

Fig. A.31. Mean Daily Wind Speed Cycle - July

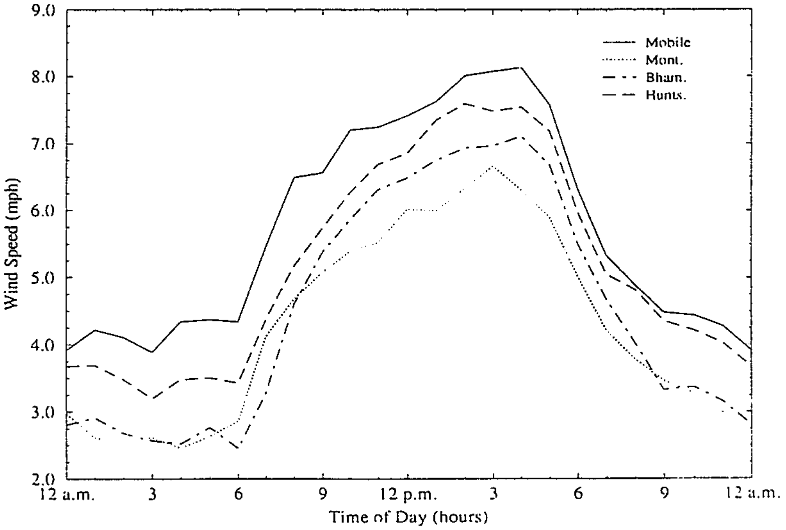

Fig. A.32. Mean Daily Wind Speed Cycle - August

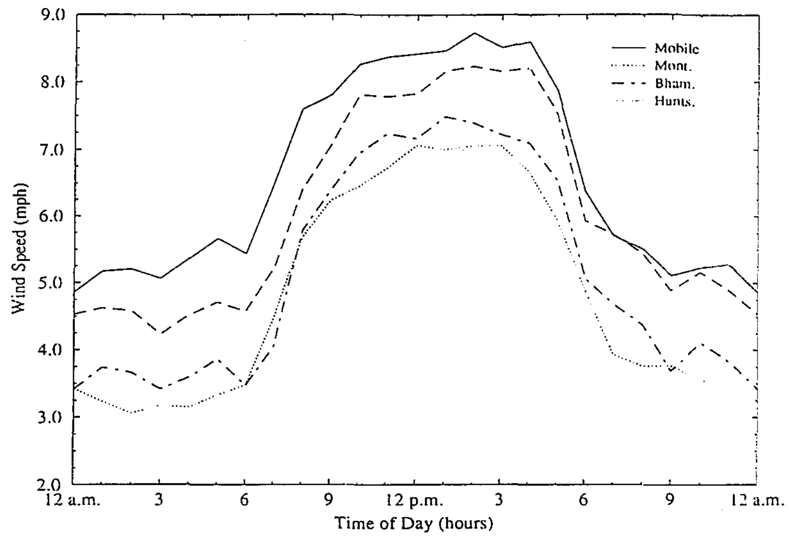

Fig. A.33. Mean Daily Wind Speed Cycle - September

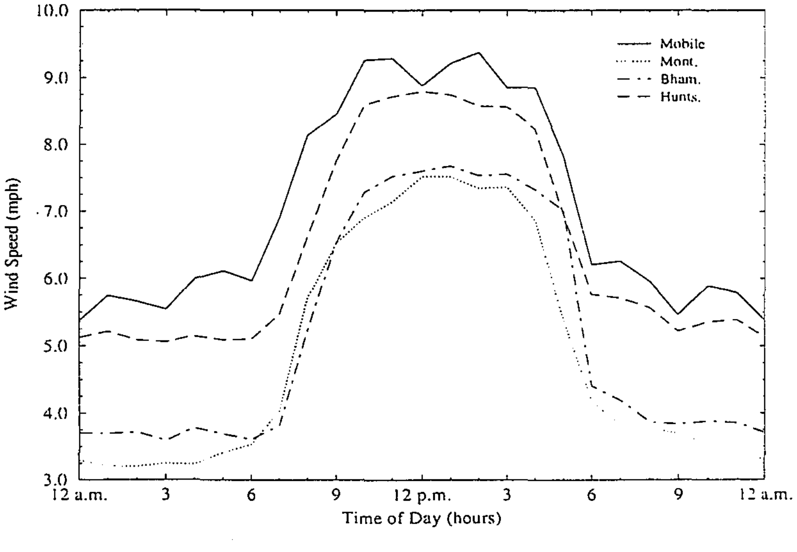

Fig. A.34. Mean Daily Wind Speed Cycle - October

