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16. Abstract
This report includes an extensive literature review and laboratory investigations for selected physical properties of concrete mixtures used in the construction of continuously reinforced concrete pavement (CRCP). Nine test parameters were investigated in this study: temperature, relative humidity, and wind speed; concrete temperature, type of aggregate, amount of mixing water and replacement of fly ash; and mixing time and consolidation effort. A total of 116 tests were performed in three categories: strength tests such as compressive, pullout, flexural and modified compressive strength; volume and weight change tests such as shrinkage and weight loss of bar specimen, moisture content, and loss measurements of cube specimen; and other tests such as time of setting and abrasion resistance.

An evaporometer developed by SDHPT was used to measure evaporation rates for several environmental condtions, and to congregate the environmental factors into one variable. The results showed good correlations with the PCA evaporation chart within the ranges tested and were found to be a very promising single parameter which can predict most of the physical properties of concrete, such as strength development and shrinkage characteristics. Design curves were developed based on the evaporation rate measured by the Evaporometer for 7 day flexural strength, half time shrinkage, and ultimate shrinkage. A procedure for correcting the strength and shrinkage with respect to the duration of the environmental condition is also presented.

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Environmental Effects on the Physical Properties of Concrete, the First 90 Days

by

Man Yop Han
Mikael P. J. Olsen

Research Report 371-1
Research Study 2-8-85-371

Sponsored by

The Texas State Department of Highways and Public Transportation
in cooperation with
The U.S. Department of Transportation
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College Station, Texas 77843

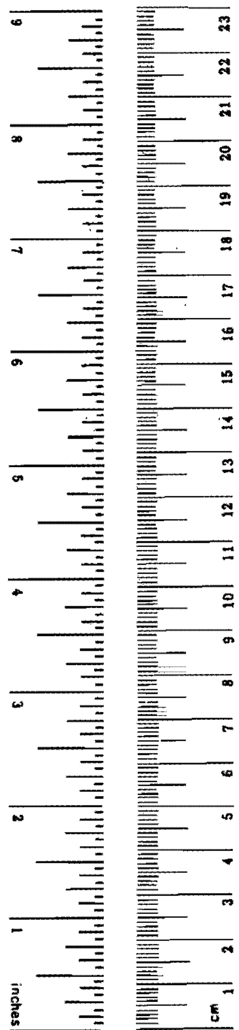
METRIC (SI*) CONVERSION FACTORS

APPROXIMATE CONVERSIONS TO SI UNITS

Symbol	When You Know	Multiply By	To Find	Symbol
	LENGTH			
in	inches	2.54	millimetres	mm
ft	feet	0.3048	metres	m
yd	yards	0.914	metres	m
mi	miles	1.61	kilometres	km
	AREA			
in^2	square inches	645.2	millimetres squared	mm^2
ft^2	square feet	0.0929	metres squared	m^2
yd^2	square yards	0.836	metres squared	m^2
mi^2	square miles	2.59	kilometres squared	km^2
ac	acres	0.395	hectares	ha
	MASS (weight)			
oz	ounces	28.35	grams	g
lb	pounds	0.454	kilograms	kg
T	short tons (2000 lb)	0.907	megagrams	Mg
	VOLUME			
fl oz	fluid ounces	29.57	millilitres	mL
gal	gallons	3.785	litres	L
ft^3	cubic feet	0.0328	metres cubed	m^3
yd^3	cubic yards	0.0765	metres cubed	m^3

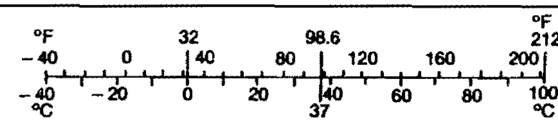
NOTE: Volumes greater than 1000 L shall be shown in m^3.

Symbol	When You Know	Multiply By	To Find	Symbol
	TEMPERATURE (exact)			
°F	Fahrenheit temperature	5/9 (after subtracting 32)	Celsius temperature	°C



APPROXIMATE CONVERSIONS TO SI UNITS

Symbol	When You Know	Multiply By	To Find	Symbol
	LENGTH			
mm	millimetres	0.039	inches	in
m	metres	3.28	feet	ft
m	metres	1.09	yards	yd
km	kilometres	0.621	miles	mi
	AREA			
mm^2	millimetres squared	0.0016	square inches	in^2
m^2	metres squared	10.764	square feet	ft^2
km^2	kilometres squared	0.39	square miles	mi^2
ha	hectores (10 000 m^2)	2.53	acres	ac
	MASS (weight)			
g	grams	0.0353	ounces	oz
kg	kilograms	2.205	pounds	lb
Mg	megagrams (1 000 kg)	1.103	short tons	T
	VOLUME			
mL	millilitres	0.034	fluid ounces	fl oz
L	litres	0.264	gallons	gal
m^3	metres cubed	35.315	cubic feet	ft^3
m^3	metres cubed	1.308	cubic yards	yd^3
	TEMPERATURE (exact)			
°C	Celsius temperature	9/5 (then add 32)	Fahrenheit temperature	°F



These factors conform to the requirement of FHWA Order 5190.1A.

* SI is the symbol for the International System of Measurements

DISCLAIMER

The information contained herein was developed on Research Study 2-8-85-371 titled "Environmental Effects on the Physical Properties of Concrete, the First 90 Days" in a cooperative research program with the Texas State Department of Highways and Public Transportation and the U.S. Department of Transportation, Federal Highway Administration.

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

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SUMMARY AND IMPLEMENTATION

In order to improve the current design and construction guidelines for a continuously reinforced concrete pavement (CRCP) that is maintenance free for at least 20 years, an extensive literature review and laboratory investigations for physical properties of concrete at early age (less than 90 days) were performed. The tests conducted can be classified into three categories: strength tests, volume and weight changes, and other tests. The strength tests include compressive, pullout, flexural and modified compressive strength; the volume and weight change tests include shrinkage and weight loss measurements of prisms and moisture content and moisture loss measurements of cubes. The remaining category of tests include time of setting test and abrasion resistance by sandblasting.

The nine test parameters investigated in this study are divided into three categories: environmental factors, material variations and quality control. Since the full factorials of these parameters are too large to accomplish within a reasonable time, the total number of tests were therefore reduced to 116, based on typical materials used and environmental conditions encountered in Texas.

An evaporometer developed by the Texas State Department of Highways and Public Transportation was used to measure evaporation rates for several environmental conditions, and to congregate the environmental factors such as air and concrete temperatures, relative humidity and wind speed into one variable. The results showed good correlations with a chart developed by the Portland Cement Association (PCA) within the ranges investigated and were found to be of great value in predicting most of the physical properties of concrete, such as strength development and shrinkage characteristics.

The type of aggregate affects flexural strength, shrinkage and moisture loss characteristics quite significantly; however, strength and abrasion resistance are not affected by the type of aggregate. The differences in the results are mainly due to the differences in porosity and surface texture of the aggregate. Even though some data scatter was observed, the increase in water content decreases the concrete quality. In this study, a 1:1 replacement of fly ash was used, which resulted in a slight strength reduction and different shrinkage and moisture loss characteristics.

Finally, the mixing time was found to be an important factor which affects selected test results significantly. The extended mixing in hot and dry weather

reduced strength and increased shrinkage and water loss. The consolidation methods employed did not affect the physical properties of concrete significantly. In general, however, the vibrating method yielded slightly higher strength, when compared to the other two methods of consolidation.

TABLE OF CONTENTS

LIST OF TABLES

LIST OF FIGURES

I. INTRODUCTION

1.1 General

Concrete pavements are generally subjected to natural weathering and repeated traffic loading during their service life. The performance of concrete pavements depends on the concrete quality, especially on tensile strength, bonding strength, and shrinkage properties. Proper mixing, placing, and curing are essential in the production of high quality concrete.

The development of shrinkage cracks at early ages is an important factor in the durability of concrete. Inadequately controlled cracking generally accelerates deterioration of a pavement. Moisture control during construction and the curing period is very important for the development of crack spacing within a reasonable range.

The loss of moisture depends on an intricate relationship of environmental conditions such as temperature, humidity, and wind speed. Besides those parameters, length of time between mixing and placement, concrete temperature at placement, degree of consolidation, and aggregate type will influence the physical properties of concrete significantly. Major findings in the above areas over the past few years are presented in the next chapter.

1.2 Objectives

The objectives of this study are to examine the factors that influence the development of the physical properties of concrete pavements during the first 90 days, and to develop procedures for using these physical properties to more accurately predict the performance of those pavements. Specifically, the following were investigated:

1. Ways to assure retention of sufficient moisture to develop the full potential of strength and durability, and
2. Shrinkage crack development as a function of changes in moisture condition brought about by changes in the environment.

1.3 Scope

In this research, the effect of most of the possible factors which affect the development of early physical properties of concrete was investigated. The majority of those factors are believed to influence the concrete properties by influencing the moisture movement, hydration and density.

The variables which are considered in this research have many combinations. The research effort was therefore divided into the following three parts:

The first part of the laboratory study investigated the effect on strength, shrinkage, moisture content, weight loss, and abrasion resistance of nine combinations of air temperature, relative humidity, wind speed, and concrete temperature which are commonly encountered in Texas. These nine environmental combinations were combined with varying water content and aggregate type for a total of 54 test conditions in this step.

The second step investigated the effect of a severe Texas environmental condition and 30 different combinations of aggregate type, water content, mixing time, mix design, and method of consolidation. The severe environmental condition was one of the nine combinations in the initial part. The total number of test conditions in this step was also 54.

The final step investigated the concrete properties under a standard environmental condition. This standard condition was also one of the nine environmental combinations above for reference purposes. The effect of consolidation effort and mixing time was also investigated in this step for a total of nine tests.

Compressive strength, flexural strength, shrinkage, water loss characteristics, abrasion, and pullout strength were measured for each test. Unit weight, air content, slump, and time of setting were measured for each batch for quality control purposes. In connection with the measurement of water loss, the Evaporometer developed by the Materials and Tests Division (D-9) of the Texas State Department of Highways and Public Transportation for measuring evaporation rates (1) was used and the results were calibrated with actual water loss values, and the PCA Evaporation Chart (2).

II. LITERATURE REVIEW

2.1 General

Like any other type of concrete structure, the performance of concrete pavements is influenced by factors that can be classified into the following categories:

1. Environmental factors
2. Construction
3. Materials selection and design, and
4. Magnitude and frequency of loading.

The material response to the above factors is of a combined nature, thus making an exact analysis of this response complex. A careful consideration and understanding of how each factor affects the concrete individually is, however, imperative. In addition, some of the complexity can be reduced by first examining the factors individually.

In the case of CRC pavements, a careful examination of the following phenomena is necessary:

1. Concrete Curing
2. Strength development, and
3. Shrinkage and shrinkage cracking

since these three items have been shown to influence the performance of CRC pavements (3, 4, 5). While they can be viewed as strictly materials properties by themselves, they can (and should) also be viewed as a result of the construction procedures, quality control employed, materials variability, and environmental factors existing at the time of construction. To investigate the causes of poor pavement performance and to improve the current design and construction procedures, the following summary of the State-of-the-Art provides a basis for this study.

2.2 Curing of Concrete

Proper curing by maintaining adequate moisture and temperature is very important for the production of good quality concrete. If proper curing is not applied, strength, impermeability, dimensional stability, and wear resistance of pavement are affected adversely (6). The effect of curing on compressive strength is shown in Figure 1 (2). The figure shows that once the specimens are exposed in air, the compressive strength development virtually ceases. Although an increase in early strength gain can be observed, the ultimate strength of the specimens is significantly lower than for a moist cured specimen. If the specimens are exposed in air throughout their lives, their ultimate strengths are less than half that of the moist cured specimen.

Surface properties of portland cement concrete are significantly affected by evaporation, the degree of which is a function of environmental factors such as air temperature, relative humidity, and wind speed (6). The environmental factors are not generally easy to control. Many attempts have been made to predict the combined effect of environmental factors (2, 6). Figure 2 (2) is a fairly well-known chart which can predict the evaporation rate under a given environmental condition. A study performed by Texas Transportation Institute (TTI) (5, 6) revealed contradictory findings and the validity of Figure 2 was questioned. The contradictory findings have, however, not been repeated in this present study and explanations are offered for their presence in the previous TTI study (See Section 4.2).

Excessive moisture loss should be prevented in order to allow complete hydration. Some curing compounds have been developed to retard evaporation and to ensure continuous hydration under low relative humidity conditions. The effects of curing compounds such as monomolecular film (MMF), water soluble linseed oil (WSLO), white pigmented compound (WPC), and their combinations in retaining the moisture in concrete have been investigated (6). These curing compounds were effective in the laboratory test. However, field observations (7) indicate that curing compounds are not as effective there as in the laboratory in allowing full development of the strength and modulus of elasticity of concrete. Continuous moist curing, if possible, is the best method for curing concrete (7).