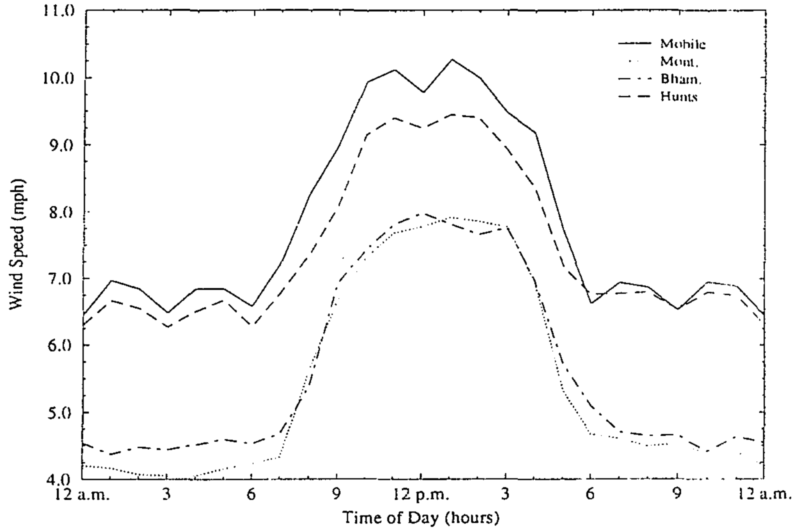

Fig. A.35. Mean Daily Wind Speed Cycle - November

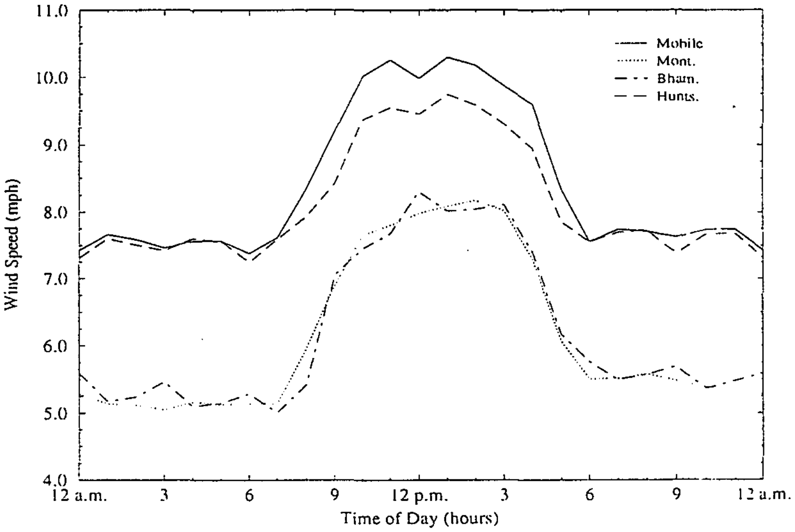

Fig. A.36. Mean Daily Wind Speed Cycle - December

APPENDIX B

Concrete Temperature vs. Ambient Temperature Data

Table B1. ALDOT and Blue Circle Cement Company Ambient Temperature - Concrete Temperature Data*