It is reported that plain concrete requires at least 3 to 4 days curing (8). Another report suggests that 5-day curing is adequate for warm and hot weather, and 7-day curing for cold weather (9). However, some PCC overlays have been

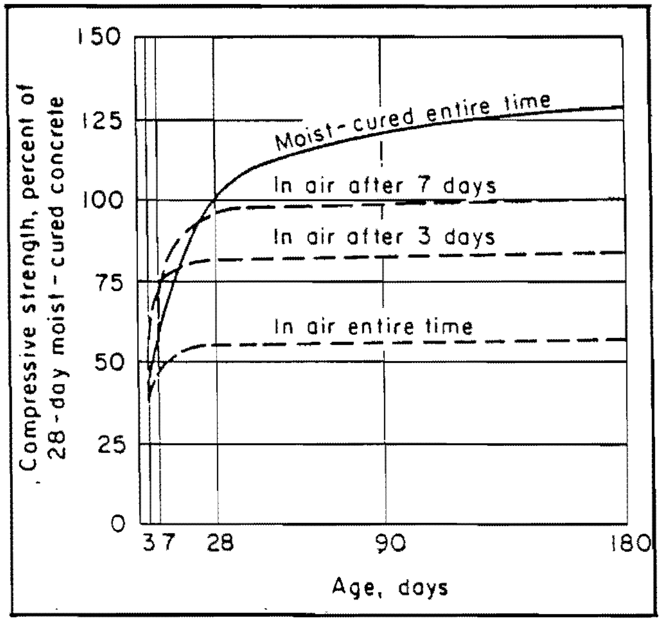


Figure 1. Curing effect on compressive strength (2)

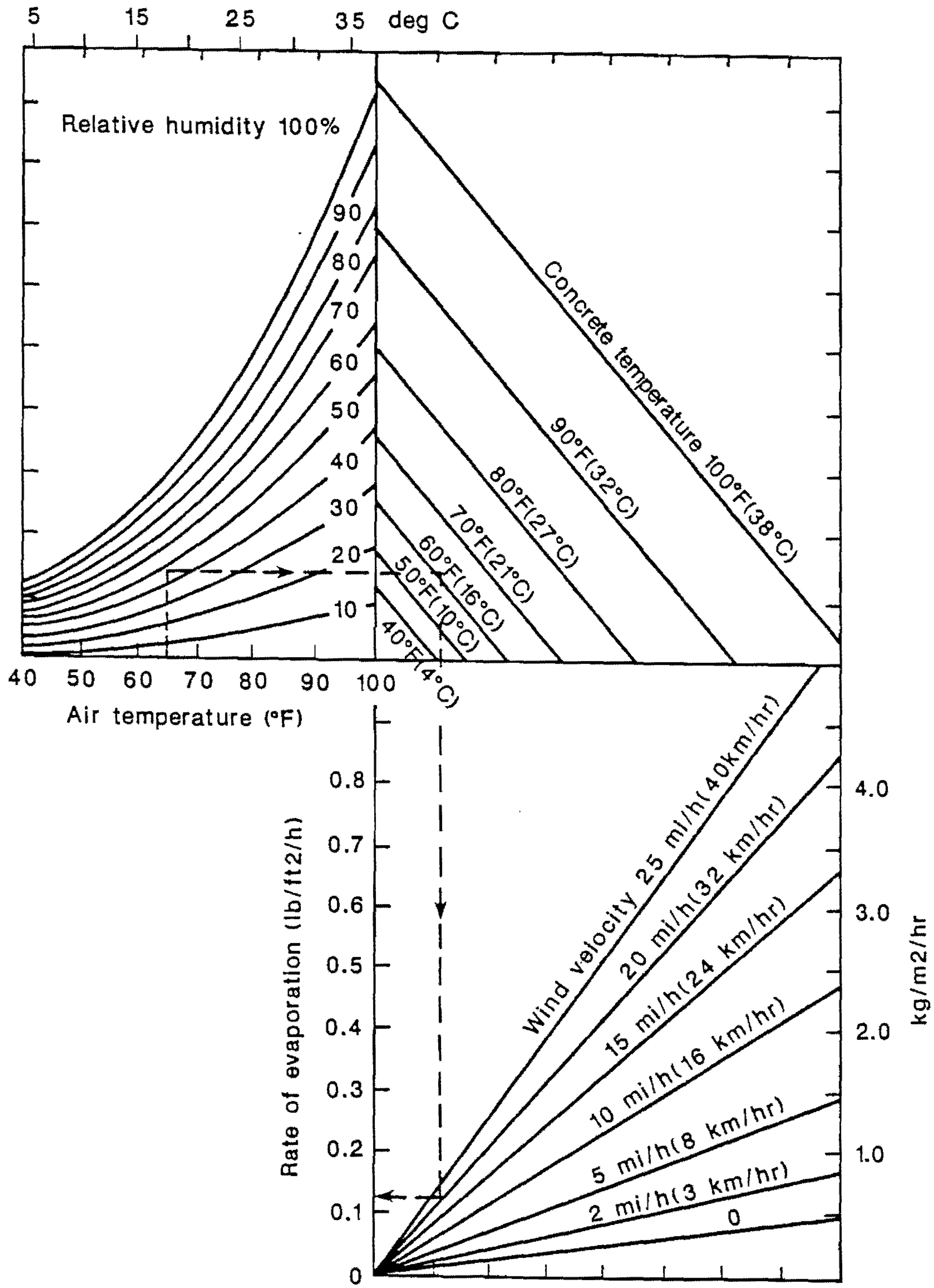


Figure 2. PCA Chart to calculate the rate of evaporation of water from freshly placed concrete (2)

put into service immediately following a 24-hour curing period by using high early strength concrete (10).

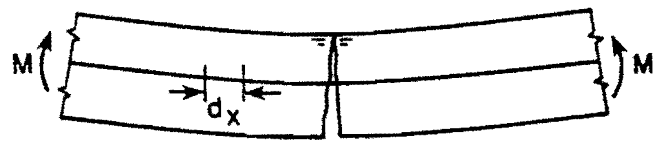
2.3 Strength Development and Measurement

The strength of hardened concrete is considered to be the most important property of concrete, although in many practical cases other properties, such as durability, volume stability, and impermeability may be more significant (11). It is also generally accepted that an improvement of strength will improve the other properties as well (11).

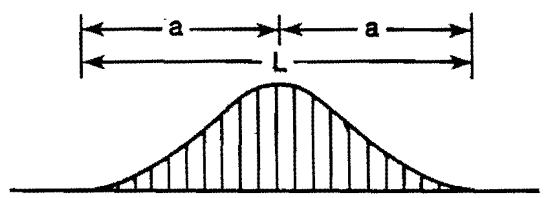
The most important concrete strength parameters affecting CRC pavement performance are bond strength and tensile strength. Figure 3 (12) shows a schematic stress distribution around a crack in CRC pavement. Very highly concentrated bond stress can be observed right next to the crack. To minimize the damage done to the concrete and to ensure adequate performance, the bond strength has to be sufficient enough to provide the necessary stress transfer of the tensile stresses in the concrete to the steel.

The tensile strength influences the crack formation and the characteristics of cracking, such as crack spacing and crack width in CRC pavements (12). A series of reports (13, 14, 15) based on field observations found certain limits for crack spacing and crack width and suggested the use of these limits in the design of CRCP. Ravina and Shalon (16) have found that tensile strength, rather than evaporation rate, is more decisive in plastic shrinkage cracking. Cracking occurs whenever the strength is less than the induced shrinkage stress. However, no information related to effect of changes in the bond characteristics between the concrete and the reinforcing steel on performance was found. It is believed that changes occur in the bond characteristics as a function of age, loading, and crack spacing. For example, during rehabilitation of CRC pavements in Illinois, the longitudinal reinforcing bars at or near existing cracks in the old pavement were found to be debonded (17). In some cases the reinforcing bar was completely debonded between cracks spaced 1 to 3 feet apart.

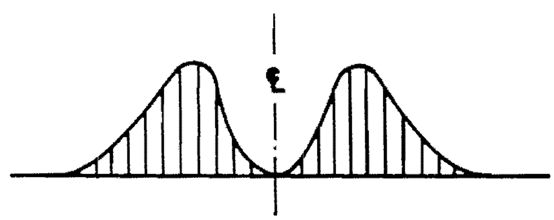
Higher tensile strength can be achieved with higher cement content, higher temperature and lower water content. On the other hand, the effects of the above factors on stresses depend on exposure conditions, and also have some adverse effects. For example, higher cement content may be useless in prevention of cracking



1-A. Cracked slab portion



1-B. Longitudinal tensile stress in the steel (schematic)



1-C. Bond stress (schematic)

Figure 3. Stress and moment of inertia variations at crack position (12)

because the stress may increase as much or more than the additional strength gain under hot weather conditions (16). A rational computer model for the prediction of crack spacing and strength development in CRC pavements is the subject for a companion report, 371-2F, titled "A Rational Computer Model for Continuously Reinforced Concrete Pavements."

In order to provide a reasonable level of serviceability of pavement, the resistance to surface wear due to traffic vehicles has to be maintained together with tensile strength. ACI Committee 201 (18), however, states that it is not possible to set precise limits for abrasion resistance of concrete. Several factors such as compressive strength, aggregate type, finishing and curing method affect the abrasion resistance of concrete (18). Tests (19, 20) and field experience have generally shown that compressive strength is by far the most important single factor controlling the abrasion resistance of concrete.

Pullout Strength: To measure the strength development of concrete in CRC pavements, three methods can be used. They are:

1. Compressive strength of cylinders or flexural strength of beams
2. Compressive or indirect tensile strength of cores, and
3. Nondestructive testing.

Whereas the testing of cylinders and beams provides information on the strength of the concrete being used in a CRCP project, the results can only provide a measure of the potential strength and not the in situ strength. To establish what the actual in situ strength is, a nondestructive test, such as the pullout strength test, has to be used. Most of the studies related to the use of the pullout test have been directed towards correlating the results of the pullout test with conventional cylinder strength data. In general, such correlations are mix specific and varying with aggregate type and size, age, moisture content, and mix proportions (11). A schematic drawing of the pullout test is shown in Figure 4 (21). This test is a slightly destructive test, but correlates highly with compressive strength (22). In order to increase the reliability in estimating concrete strength, a maturity concept has frequently been employed with pullout tests (22, 23). However, when the pullout test is used to determine the strength development of CRC pavements, it appears that a correlation with beam strengths would be more valuable than the usual

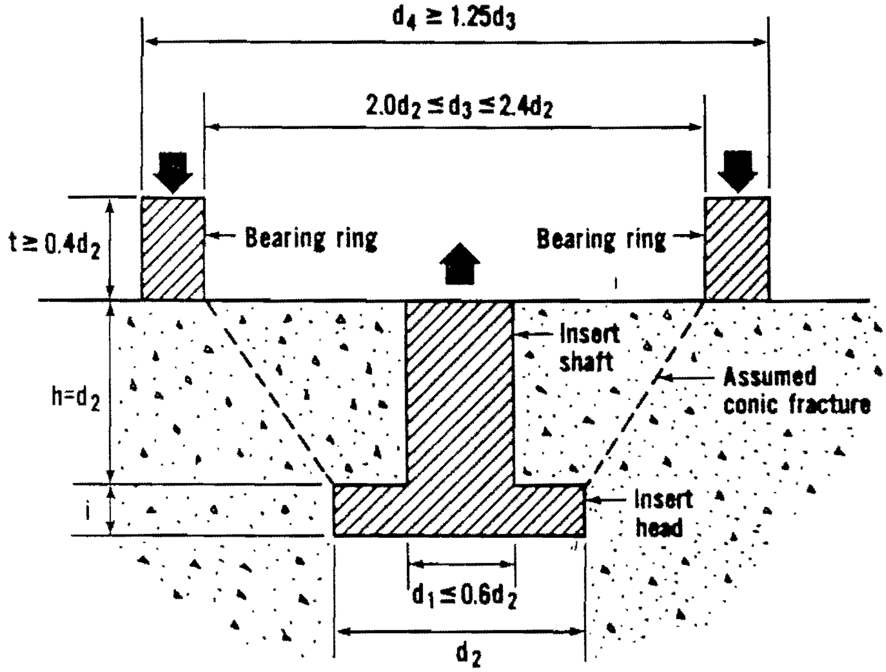


Figure 4. Schematic drawing of pullout test (21)

correlation with the standard cylinder strengths since the beam strength is widely used in Texas during pavement construction. Factors such as the geometry of the pullout specimen, depth of embedment, and size of aggregates in the concrete remain equally important when interpreting the pullout test results.

A series of tests was performed by Stone and Giza (24) to investigate the effect of changes in geometry of the test apparatus and the effect of various concrete aggregate properties on the reliability of the pullout test. They found that for a fixed value of cylinder compressive strength, the average of the ultimate pullout load decreased nonlinearly with increasing apex angles and with decreasing depth of embedment. They also found that the aggregate located in the failure plane played a significant role both in average and deviations of pullout load (24).

The variations of ultimate pullout load for concrete specimens are not significantly different for the apex angles between 58 and 86 degrees, but there are significant differences between apex angles of 46 and 30 degrees (24). The apex angle specified in the current ASTM specification C-900 falls between 54 and 70 degrees (21).

The effect of embedment with a constant apex angle of 58 degrees has also been studied, and the results indicate that the variations of ultimate pullout load for concrete increase with increasing depth of embedment beyond a depth of one inch and with no significant difference detected at depths of one inch or less (24).

Concrete mixtures containing aggregate sizes up to 3/4 inch have approximately the same average ultimate pullout load. As for the deviation of the load, concrete mixtures with an aggregate size of 3/4 inch have significantly higher variation than mixtures with a smaller aggregate size (24). In general, a greater diameter of insert is required for a greater aggregate size.

A number of investigations have proven the pullout tests performance for evaluation of in situ concrete strength (24, 25). Sometimes inserts were placed by hand on site, and it was concluded that more care and improvements for the equipments and the techniques of placing and extracting the inserts were needed (26).

2.4 Shrinkage and Shrinkage Cracking

Shrinkage: There are four types of shrinkage:

1) Plastic shrinkage which occurs within the first few hours after placing,
2) Autogeneous volume change which occurs because of hydration,
3) Carbonation shrinkage which occurs as a result of chemical reaction between hydration products and carbon dioxide, and
4) Drying shrinkage which is associated with the loss of water.

The drying shrinkage which is measured in the laboratory includes both drying shrinkage and autogeneous volume change (27).

The shrinkage of concrete is for the most part caused by the contraction of the cement paste due to drying. As the cement paste dries and shrinks, its motion is restrained by the aggregate embedded in it. The degree of this restraint to shrinkage depends on the amount and the stiffness (modulus of elasticity) of the embedded aggregate (28, 29, 30).

Hansen and Mattock (31) reported that a linear relationship exists between shrinkage strain and the ratio of volume to surface area (v/s) of the specimen. Their results were verified under laboratory conditions, with 70°F and 50 % relative humidity. Their experiment indicates that the shrinkage of small specimens is generally greater than the shrinkage for the actual size of a structure. Similar results were reported by Kraai (32) in 1984. He suggested that a 4-foot square 8-inch thick slab gave almost the same result as field measurements. The results of Kraai's investigation (32) is summarized in Figure 5. It can be observed that the shrinkage value of laboratory specimens can be two to six times greater than the the shrinkage of a 4-foot square 8-inch thick slab depending on the specimen size. The smaller the size, the greater the difference is. The comparisons are based on tests of 4× 4× 11 - inch prisms and 4-foot square slabs 8 inches thick. The prisms were tested according to ASTM C-157, but the slabs were 100 percent field cured. Note that the highest shrinkage occurs with the smallest specimen (11, 33).

A similar study performed in Texas (34) found that shrinkage of specimens stored in open air was smaller than that of companion specimens stored in the laboratory at constant temperature and relative humidity, by a factor of 0.62 or 0.82, depending on the field location. The two factors were obtained from the

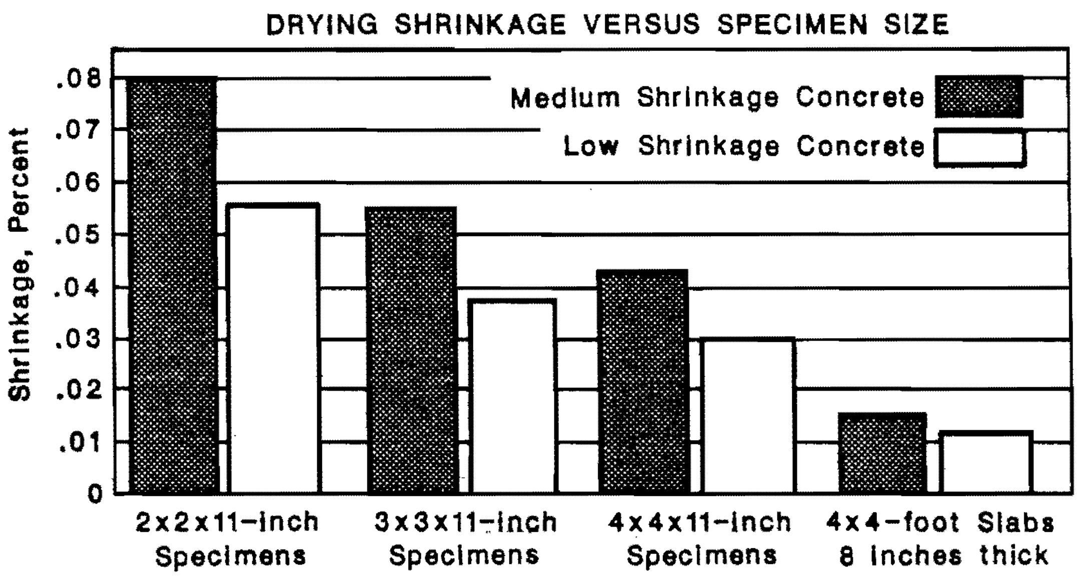


Figure 5. Effect of specimen size on drying shrinkage (32)

Dallas and Odessa areas, respectively.

Hansen and Mattock (31) also suggested that shrinkage can be estimated using a hyperbolic function of time. The proposed function is:

$$\epsilon_s = \frac{\epsilon_s^{\infty} \times t}{N_s + t}$$

where ϵ_s = shrinkage strain

ϵ_s^{∞} = ultimate shrinkage strain

t = time in days since measurements begin

N_s = the time in days to reach half of ϵ_s^{∞}

In the equation, the shape and size effect is included in the coefficient N_s as a volume/surface ratio (v/s). Both the final shrinkage strain and the coefficient N_s were found to be linearly proportional to the volume/surface ratio in semi-logarithmic plot (31).

However, there are several different ways to interpret the factors in the equation. ACI committee 209 (35) used the equation to predict shrinkage as a function of time. In their report several other factors such as initial moist curing, ambient relative humidity and temperature, and the v/s ratio are considered in the coefficient of the equation. The coefficient of shrinkage half time, N_s, is assumed to be constant and only the ultimate shrinkage, ϵ_s^{∞}, is assumed to be affected by the above factors. On the other hand, a more recent study (36, 37) claims that the size and shape of specimen affects the shrinkage half time, N_s, rather than the ultimate shrinkage, ϵ_s^{∞}.

In order to reduce the rate of slump loss and water requirement, and to obtain a uniform time of setting under hot weather conditions, retarders (type B) and water reducing retarders (type D) specified in ASTM C-494 are often used. Retarders (sodium ligno-sulphonate) tested by Shalon and others (16, 38, 39) showed, as expected, a later transition time, and increased total early plastic shrinkage when compared to plain mortar (1.3 % against 0.93 %) (38). The increased shrinkage is due to the increased time in the plastic stage of paste and possible changes in paste microstructure (39).

Sometimes shrinkage compensating cement concrete is used to reduce shrinkage cracking. Fifty-nine investigated concrete structures were, on the average, rated with very good performance in reducing drying shrinkage cracks (40). However, the use of this type of cement has some side effects which stem mainly from the control of the initial expansion.

When the shrinkage data are analyzed and used for predicting time dependent variations, three types of errors can be involved (40): 1) variations of material properties, 2) variations in environmental conditions, and 3) variations of shrinkage mechanism. A statistical process called the Bayesian method, which can eliminate the variations of material properties, has been suggested and its performance has been proven. This approach is based on the short term data and extrapolation method (41, 42, 43). Another study (44) based on spectral analysis of a stochastic process tried to eliminate the randomness of shrinkage and to calculate the random shrinkage stress.

Shrinkage Cracking: Plastic shrinkage without cracking is not objectionable (45). During the service life of the concrete, however, it is possible for the plastic shrinkage cracks to join each other and form cracks that extend through the concrete section. Initial cracks (microcracks) cannot be observed until the cracks grow large enough and become macrocracks (42). However, their influence on the strength properties of the concrete specimen cannot be neglected. Short term preloading may change the test results significantly due to microcracking (45, 46).

Cracking is unavoidable for freshly placed concrete in most cases. Although cracking is unavoidable, it will not be detrimental to concrete serviceability if the cracking can be controlled within a reasonable range (6, 21). Lerch (45) reported that plastic shrinkage cracks are not usually progressive, even though they have considerable depth.

The evaporation rate, which is a function of environmental factors, is the most important factor affecting plastic shrinkage and plastic shrinkage cracking of concrete (5, 38). It is believed that cracking takes place whenever the rate of evaporation is greater than the rate at which water rises to the surface of the recently placed concrete (bleeding) (8). Moisture migration from concrete to the environment is a very important phenomenon for shrinkage and creep, but unfortunately, also a very complex phenomenon to analyze. Moisture movement in concrete takes place in two basic phases, vapor and liquid phases, through a combination of several mechanisms which vary as the moisture content of concrete varies (47). Heat transfer, occurring in combination with moisture transfer, makes the phenomenon even more complex. Siang (47) has constructed a computer program which can consider the combined effect of heat and mass transfer through concrete. The main problem with this program is that it requires knowledge of physical constants that are difficult to determine experimentally for some specific mixes.

The type of cement also affects the moisture migration and shrinkage of concrete. A study (48) on the correlations between moisture and shrinkage characteristics of paste and concrete concluded that the type of cement affects the moisture migration properties and shrinkage. The rate of hydration and micro structure of the concrete are other factors which influence the plastic shrinkage and plastic shrinkage cracking by changing the diffusivity of concrete (38).

The Portland Cement Association (PCA) (6, 8) recommends that if the rate of evaporation exceeds 0.2 lb/sqft/hr, the following special treatments are needed to minimize the possibility of plastic shrinkage cracking (8):

1) Dampening of subgrade and formwork,
2) Placement of the concrete at the lowest practical temperature,
3) Erection of windbreaks and sunshades,
4) Reduction of the time between placement and start of curing,
5) Minimization of evaporation, particularly during the first few hours subsequent to placing concrete, by a suitable means such as applying moisture by fog spraying.

Ravina and Shalon (49), however, reported that short-time bleeding mortar did not crack under a highly evaporable condition which generated heavy shrinkage cracking in long-time bleeding mortar. Even though long-time bleeding mortar showed a delay of subsurface evaporation at the onset of shrinkage, the total shrinkage was more than double that of the short-time bleeding mortar. They found no correlation between bleeding and cracking and concluded that the above bleeding hypothesis was incorrect for total plastic shrinkage and plastic shrinkage cracking (49).

In the same study Ravina and Shalon (49) also found that direct exposure to solar radiation may not cause plastic shrinkage cracking despite the increase in evaporation. The reason for this is that the consistency of the concrete affects the rate of strength development and that a reduction in the rate of strength development may be more decisive than the reduction of stress and restraint obtained by increasing the consistency of the concrete. Other laboratory results support their conclusions (50).

Presetting cracking, which depends on differential settlement rather than on the magnitude or rate of bleeding, is often coupled indiscriminately with plastic shrinkage cracking, thus causing erroneous conclusions. Differential settlement, a result of flash set due to a very low gypsum content, is the cause of the presetting cracking (49).

A computer program, which can calculate deflections and stresses in an unreinforced concrete pavement slab that is subjected to variable temperature and humidity, was used to analyze the thermal properties, elastic properties and time-dependent properties. The results suggested that the following methods would be helpful for reducing cracking (51):

1) Increase the thickness of slab,
2) Decrease the plan dimensions of the slab,
3) Reduce soil stiffness, and
4) Maintain a low concrete temperature.

2.5 Factors Affecting Concrete Properties

2.5.1 Environmental Factors

Air Temperature: It is generally accepted that high temperatures have, in many respects, only detrimental effects on concrete properties. High temperatures during the curing period, resulting in significant shrinkage, have been reported as the cause of erratic and closely spaced crackings of CRC pavement (52, 53, 54). When a pavement is cured under lower temperatures and more humid conditions, desirable crack spacing and crack patterns can be developed (55, 56). Similarly, a pavement placed and cured under a lower differential temperature between placement and curing periods would be expected to develop more uniform crack spacings (57, 58).

The environmental conditions primarily affect the top of the slab and not the bottom (6). The concrete in high temperatures develops high early strength, but will have lower ultimate strength. Figure 6 (59) shows the dependency of strength

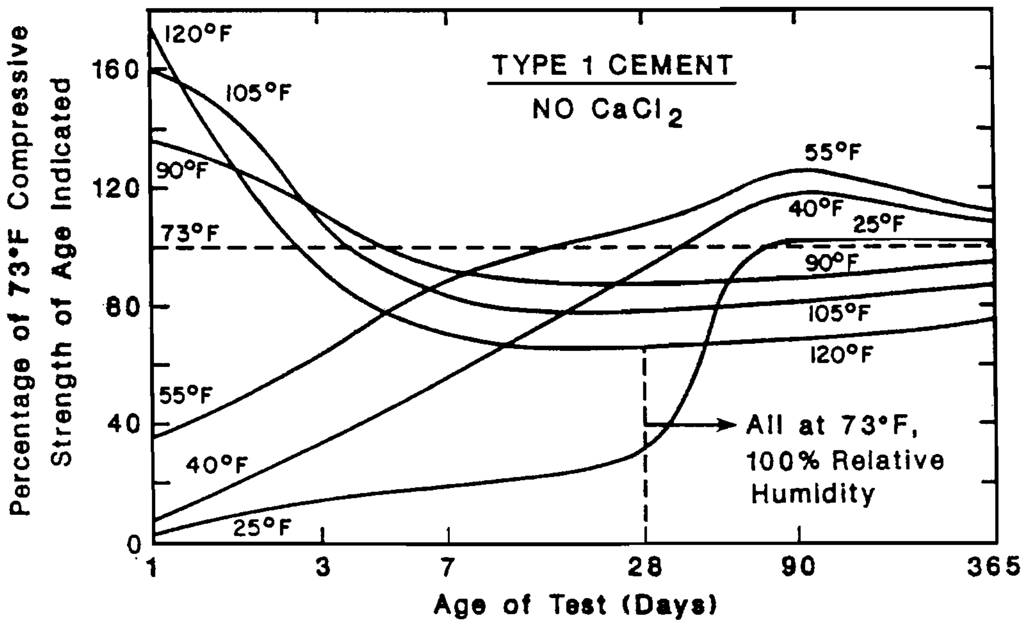


Figure 6. Effect of temperature on the compressive strength of type I cement; Air content, $4 \pm \frac{1}{2}$ percent; cement content, 5.5 sacks per cubic yards (59).

development on the temperature.