ALDOT DATA SET		BLUE CIRCLE DATA SET NO. 1		BLUE CIRCLE DATA SET NO. 2	
T_a (°F)	T_c (°F)	T_a (°F)	T_c (°F)	T_a (°F)	T_c (°F)
50	65	63	73	54	67
47	62	53	67	76	70
47	60	65	81	72	72
52	58	65	82	47	67
59	64	47	62	37	68
62	64	43	62	38	65
60	85	46	62	43	68
58	68	47	65	70	72
52	70	58	70	43	67
56	68	55	72	50	56
60	72	54	70	60	56
55	70	38	59	64	59
51	72	48	67	73	64
62	69	53	73	74	66
57	70	58	75	73	64
73	80	41	61	71	63
74	80	62	76	60	74
75	82	48	70	44	68
68	82	64	79	55	70
70	85	65	77	60	76
75	86	54	72	66	78
73	84	58	77	65	78
75	86	48	66	44	60
95	87	58	72	57	64

*T_a = ambient temperature
T_c = concrete temperature

Table B1. ALDOT and Blue Circle Cement Company Ambient Temperature - Concrete Temperature Data (cont.)

ALDOT DATA SET		BLUE CIRCLE DATA SET NO. 1		BLUE CIRCLE DATA SET NO. 2	
T_a (°F)	T_c (°F)	T_a (°F)	T_c (°F)	T_a (°F)	T_c (°F)
80	86	72	82	54	65
86	88	59	70	50	64
82	87	70	82	58	67
81	88	55	68	74	84
85	88	71	82	65	64
81	88	82	87	84	72
81	90	80	86	82	70
88	90	89	88	70	78
94	87	82	88	78	86
55	59	86	89	74	79
47	58	86	89	68	78
49	60	78	86	72	80
72	78	76	84	85	88
64	67	82	88	84	89
58	71	93	91	76	81
66	65	80	88	77	82
80	86	88	90	82	90
78	87	85	89	85	89
77	88	88	90	80	86
78	87	95	91	82	88
81	88	93	88	85	88
82	82	94	89	86	87
92	94	84	88	86	90
60	55	84	87	60	70

Table B1. ALDOT and Blue Circle Cement Company Ambient Temperature - Concrete Temperature Data (cont.)

ALDOT DATA SET		BLUE CIRCLE DATA SET NO. 1		BLUE CIRCLE DATA SET NO. 2	
T_a (°F)	T_c (°F)	T_a (°F)	T_c (°F)	T_a (°F)	T_c (°F)
62	62	93	88	68	70
60	65	94	90	79	76
51	64	89	90	81	78
51	63	83	90	82	80
43	54	85	89	60	75
51	64	86	89	60	74
50	52	85	91	60	75
64	57	79	85	70	77
47	60	87	90	72	78
60	54	88	90	82	84
54	54	89	89	68	72
63	70	71	84	78	78
68	74	71	83	67	74
52	57	86	88	67	79
64	52	84	90	68	78
60	57	89	89	68	79
74	78	84	89	67	77
79	8	80	87	67	78
79	79	84	90	70	78
81	81	84	88	82	81
80	81	78	87	80	83
79	81	85	87	80	82
76	81	82	90	64	81
84	82	84	87	66	85

Table B1. ALDOT and Blue Circle Cement Company Ambient Temperature - Concrete Temperature Data (cont.)

ALDOT DATA SET		BLUE CIRCLE DATA SET NO. 1		BLUE CIRCLE DATA SET NO. 2	
T_a (°F)	T_c (°F)	T_a (°F)	T_c (°F)	T_a (°F)	T_c (°F)
78	82	68	83	70	81
76	84	79	88	70	80
87	84	86	90	72	80
81	81	84	87	71	80
92	88	70	83	90	89
81	88	83	88	87	84
99	87	75	85	78	85
93	84	72	80	90	85
84	85	65	79	74	80
95	82	69	78	73	80
90	80	74	82	74	80
88	86	75	83	75	83
87	80	81	87	75	80
83	80	81	84	75	82
47	54	73	82	73	84
52	59	74	82	72	80
50	62	78	83	85	82
54	60	79	84	87	83
40	68	75	80	79	86
49	56	75	81	81	86
56	56	73	78	70	85
40	57	75	82	70	84
48	59	77	83	70	84
48	58	78	86	70	80

Table B1. ALDOT and Blue Circle Cement Company Ambient Temperature - Concrete Temperature Data (cont.)