Undesirable hot weather effects on fresh concrete include (8, 16):

1) Increased water demand,
2) Increased rate of slump loss,
3) Increased tendency for shrinkage cracking, and
4) Increased difficulty in controlling entrained air content.

Undesirable hot weather effects on hardened concrete include:

1) Decreased strength because of high water demand,
2) Decreased durability, and
3) Decreased uniform surface appearance.

Relative Humidity: If the relative humidity is below 80 percent, the rate of hydration decreases rapidly and, as a result, further improvement of concrete quality virtually ceases (59). Figure 7 (59) shows the degree of saturation of cement after six months of storage at different relative humidities. At vapor pressures below 0.8, the degree of hydration is low, and is negligible at vapor pressures below 0.3. Figure 7 also shows that only about one half of the water present in the paste can be used for chemical combination when no water is lost, i.e., when the vapor pressure is 1.0.

Another problem, which is related to evaporation is that plastic shrinkage cracking occurs very often in low relative humidity conditions and especially when it is combined with high temperature and high wind speed (6, 16 60). An evaporometer, which can measure the rate of evaporation on a surface of free water, has been developed and is used in this project (1). This apparatus is easy to use both in the field and in the laboratory and considers the direct effect of different combinations of environmental conditions. However, the evaporation rate measured with this apparatus is not an absolute value and needs to be calibrated in order to determine the actual evaporation rate from a concrete surface.

Wind Speed: Wind is another important factor which affects the evaporation rate significantly. Therefore, many studies have recommended the use of wind breakers when strong wind is expected (8). In a laboratory test (61), there was little difference in weight change, shrinkage and creep of hardened cement mortar between specimens exposed to 5 m/s wind (11.3 mph) and specimens stored in no wind. Therefore, wind effects on creep and drying shrinkage of structural concrete

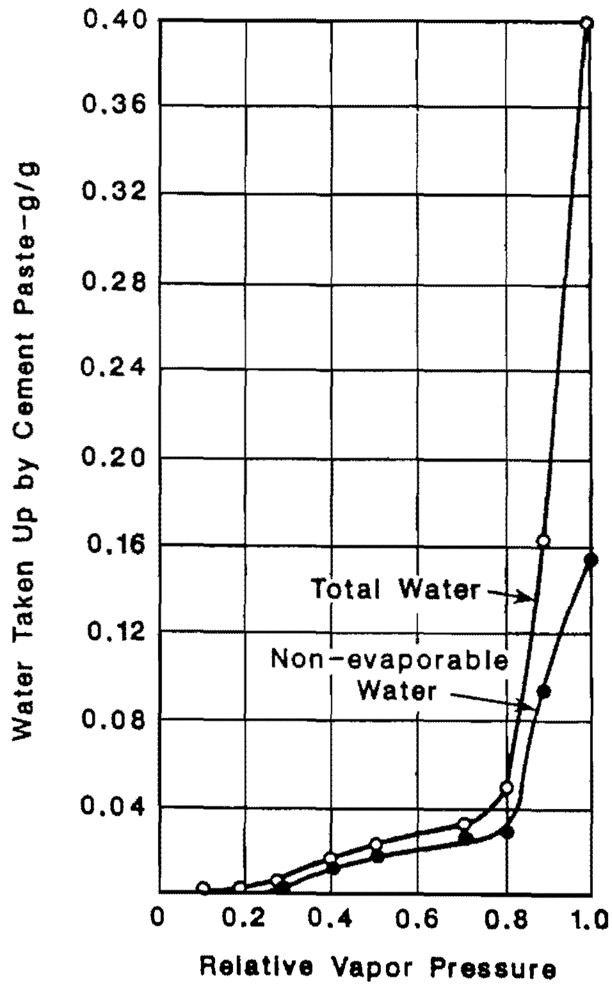


Figure 7. Water taken up by dry cement exposed for six months to different vapour pressures (59)

members are concluded to be insignificant (27). However, the above conclusion is only valid for hardened concrete. As for fresh concrete, wind has a prominent effect on evaporation rate, and, hence, induces plastic shrinkage. Using a curing compound is a very useful and practical method to improve the protection against evaporation. However, research by Texas Transportation Institute (5) showed that concrete specimens covered with a single application of curing compound, and exposed to windy conditions with a temperature of 140°F and a relative humidity of 25 %, can have the same or higher evaporation rate than concrete specimens exposed to no wind and not treated with a curing compound during the first several hours. This illustrates the strong influence of wind on drying, even when a single application of curing compound is applied (5).

2.5.2 Material Variability

Concrete Temperature: The most important factor with respect to evaporation is the mortar temperature (16). The relationships between concrete temperature and strength as a function of age are shown in Figure 6 (59). As shown in this figure, high temperature concrete has high early strength but low ultimate strength. The effect of concrete temperature on the resulting slump and on water requirement to change slump is shown in Figure 8 (8). The water requirement increases slowly at low temperatures but then increases rapidly at a higher temperature. The greater the concrete temperature, the larger the amount of water required to produce the same amount of slump. The increased water demand also increases the drying shrinkage and decreases the strength, durability, watertightness, and dimensional stability of the resulting concrete (62).

The concrete temperature consists of the temperatures of water, coarse aggregate, fine aggregate, and cement. Controlling mixing water temperature is the most effective method of controlling concrete temperature. In order to keep the temperature low, refrigeration and/or ice can be used (8, 63). When using ice, mixing should be continued until the ice is completely melted. Insulation or painting the mixer surface white is helpful in lowering temperature (8).

Aggregate Type: The creep and shrinkage behavior depends significantly on the aggregates used in the concrete as well as on the environmental conditions (34).

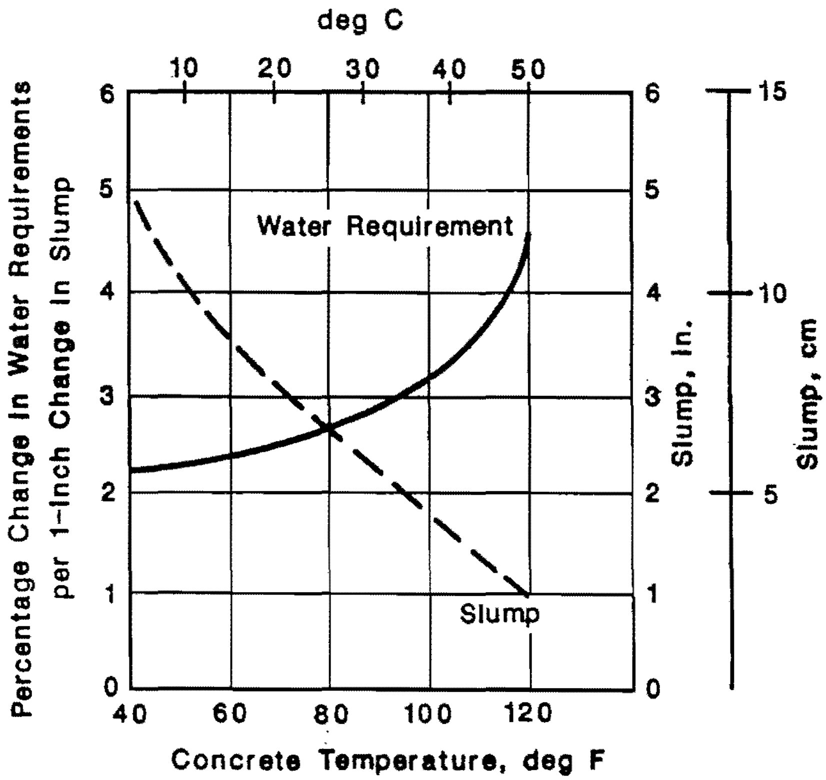


Figure 8. Effect of concrete temperature on slump and on water required to change slump. Cement content: 517 lb/yd^3; $4\frac{1}{2} \pm \frac{1}{2}$ percent air; maximum size of aggregate, $1\frac{1}{2}$ in; average of data for type I and II cement (8)

The physical properties and gradations of the aggregate also affect the concrete durability and air entrainment characteristics, but the amount of aggregate used in concrete is more significant than the size and gradation of aggregate with respect to the shrinkage achieved (27, 64).

Although aggregate generally restricts the shrinkage of concrete, a large amount of clay increases shrinkage significantly. It has been reported that concrete made with unwashed sand and gravel gave 70 to 100 percent more shrinkage than concrete made using completely washed materials (27).

A concrete slab made with a mixture of round silicious gravel and crushed limestone has higher strength than concrete made with either round or crushed coarse aggregate (5). No difference in strength was found between concrete with silicious gravel and crushed limestone aggregate (5). The type of aggregate does, however, have a significant effect on the drying shrinkage, thermal expansion and contraction, modulus of elasticity, ultimate tensile strain capacity, and extensibility (65). The crushed limestone concrete has greater shrinkage and ultimate tensile strain than the silicious gravel concrete (28, 64). The coefficient of expansion and contraction and the modulus of elasticity of crushed limestone concrete were smaller than those of the sand and gravel concrete. In field studies, crushed limestone concrete shows less spalling, for a similar crack spacing, than silicious gravel concretes (55, 56, 66). A possible explanation is that the limestone concrete has lower modulus of elasticity, lower thermal conductivity, and better bonding characteristics than the silicious gravel concrete (66). Another possible cause is that the limestone concrete has a greater ultimate tensile strain and therefore gives better performance than the silicious gravel concrete, in spite of the greater shrinkage (66).

Neither type nor texture of subbase affects the strength of concrete slabs. In a Texas study (5), researchers found that placing fresh concrete on a dry subbase even at 140°F did not affect the strength of the concrete slab significantly and concluded that the subbase conditions are not critical to the concrete strength development. In other words, dampening the subbase does not necessarily provide any differences in concrete strength development, but it is still recommended, to minimize the possibility of plastic shrinkage cracking, cracking in hot weather, and to minimize the removal of water from the concrete to the subbase.

Water Content: The presence of internal pores in the aggregate particles influences the properties of concrete by changing the water content. There is no clear-cut relation between the strength of concrete and the water absorption of the aggregate used: the pores at the surface of the particle are believed to affect the bond between the aggregate and the cement paste, and may thus exert some influence on the strength of concrete (67).

If the aggregate is batched in a dry condition, it is assumed that sufficient water will be absorbed from the mix to completely saturate the aggregate. However, if the particles are coated with cement paste which prevents further absorption, the actual w/c ratio is greater than the expected value. This effect is significant mainly in rich mixes (67).

A coating of aggregate particles with cement paste takes place within approximately 15 minutes from the time of initial mixing. This causes the absorption of water to slow down or stop with time. It is therefore often useful to use the quantity of water absorbed after about 15 minutes instead of the total water absorption, which may never be achieved in practice (67).

Mix Design: The relative strength at early age of high cement content concrete is greater than that of low cement content concrete. However, this difference decreases with time. Furthermore, high cement contents increase shrinkage (27, 28). Entrained air reduces the concrete strength by up to about 5 percent (28). It has been reported that there exists an optimum gypsum content which minimizes concrete shrinkage. The optimum proportion of gypsum can reduce the shrinkage up to 30 percent compared to cement without gypsum. The addition of gypsum retards setting of concrete and is a necessary ingredient for the control of the setting time (27).

In recent years the use of fly ash as an admixture or a partial replacement for the cement in concrete has become more popular in pavement construction (68). In the past 10 years in Texas, the State Department of Highways and Public Transportation has conducted research in the use of fly ash in concrete and is now allowing the use of preapproved sources of fly ash in special provisions (68). However, no data is available on the shrinkage and strength of fly ash concrete mixtures for CRC pavements exposed to severe environmental conditions. This data is needed for use in the CRCP design procedure, and for quality control purposes during construction.

Fly ash is the incombustible residue from the combustion of coal. It is classified as a pozzolan which is a silicious and aluminous material possessing no cementitious value, but which reacts with $Ca(OH)_2$ to form calcium silicate hydrates. This generally improves durability, strength, and impermeability of hardened concrete (69). The use of fly ash will lower the heat of hydration, and can cause a low rate of early strength gain, depending on the chemical composition of the fly ash (70). Two distinctive classes are defined in ASTM: Class F and Class C which are based on coal sources. They have slightly different chemical compositions and as a result, differ in usage (71). Class C fly ash may be added in amounts up to 35 percent by weight of cement; the additional rate depends on the particular applications as well as individual fly ash quality (11).

2.5.3 Quality Control

Time between Mixing and Placement: It is generally accepted that the longer the delay between initial mixing and placement of concrete, the greater the strength reduction. This effect is more critical in hot weather than in cold weather. Slump loss and requirement for retempering are other factors that will increase in hot weather. Retempering significantly increases shrinkage and decreases strength and durability. The time between mixing and placing should therefore be minimized, and retempering should not be performed unless otherwise specified. Generally it is required that placement of the concrete should commence immediately after the delivery of concrete. In order to avoid hot, arid and windy conditions, it is suggested that placement occur in the late afternoon or evening (8).

Consolidation Effort: Many reports indicate that proper placement and consolidation are the most important factors in producing a good quality concrete (5, 6, 12, 53, 72). Most pavement failures in the state of Ohio have been attributed to insufficient concrete consolidation around the steel and the lower portion of the slab (12). In an Illinois study (57), poor consolidation was also sited as a possible cause for disintegration.

Mechanical vibration improves the strength and surface properties of concrete. A great difference in durability can be observed with differences in consolidation and void content. Excessive vibration increases the settlement of solid particles.