ALDOT DATA SET		BLUE CIRCLE DATA SET NO. 1		BLUE CIRCLE DATA SET NO. 2	
T_a (°F)	T_c (°F)	T_a (°F)	T_c (°F)	T_a (°F)	T_c (°F)
42	56	73	83	70	82
63	62	72	80	71	80
61	61	73	85	71	82
56	62	74	85	72	83
58	54	75	85	74	82
47	51	72	79	78	85
41	53	67	76	84	85
81	76	74	83	86	87
70	84	71	80	84	89
75	84	68	80	73	78
87	87	71	82	73	81
78	85	58	75	73	81
74	85	68	77	71	80
81	86	68	80	71	80
72	82	63	78	72	81
89	86	61	75	73	80
76	85	55	70	74	80
73	83	49	68	74	82
75	85	50	68	74	82
90	86	46	66	86	82
87	87	42	59	80	83
73	84	40	58	82	88
92	85	44	67	84	88
78	81	47	70	88	89

Table B1. ALDOT and Blue Circle Cement Company Ambient Temperature - Concrete Temperature Data (cont.)

ALDOT DATA SET		BLUE CIRCLE DATA SET NO. 1		BLUE CIRCLE DATA SET NO. 2	
T_a (°F)	T_c (°F)	T_a (°F)	T_c (°F)	T_a (°F)	T_c (°F)
79	82	52	72	72	81
80	84	67	82	72	80
79	81	54	70	73	80
79	81	57	71	73	81
91	85	60	72	76	87
88	85	59	70	72	81
84	83	55	69	73	82
		54	69	76	84
		45	68	71	80
		45	62	70	80
		45	67	70	80
		44	68	71	81
		46	70	72	81
		45	69	72	81
		45	70	72	82
		61	77	75	86
		65	77	76	85
		58	73	74	80
		60	74	74	80
		36	56	72	80
		43	68	82	84
		46	68	78	84
		33	56	77	83
		34	55	76	79

Table B1. ALDOT and Blue Circle Cement Company Ambient Temperature - Concrete Temperature Data (cont.)

ALDOT DATA SET		BLUE CIRCLE DATA SET NO. 1		BLUE CIRCLE DATA SET NO. 2	
T_a (°F)	T_c (°F)	T_a (°F)	T_c (°F)	T_a (°F)	T_c (°F)
		36	55	76	80
		36	68	74	79
		38	64	75	80
		36	67	72	82
		66	78	74	80
		44	69	74	83
		46	70	85	88
		47	69	68	78
		38	50	69	78
		45	62	70	78
		65	72	72	80
		65	70	70	84
		62	65	72	80
		48	60	72	80
				73	82
				74	82
				74	80
				74	81
				70	84
				73	82
				82	84
				84	85
				83	82
				74	83

Table B1. ALDOT and Blue Circle Cement Company Ambient Temperature - Concrete Temperature Data (cont.)

ALDOT DATA SET		BLUE CIRCLE DATA SET NO. 1		BLUE CIRCLE DATA SET NO. 2	
T_a (°F)	T_c (°F)	T_a (°F)	T_c (°F)	T_a (°F)	T_c (°F)
				90	88
				92	89
				74	83
				80	87
				84	89
				85	88
				85	87
				86	87
				91	87
				76	86
				85	87
				91	88
				76	81
				89	89
				90	88
				81	84
				63	78
				66	78
				84	86
				70	78
				78	82
				74	80
				76	82
				82	80