Fines are worked to the surface and as a result, the surface region becomes more consolidated than the region immediately underneath. The surface region will settle when the vibration ceases. If setting of the concrete occurs before the surface zone reaches underlying matter, this causes surface deterioration in the form of flaking (5). However, the effectiveness of vibration depends on the frequency, amplitude, and the duration. The effectiveness of vibration increases as amplitude and duration increase. Also, there exists an optimum frequency which provides maximum consolidation effort for a given concrete mix design. These optimum frequencies, amplitudes, and durations should be determined by tests to secure adequate degree of consolidation (5, 72). During construction the amount of evaporation is of great importance, since it affects the concrete workability and thereby the degree of consolidation achieved. Such variations can influence both the strength and durability of the CRC pavement (72).

2.6 Summary

The previous sections summarize the State-of-the-Art in the areas of concrete curing, strength development, shrinkage, and shrinkage cracking. Concrete curing, strength development, shrinkage, and shrinkage cracking are very important in establishing material behavior during the life of CRC pavements and have been partially or fully incorporated into design and construction procedures for CRCP. The literature review, however, has also shown that only limited data is available regarding the combined influence of the environmental factors and the material variability during and after construction. During construction, the air temperature, relative humidity, and wind speed vary depending on the season of the year. The concrete temperature during the initial hardening and curing stages of the concrete varies depending on the air temperature and amount of evaporation. The response of the concrete also depends on the particular mix design used, i.e., the use of fly ash or other admixtures, as well as the aggregate type. During construction, the amount of water retained in the concrete will vary according to the amount of evaporation, the total mixing time, and time of transportation of the concrete from the batch plant to the job site. This variation in water content affects the workability of the concrete and the ability of the particular consolidation effort to adequately liquify the concrete. This in turn will determine how well the concrete will be consolidated. In the following chapter an experiment is described that was designed to provide more detailed data on the effect of the environment on concrete strength development, shrinkage, shrinkage cracking, changes in moisture content and moisture loss, and abrasion resistance.

III. EXPERIMENTAL METHODS AND PROCEDURES

3.1 General

In the review of the literature regarding the critical variables responsible for the behavior of the concrete in CRC pavements during and after construction, and therefore ultimately the performance of the pavement, it was found that the environmental factors air temperature, relative humidity, and wind speed interact with the type of mix design and construction parameters. Among the construction parameters, the total time between the initial addition of the cement to the concrete and the placement of the concrete is important. In general, the interaction can be characterized by the amount of evaporation potential existing in the concrete from the time of transportation to the job site until the final application of curing compound. At this point, the evaporation is reduced but still affected by the environmental conditions. Only continously moist curing provides an environment where no evaporation occurs from the concrete.

Consequently, if the amount of evaporation can be measured for typical environmental conditions in Texas and for commonly used concrete mixtures, the influence of these environmental conditions can be assessed for the critical material parameters, shrinkage and strength, which are known to influence performance of CRC pavements. The variations in these material properties will also produce a range of material property values that can be used by existing CRCP models to check the expected crack spacing and thus the performance under typical environmental conditions in Texas.

To adequately establish the effect of the environmental conditions on strength development, shrinkage, and abrasion, a minimum of 2 beams, 12 cylinders, 3 shrinkage bars, and 12 moisture content specimens are necessary. This number allows the specimens to be tested differently as well as the establishment of correlations and testing errors. However, in order to manage the large amount of data, a systematic approach is needed for the batching and testing procedures, and data collection.

The variables selected in this investigation can be classified as follows:

A.	Environmental Factors		
	1.	Air Temperature:	$50°F, 73°F, \&104°F$
	2.	Relative Humidity:	30%, 63%, & 95%
	3.	Wind Speed:	0 mph, 6 mph, & 9 mph
b.	Material Variability		
	4.	Concrete Temperature:	50°F, 73°F, & 104°F
	5.	Aggregate Type:	River Gravel & Limestone
	6.	Water Content:	Required amount to produce 1″ Slump, 1.5″ Slump, & 2″ Slump
	7.	Mix Design:	Plain & Fly Ash Concrete
c.	Quality Control		
	8.	Mixing Time:	7 min, 20 min, & 60 min
	9.	Consolidation Effort:	Spading, Rodding, & Vibrating

A more detailed description and justification of the variables chosen is given in the following sections.

3.2 Development of the Concrete Batch Design

Typical environmental conditions chosen have been selected according to the annual weather reports for Texas. In these reports the average yearly temperature for Houston is shown to vary from 50°F to 95°F, and the typical average values of relative humidity and wind speed are shown to be 65% and 9 mph, respectively. The average temperature conditions in El Paso vary from 40°F to 104°F, and the average relative humidity and wind speed are 25% and 6 mph, respectively. The standard curing conditions of 73°F, 95 % relative humidity, and 0 mph wind speed specified by ASTM standards were used as a reference. Based on this climatic information, test condition temperatures of 50°F, 73°F, and 104°F were selected. The relative humidity and wind speeds selected were 25% and 65%, and 6 and 9 mph, respectively. Due to difficulties in maintaining 25% relative humidity, this value was later changed to 30%. Based on the climatic combinations from the weather records, two coupled sets of climatic conditions were selected, 30% relative humidity with 6 mph wind speed and 65% relative humidity with 9 mph wind speed;

73°F, 95% relative humidity, and 0 mph wind speed were chosen as a reference environment. When the three temperatures given above were coupled with the two RH and wind speed combinations, a total of six different environmental conditions were obtained. By using two different temperatures for the materials prior to mixing (73°F in 50°F environment and 73°F in 104°F environment), the total number of experiments is nine (1 reference environment + 6 environmental conditions + 2 material temperatures) as shown in Table 1.

To evaluate the effect of changes in water content of the aggregates, water was either added or subtracted from the 1.5 inch slump reference mix to produce a 1.0 inch and 2.0 inch slump mix. During construction, the SDHPT personnel use the slump test to check the quality of the concrete mix delivered to the job site. The allowable range according to Item 360.4(4) in reference 73 is between 1 and 3 inches, with a target of 1.5 inch. It is realized that slump is not a good indicator for controlling research mixtures. Nonetheless, to simulate the conditions in the field, it was decided to use the slump test. In Table 2 the actual water content in SSD condition is shown for a batch size of one cubic yard as a function of the different test environments. Then, with the two coarse aggregate types investigated (river gravel and crushed limestone) and three different slumps, a total of six different mixtures was obtained. The complete experimental design is shown in Table 3.

In order to compare the effect of mixing time and method to the standard curing condition, eight more tests were added. The air temperature and relative humidity for the standard condition were 73°F and 95%, respectively. All the other factors, except for these two variables, were fixed. The concrete was a 1.5 inch slump, limestone concrete. The mix design of the 7 minute, vibrating plain concrete is the same as those used in the other tests in the 104°F, 30% RH, and 6 mph condition (Table 3). The standard curing conditions are listed in Table 4.

On a city job, concrete delivery is frequently delayed because of traffic. Delays in delivering concrete in hot weather can require significant amounts of additional water to maintain proper workability. As previously stated, this practice can have an adverse effect on the physical properties of concrete. In order to simulate this delay in placement, the maximum allowable delay of 60 minutes after the mixing was used in this study. To compare, 20 minute mixing time was also investigated, representing an intermediate mixing time together with the standard 7 minute

Table 1. Experiments and selected material temperatures.

Temperature(°F)		R.H. (%)
Air	Conc.	Wind (mph)
50°F	50°F	65% & 9 mph 30% & 6 mph
	73°F	65% & 9 mph
73°F	73°F	95% & 0 mph 65% & 9 mph 30% & 6 mph
104°F	73°F	30% & 6 mph
	104°F	65% & 9 mph 30% & 6 mph

Table 2. Average SSD water content for each test (lb/cy).

Temperature		River Gravel			Limestone		
Air	Concrete	1" Slump	1.5" Slump	2" Slump	1" Slump	1.5" Slump	2" Slump
50° F	50° F	208	213	213	215	214	220
	73° F	218	221	223	210	215	221
73° F	73° F	207	214	214	212	215	218
104° F	73° F	209	223	223	225	227	233
	104° F	232	232	243	215	213	230
Mix Design	Mixing Time						
Plain	7 min.	232	232	243	215	213	230
	20 min.	230	231	243	229	223	248
	60 min.	242	250	253	229	225	248
Fly Ash	7 min.	217	221	222	214	224	212
	20 min.	229	213	223	217	206	225
	60 min.	237	229	233	221	221	239

Table 3. Experimental design for the effect of air temperature, relative humidity, concrete temperature, wind velocity, aggregate type, and moisture content.

Temperature(°F)		R.H. (%)	River Gravel			Limestone		
Air	Conc.	Wind (mph)	1" Slump	1.5" Slump	2" Slump	1" Slump	1.5" Slump	2" Slump
50°F	50°F	65% & 9 mph	7/19	8/21	9/23	10/25	11/27	12/29
		30% & 6 mph	7/20	8/22	9/24	10/26	11/28	12/30
	73°F	65% & 9 mph	1/43	2/44	3/45	4/46	5/47	6/48
73°F	73°F	95% & 0 mph	1/1	2/4	3/7	4/10	5/13	6/16
		65% & 9 mph	1/2	2/5	3/8	4/11	5/14	6/17
		30% & 6 mph	1/3	2/6	3/9	4/12	5/15	6/18
104°F	73°F	30% & 6 mph	1/49	2/50	3/51	4/52	5/53	6/54
	104°F	65% & 9 mph	13/31	14/33	15/35	16/37	17/39	18/41
		30% & 6 mph	13/32	14/34	15/36	16/38	17/40	18/42

* a/b : 'a' is batch number, 'b' is test number

Conditions(Variable):

A. Temperature of Air: 50°F, 73°F, 104°F

B. Relative Humidity: 30%, 65%, 95%

C. Concrete Temperature: 50°F, 73°F, 104°F

D. Wind Speed: 9 mph, 6 mph, 0 mph

E. Aggregate Types: River Gravel & Limestone

F. Water Content of Mix: Required amount of water to produce 1", 1.5", 2" Slump. (see Table 2)

Conditions(Given):

G. Mixing Time: 7 min.

H. Mix Design: Plain Concrete

I. Consolidation Method: Vibrating

Table 4. Experimental design for the effect of aggregate type, moisture content, mixing time, and methods of consolidation on plain and fly ash concrete.

Mix Design	Mixing Method	Mixing Time	River Gravel 1" Slump	River Gravel 1.5" Slump	River Gravel 2" Slump	Limestone 1" Slump	Limestone 1.5" Slump	Limestone 2" Slump	Standard Test**
Plain Concrete	Spading	7 min	13/55	14/57	15/59	16/61	17/63	18/65	5/109
		20 min	13/67	14/69	15/71	16/73	17/75	18/77	5/111
		60 min	13/79	14/81	15/83	16/85	17/87	18/89	5/114
	Rodding	7 min	13/56	14/58	15/60	16/62	17/64	18/66	5/110
		20 min	-	-	-	-	-	-	5/112
		60 min	-	-	-	-	-	-	5/115
	Vibrating	7 min	13/32	14/34	15/36	16/38	17/40	18/42	5/13
		20 min	13/68	14/70	15/72	16/74	17/76	18/78	5/113
		60 min	13/80	14/82	15/84	16/86	17/88	18/90	5/116
Fly Ash (20 %)	Vibrating	7 min	19/91	20/92	21/93	22/94	23/95	24/96	-
		20 min	19/97	20/98	21/99	22/100	23/101	24/102	-
		60 min	19/103	20/104	21/105	22/106	23/107	24/108	-

a/b : 'a' is batch number, and 'b' is test number.

Most Severe Conditions:

A. Air Temperature: 104°F
B. Relative Humidity: 30%
C. Concrete Temperature: 104°F
D. Wind Speed: 6 mph

** Standard Test Condition

A. Air Temperature: 73°F
B. Relative Humidity: 95%
C. Concrete Temperature: 73°F
D. Wind Speed: 0 mph
E. Water Content of Mix: Required amount of water to produce 1.5" slump (see Table 2)
F. Mix Design: Plain Concrete
G. Aggregate Type: Limestone

mixing time. During the simulated 20 and 60 minute delays, the mixing continued after the initial mixing for the standard 7 minutes. Twenty and 60 minutes after the addition of the cement, the concrete was remixed for an additional 2 minutes and retempered with water to obtain the desired slump prior to placement.

In many cases, insufficient consolidation is reported as the cause of unexpected early failure. In order to compare the effect of consolidation effort, three different consolidation methods were considered. Vibrating concrete until the sheen appeared on the whole surface was assumed to represent 100 percent consolidation effort, and spading the concrete 25 times per sq.ft. was assumed to represent 85 percent consolidation effort. The method of rodding, which was assumed to represent 95 percent consolidation effort was also employed to investigate the differences between the laboratory test and variations in consolidation effort in the field.

Due to the increase in the use of fly ash as partial replacement for cement in concrete pavement mixtures, a concrete mix with 20% replacement with a type C fly ash available in Texas was investigated under the most severe environmental condition of 104°F temperature, 6 mph wind speed, and 30% relative humidity.

By combining the effect of mixing time, consolidation effort, and the use of fly ash, nine testing parameters were selected. These parameters were combined with the combinations of the aggregate type and water content (slump). The resulting experimental design is summarized in Table 4. The 7 minute vibrating plain concrete tests appearing in this table were the same as the tests of 104°F, 30% RH, and 6 mph shown in Table 3. As for the rodding method, only 7 minute mixing was considered because the delay of placement will not occur in ordinary laboratory procedures.

As mentioned earlier, two different coarse aggregates — river gravel and crushed limestone — were used in this study. The coarse aggregate was obtained from Parker Brothers Co. in Houston, Texas, and the fine aggregate from Bryco, Inc., in Bryan, Texas. The results of the unit weight, specific gravity, absorption capacity, and gradation of the coarse and fine aggregate are presented in Appendix A.

For the total of 24 different mix designs, which were necessary for the conduction of the total of 116 tests previously described, basic design values were selected from the Texas State Highway Department's "Standard Specifications for Construction of Highways, Streets and Bridges" (73), and summarized in Table 5.

Table 5. Selected SDHPT specifications for CRCP.

Item	Specification
Cement Factor	Unless otherwise specified on the plans, the concrete shall contain not less than 5 sacks of cement per cubic yard.
Air Content	Entrain 5% air ± 1% based upon measurement made on concrete immediately after discharge from the mixer.
Coarse Aggregate Factor	Shall not exceed 0.85.
Water/Cement Ratio	Shall not exceed 6.25 gal/sk or 0.554 lb/lb.
Slump	Shall not be less than 1 in. or more than 3 in., designed to be 1–1/2 in.
Flexural Strength	Shall not be less than 575 psi at 7 days.

Note: These selected specifications were taken from Item 360 and 366 (73).

For the initial mix design, a cement factor of 5.5 sk/yd^3 and a total air content of 5.0%, using an air entraining agent, were used. With this information, the test results contained in Appendix A, and the design process contained in the Texas State Highway Department's "Construction Bulletin C-11," the initial mix design was developed. The tolerance for each slump was set at 0.25 inch, resulting in the slump between 0.75 inch and 1.25 inch to be considered as 1 inch slump, the slump between 1.25 inch and 1.75 inch to be considered as 1.5 inch slump, and the slump between 1.75 inch and 2.25 inch to be considered as 2 inch slump.

To determine whether the mix designs met the SDHPT's specifications for CRCP concrete, 1.5 cu.ft. trial batches were used. During the mixing process, attempts were made to produce concrete that had a 5.0% air content and a 1.5 inch slump. The amount of water to change the slump and the amount of air entraining agent were recorded. One beam and three cylinders were cast, followed by curing under 95% relative humidity and 73°F. After 7 days, the beam was tested for Modulus of Rupture by the center point method (ASTM C-293) and the three cylinders for compressive strength test (ASTM C-39). The broken pieces of the beam were subjected to the modified compressive strength test according to ASTM C-116. The tests conducted and the number of replica tests are summarized in Table 6.

3.3 Development of the Testing Program

Among the most important variables in this research is the evaporation rate for each environmental condition. It significantly affects the moisture movement behavior in concrete, and thereby the shrinkage of the concrete, as well as the strength development of concrete. The Evaporometer developed by the Materials and Test Division (D-9) of Texas State Department of Highways and Public Transportation (1) was used to measure the evaporation rate. A schematic drawing of the equipment is shown in Figure 9. First, the filter paper on top was soaked and the capillary column filled with water. Next, as time passed, the water in the column was drawn upward due to the evaporation from the filter paper. The drying time for every half inch increment of water column was measured, and the amount of evaporated water determined. Finally, the amount of evaporated water was compared with the values obtained from the PCA Chart (Figure 2).

Table 6. Conducted tests.

TEST	ASTM Spec.	1	2	3	7	14	28	60	90	Specimen Type	Size	Number
Trail Mix (Total Number = 30)												
Moisture Content	C566-78	1										
Slump Test	C143-78	1										
Unit Weight	C138-81	1										
Air Content	C231-81	1										
Compressive Strength	C39-81				3					Cylinder	6"X12"	3
Mod. Comp. Str.	C116-68				3					Beam	6"X6"X36"	*[2]
Flexural Strength	C293-79				2[1]					Beam	6"X6"X36"	1
Each Test (Total Number = 116)												
Moisture Content	C566-78	1										
Slump Test	C143-78	1										
Unit Weight	C138-81	1										
Air Content	C231-81	1										
Time of Setting	C403-80	2								Cylinder	6"X12"	2
Compressive Strength	C39-81			3	3		3		3	Cylinder	6"X12"	12
Mod. Comp. Str.	C116-68				3					Beam	6"X6"X36"	*[2]
Flexural Strength	C293-79				2[1]					Beam	6"X6"X36"	1
Pullout Test	C900-82			3	3		3		2	Beam	6"X6"X36"	1
Sandblasting Test	C418-81						8		8	Beam	6"X6"X36"	*[3]
Shrinkage & Wt Loss	C157-80	3	3	3	3	3	3	3	3	Prism	3"X3"X11"	3
MC of Concrete		12		3	3		3		3	Cube	3"X3"X4"	12

Note:

[1] 36″ beam was tested twice.

[2] Modified Compressive Test with broken pieces of beam.

[3] Tested on the bottom face of beam.

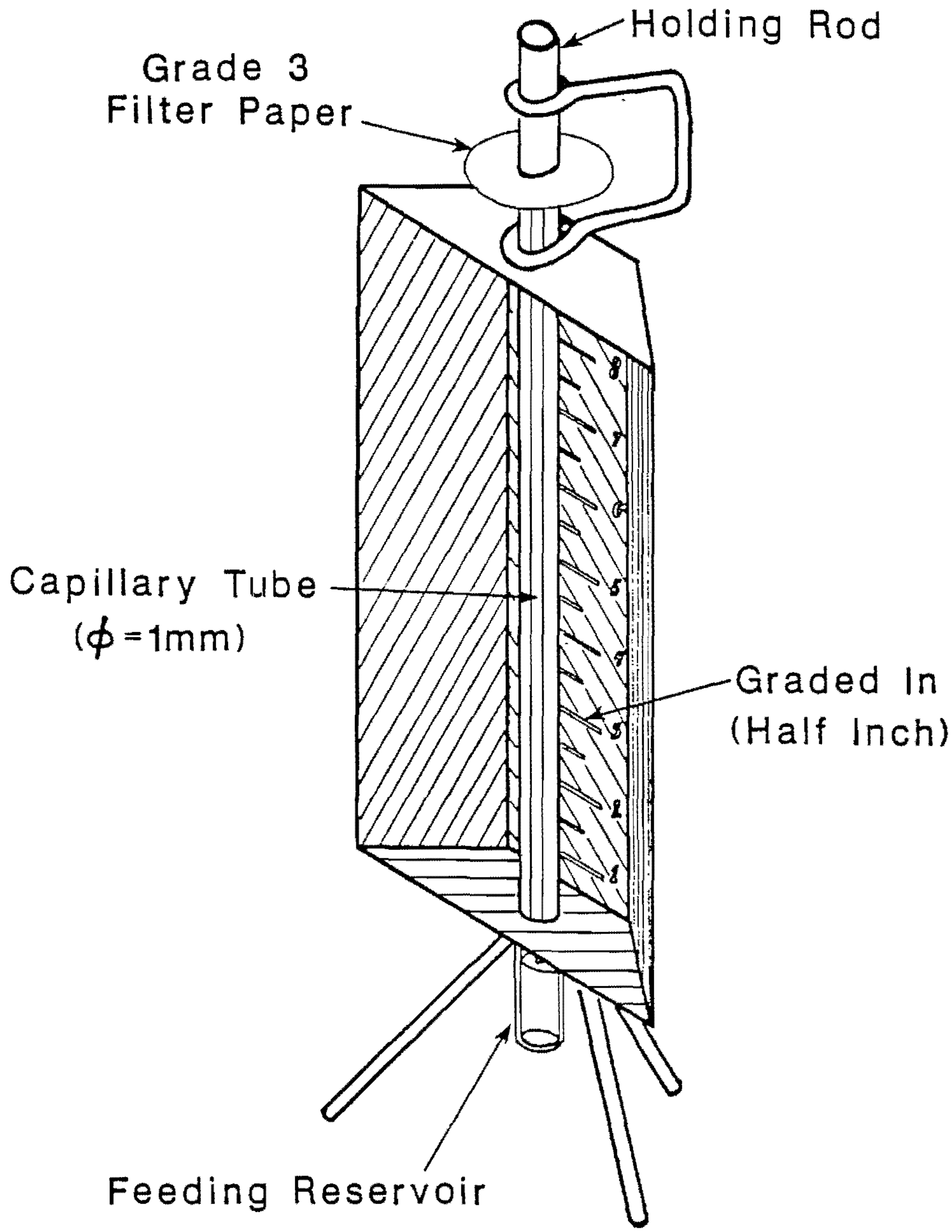


Figure 9. Schematic drawing of Evaporometer (1)

A set of metal forms which has six or five holes on the side panels was used to place the pullout inserts for the pullout test (ASTM C-900). The diameter and the depth of the inserts was 9/16 inch. The inner diameter of the reaction ring was 1-11/32 inch, thus producing an apex angle of 70 degrees. In order to have adequate clearance between each of the pullout tests, these inserts were spaced 6 inches apart. One side panel had six inserts and the other side panel five inserts, arranged in an alternate order. A total number of eleven inserts was placed on one beam. Three inserts were pulled out at each test age, except for the 90 days, when only two pullout tests were performed. The pullout hydraulic jack was calibrated before the test, and on a regular basis every month.

The sandblasting test was performed on the bottom side of the pullout beam at 28 days and 90 days according to ASTM C-418. The test was performed at eight different locations as specified by ASTM, with the exception that the specimen was not SSD condition during the test, but in air dry condition. Only the reference specimens stored in the moisture room were tested in the SSD condition and used as a reference.

A total of three shrinkage specimens per test condition and age was cast. Weight change was measured in conjunction with the length change of these specimens. An electronic balance with an accuracy of plus or minus one-tenth of one gram was used to measure the weight changes. Some of the loosely attached material was removed on the first day right after the removal of the form in order to reduce the possibility of losing this material during the duration of the test.

Four small cubes were made from each of the sixteen-inch long bar molds by inserting nonabsorbant dividers right after the consolidation. These specimens were used to measure the moisture content and moisture loss. Initial weights and weight changes were recorded at certain ages (see section 3.5). To determine the moisture content, the specimens were oven dried at 110°C for 24 hours. The complete testing program is shown in Table 5 for each of the total of 116 tests.

3.4 The Batch Process

The maximum size of the two coarse aggregates ordered for this study was 1-1/2 inches. However, the size of the shrinkage molds was $3 \times 3 \times 11.2$ inches which restricts the maximum size of coarse aggregate to 1 inch. The aggregates which pass the 1 inch sieve and are retained on the # 8 sieve were therefore collected and stored together with the sand in an environmental room at least one day before the batching of the concrete took place. This allowed the aggregates time to reach the desired temperature. Similarly, the mixers and other equipments were stored in the same environmental room at least one day before the batching. When the material temperature was different from the air temperature, a different temperature room was used during batching.

The volume for making one complete test was 5.4 cu.ft.; however, only a 3 cu.ft mixer was able to fit in the environmental rooms. The batch was therefore divided into two portions. One beam, six cylinders and three shrinkage specimens or twelve cube specimens were made from each batch. The concrete was mixed for 3 minutes, rested for 3 minutes, mixed again for 4 minutes, and then discharged to wheel barrows for casting of specimens. Slump was the controlling factor in the batching process, and water was added to achieve the specified slump. Air content and unit weight were measured after mixing and temperature and relative humidity of the room were recorded before, during and after mixing.

The specimens were consolidated on a vibrating table until a sheen appeared on the whole surface. The duration time depended on the size of the specimens. Surface was finished by hand troweling after the consolidation. The shrinkage specimens were made at the same time as the pullout beam specimen, and the cubes for moisture content measurements were cast together with the other plain beam for the flexural strength test. Plastic molds were used for the cylinder specimens instead of steel molds. A curing compound was applied to the top of the specimens as soon as the surface sheen had disappeared from the surface. The time of setting test was performed for each batch.

The specimens were stored in the specified environmental conditions for 24 hours. At the end of this 24 hour period, all the specimens were demolded and curing compound applied on the newly exposed surfaces. For the shrinkage and moisture content specimens, the first measurement of lengths and weight was performed after the curing compound had dried. The specimens remained in the specified environmental room until they reached the age of 90 days.

3.5 Concrete Testing

There were four main test ages: 3, 7, 28 and 90 days. At these ages, a compressive strength test, a pullout test, a shrinkage and weight loss test, and a test for moisture variations were performed. Flexural strength test and modified compressive strength test were only performed at 7 days. Additional measurements were made for the shrinkage specimens on the first, second, 14th and 60th days. The proposed tests, together with the ASTM specifications, the number of tests per age, and the specimens used in this research, are summarized in Table 6.

IV. DISCUSSION OF THE RESULTS

4.1 Introduction

This chapter presents the results of the testing and analysis program conducted as part of the laboratory investigation. The results are categorized according to the types of the tests: strength tests, shrinkage and moisture variations, and time of setting and abrasion. The complete tabulated data obtained from this investigation is presented in Appendices D and E. Only the most pertinent data is presented here.

4.2 Evaporation

4.2.1 Evaporation Rate

Environmental conditions investigated in this study have different levels of effect on moisture movement in concrete. Their primary effects on the movement of moisture in concrete are based on two distinct aspects: temperature effect on the rate of hydration, which affects diffusivity, and relative humidity and wind effects on the rate of moisture loss. Temperature also affects the rate of drying by changing the mobility of water molecules, which is a function of the internal energy of water.

Evaporation rate in each different environmental condition was measured with the Evaporometer developed by the Materials and Tests Division of the Texas State Department of Highways and Public Transportation (1). The evaporation time for a half inch column of water was measured, and the evaporation rate was calculated. Table 7 shows the Evaporometer test results together with the PCA chart readings for the six different environmental conditions employed. The six environmental conditions are arranged in increasing order of the evaporation rates. The PCA chart gives values from 0.030 to 0.250 lb/sq.ft./hr, and measured evaporation rates were found to be between 0.066 and 0.340 lb/sq.ft./hr. In Table 7, the wind speed measurements are also summarized. The concrete specimens were exposed to wind generated by an electric fan. The measured wind speeds ranged between 10.4 and 7.0 mph for 9 mph, and between 7.5 and 4.5 mph for 6 mph. Most of the concrete specimens were placed between 1 and 4 feet from the fan, and between 2 and 5

Table 7. Evaporation rate by Evaporometer.

Evaporation Time Measurements

Measured Condition		Measured Evaporation		PCA Chart
Temperature (°F)	R.H. & Wind (% & mph)	Time & Rate (sec)	(lb/sqft/hr)	Reading (lb/sqft/hr)
50°F	65% & 9mph	82	0.066	0.030
	30% & 6mph	53	0.103	0.045
73°F	65% & 9mph	41	0.133	0.070
	30% & 6mph	32	0.170	0.090
104°F	65% & 9mph	21	0.260	0.180
	30% & 6mph	16	0.340	0.250

Wind Speed Measurements

Measured Distance from the fan (ft)	Measured Speed	
	High Speed for 9mph	Med. Speed for 6mph
0	14.0mph	11.5mph
1	10.2mph *	8.2mph
2	9.2mph *	7.5mph *
3	8.0mph *	6.5mph *
4	7.0mph *	5.5mph *
5	6.0mph	4.5mph *
Average**	8.6mph	6.0mph

* Specimens are exposed in this range

** Average of the exposed wind speed

feet, depending on the test conditions. Evaporation measurements were taken at appropriate distances from the fan to achieve the specified wind speed.

The measured values represent evaporation from a filter paper and not from a concrete surface, and the drying water was transported through a 0.05 inch diameter capillary glass tube and not through a tortuous pore system with variable crossectional areas. The mechanism governing the rate of evaporation in the Evaporometer and concrete is, however, the same. This is illustrated in Figure 10 by the linear correlation between the evaporation rate from the Evaporometer and the PCA chart. As seen from Figure 10 and Table 7, the Evaporometer values are greater than the PCA chart values. This is to be expected, since the internal capillary pore structure in concrete involves tortuosity that decreases the flow of water to the surface.

For all temperatures, the environmental condition of 65% relative humidity with 9 mph wind shows lower evaporation rate than that of 30% relative humidity with 6 mph wind. For the two environmental conditions, the difference in evaporation rate between the PCA chart and the Evaporometer values increases with an increase in temperature. This is also attributed to the presence of a tortuous pore system in the concrete as previously mentioned.

The value recommended by PCA of 0.2 lb/sq.ft./hr as the critical level for the evaporation rate corresponds to a value of 0.29 lb/sq.ft./hr for the Evaporometer. In evaluating the influence of the climatic conditions in the field during placement, the Evaporometer can be used to measure the evaporation. This measured value can then be corrected to actual concrete evaporation from the PCA chart using either Figure 10 or the following equation (r^2=0.989):

$$PCA = -0.1376 + 0.8307 \cdot E$$

where

PCA = evaporation from PCA chart

E = evaporation from Evaporometer

The differences between the evaporation rate for the two climatic conditions increase with an increase in temperature. The least severe condition is found to be 50°F, 65% and 9 mph, and the most severe condition is 104°F, 30% and 6 mph.

Even though the correlation plot shows slightly non-linear configuration, the validity of the PCA chart is not reduced. The contradictory findings reported in

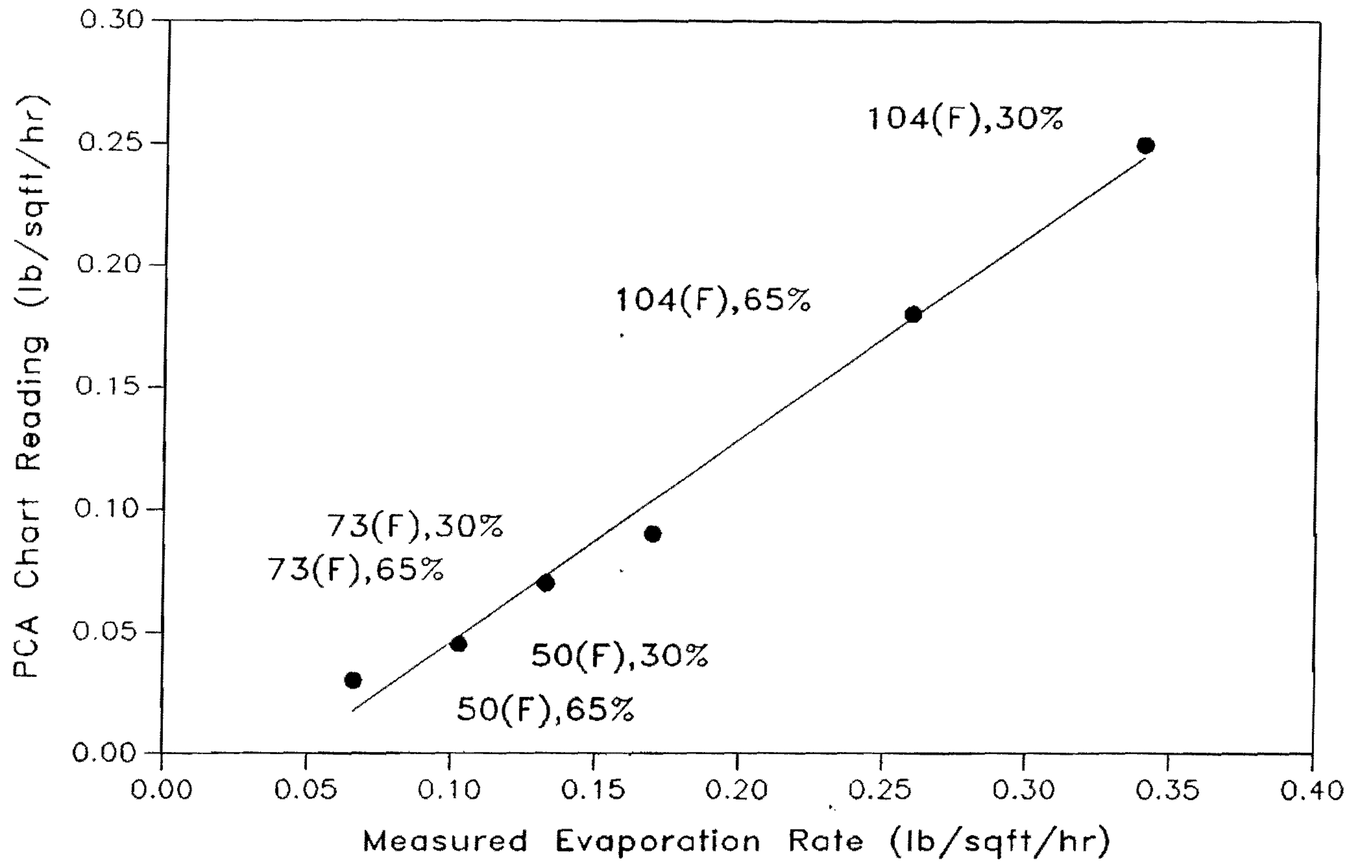


Figure 10. The correlation between Evaporometer measurement and PCA chart reading.

the previous TTI study (5, 6) have not been verified in the present study. By reviewing Table 8 from the previous TTI report (6), a large discrepency among the evaporation rates can be found for the following three environmental conditions: 73°F, 10 mph and 20 mph, and 100°F, 20 mph. Figure 11 (5) shows the measured changes in concrete surface temperature. According to this temperature plot, the surface temperatures at 73°F did not change significantly, and remained below 80°F. On the other hand, the surface temperatures at 100°F varied between 80°F and 120°F. The footnote in Table 8 states that the material temperature is assumed to be 80° when the reading is taken from the PCA chart. Obviously this assumption does not correspond to the actual measurements. If PCA chart readings are taken with an average temperature of 75°F, the evaporation rate for 73°F, 10 mph is very close to the PCA chart reading.

Mixing and batching procedures were performed in the same environmentally controlled room for the present and the previous studies. What was discovered during the batching process was a rapid increase in relative humidity and a slight decrease in temperature due to the unavoidable evaporation during the mixing and batching procedure. Because of the narrow and confined space of the room, the environmental conditions were changed quite rapidly from the planned condition. If these two factors — a wrong assumption for concrete temperature and a rapid change on environmental condition — are considered, the substantially lower evaporation rate at high wind speed reported earlier (6) can be explained.

4.2.2 Conclusion

The following conclusions regarding the evaporation rate are based on the results of the laboratory tests:

1. Measurements taken with the Evaporometer developed by the Materials and Tests Division of the Texas State Department of Highways and Public Transportation show very good correlations with values obtained from the PCA chart.
2. The rate of evaporation, which is a function of the environmental condition, can reliably and conveniently be measured in the field with the Evaporometer during construction.

Table 8. Comparision of evaporation rates (3).

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

[a] Values obtained from specimens with no cure.
[b] From PCA chart using an average concrete temperature of 80°F.

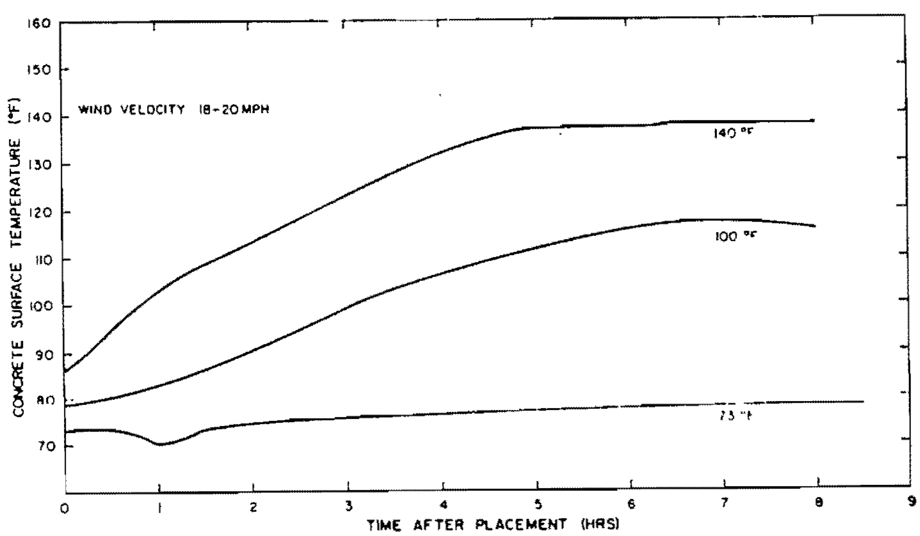


Figure 11. Concrete surface temperature versus time after placement (4).

3. The PCA chart, whose validity was challenged in a previous study (5,6), was found to be valuable in estimating the evaporation rate from concrete.
4. The use of the PCA chart requires special care in selecting the input parameters.
5. An equation has been developed that corrects the rate of evaporation measured with the Evaporometer to the rate of evaporation of the concrete.

4.3 Strength Development

4.3.1 Compressive Strength and Pullout Strength

Figure 12 illustrates the effect of environmental conditions on the compressive strength development of concrete between 3 and 90 days of age. Figure 12a is for river gravel and Figure 12b is for limestone as the coarse aggregate type. Both types of concrete mixtures had a slump of 1.5 inches. The evaporation rate increases from left to right in the figure. The 3 day compressive strengths increase as evaporation rate increases. The tendency disappeared for the 7 day strength for river gravel concrete and 28 day strengths for both types of aggregates. Finally, slightly decreasing compressive strengths can be observed after 90 days. The specimens stored at 50°F increased their strength continuously, and almost doubled the strength between 3 and 90 days. The specimens stored in 104°F experienced only a 25% increase between 3 and 90 days. With the exception of the 3 day results, this shows that, under low evaporation conditions, moisture remains in the concrete for a long time; as a result, the concrete is able to hydrate continuously. At a high evaporation condition, however, the rapid removal of moisture causes the strength development to be significantly retarded. As observed earlier, the 3 day compressive strength increases as the evaporation rate increases. This is attributed to the influence of temperature, which produces short-term strength increases at a curing temperature above 73°F, but long-term strength reductions (59).

In general, longer mixing time is believed to reduce the compressive strength of concrete at all ages. Figure 13 illustrates this effect for the most severe drying condition. The longer the mixing time, the lower the compressive strength. The statement is true regardless of the type of aggregate, the type of admixture, and the age of the concrete.

In Figures 14 through 16, the influence of aggregate type and amount of mixing water on the compressive strength is shown for different environmental conditions. As expected, a definite decrease of the strength with an increase of slump is observed regardless of the type of aggregate and exposure conditions. This is because of the w/c ratio law that states when more water is introduced into the concrete mix, the spaces occupied by the excess water create void spaces after drying. The amount of void spaces determines the degree of strength reduction.

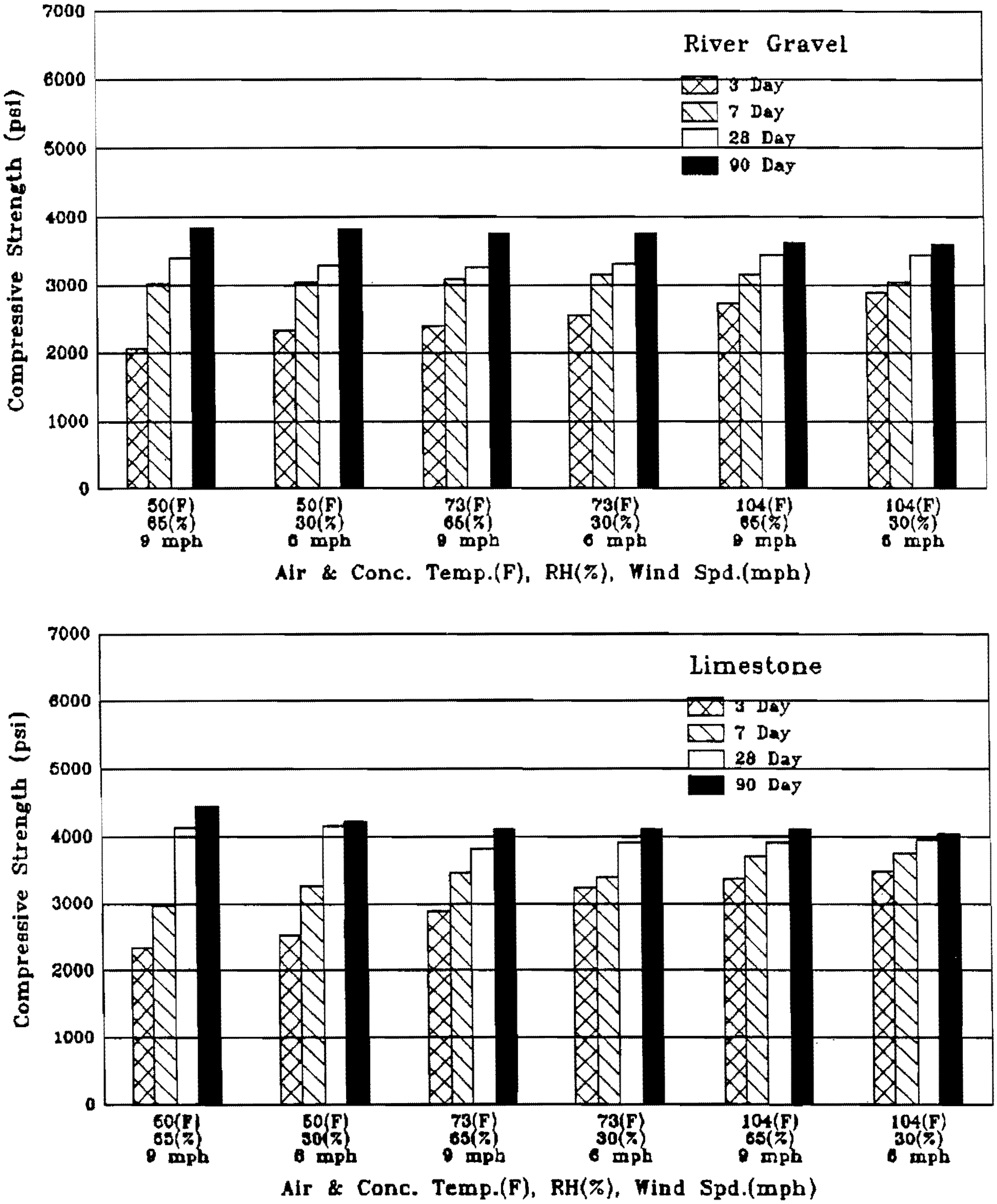


Figure 12. The environmental effects on the compressive strength of 1.5 inch slump concrete; a) River gravel b) Limestone

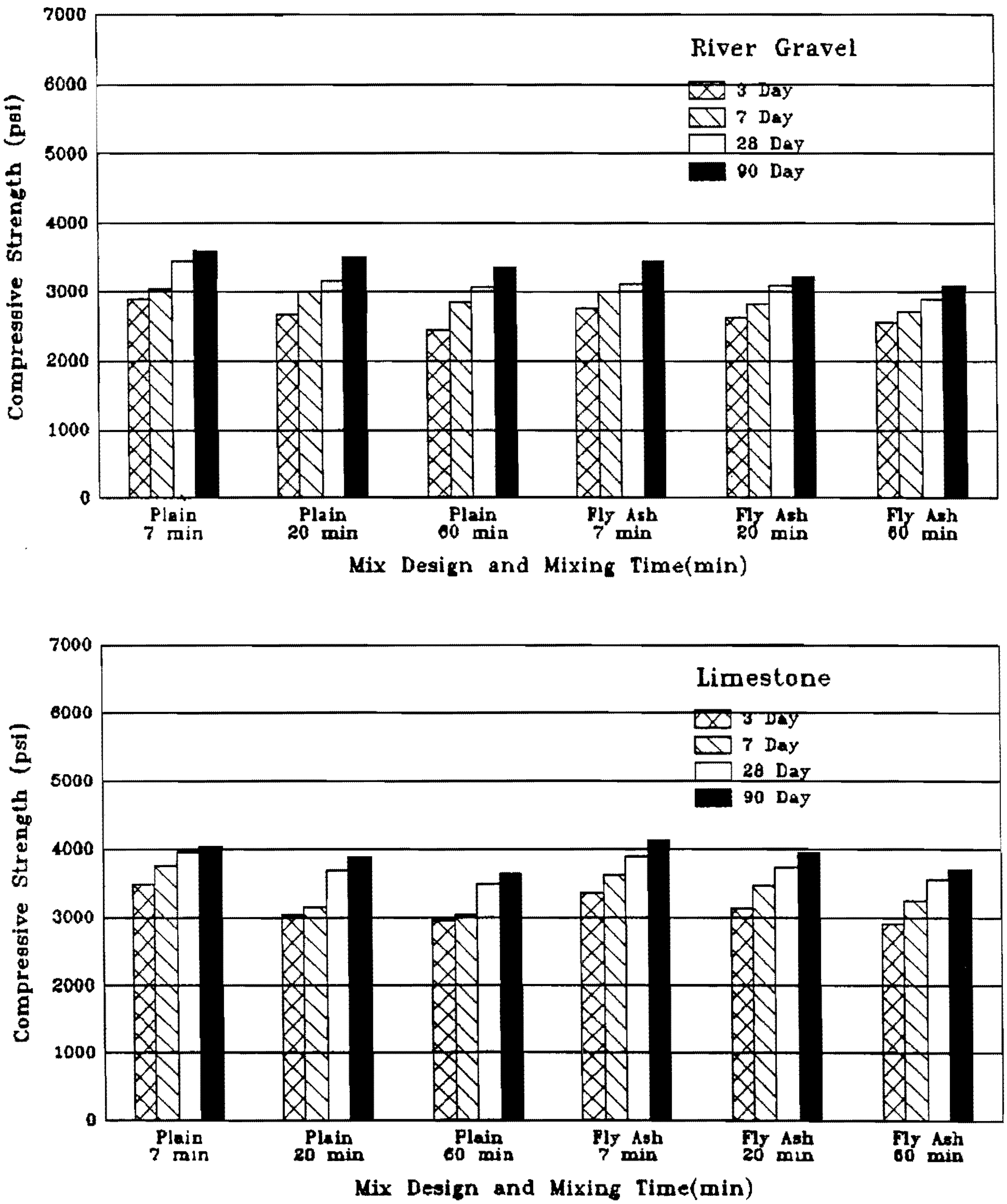
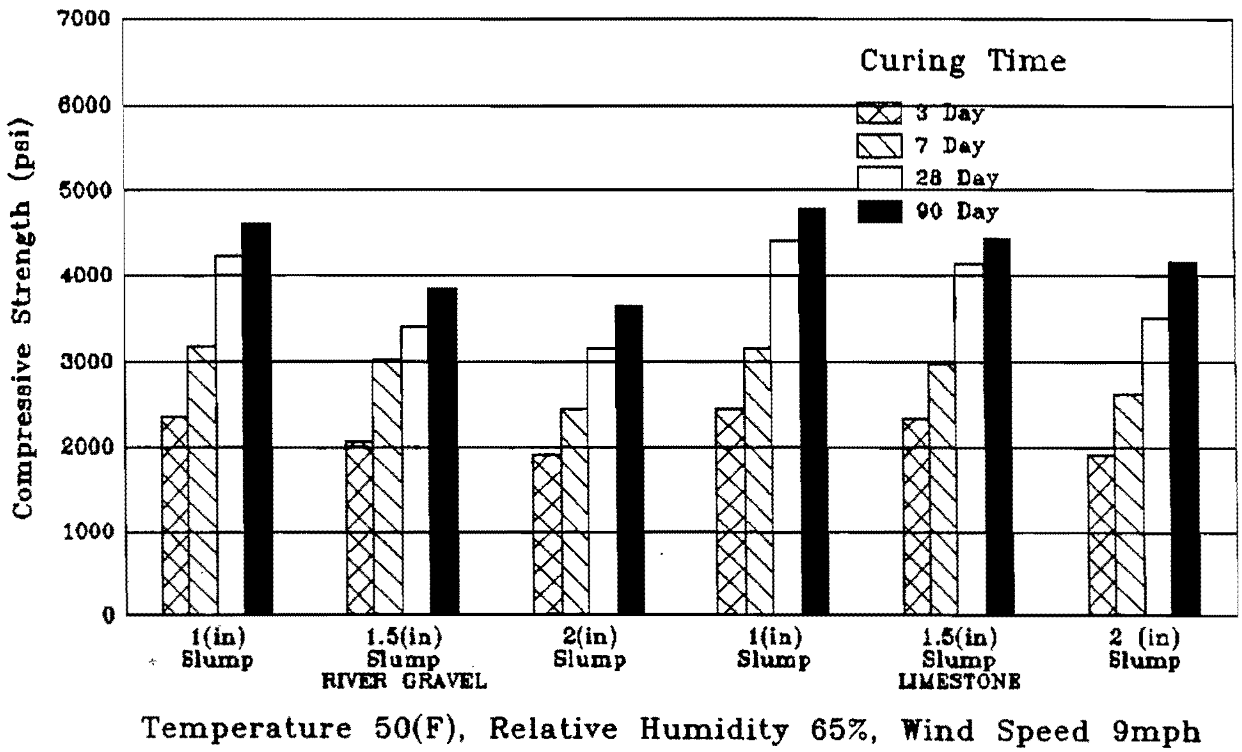


Figure 13. The effect of mixing time and fly ash on the compressive strength of 1.5 inch slump concrete under severe evaporation conditions (104°F, 30% RH, and 6 mph wind); a) River gravel b) Limestone



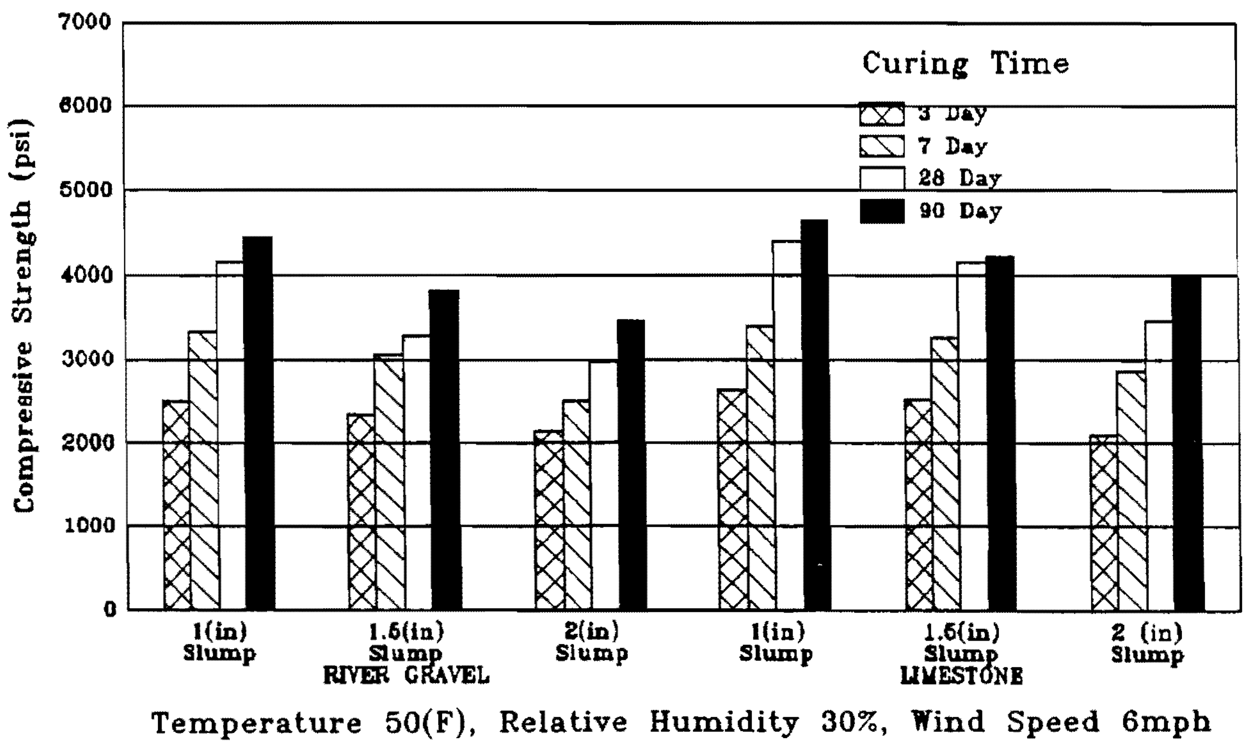
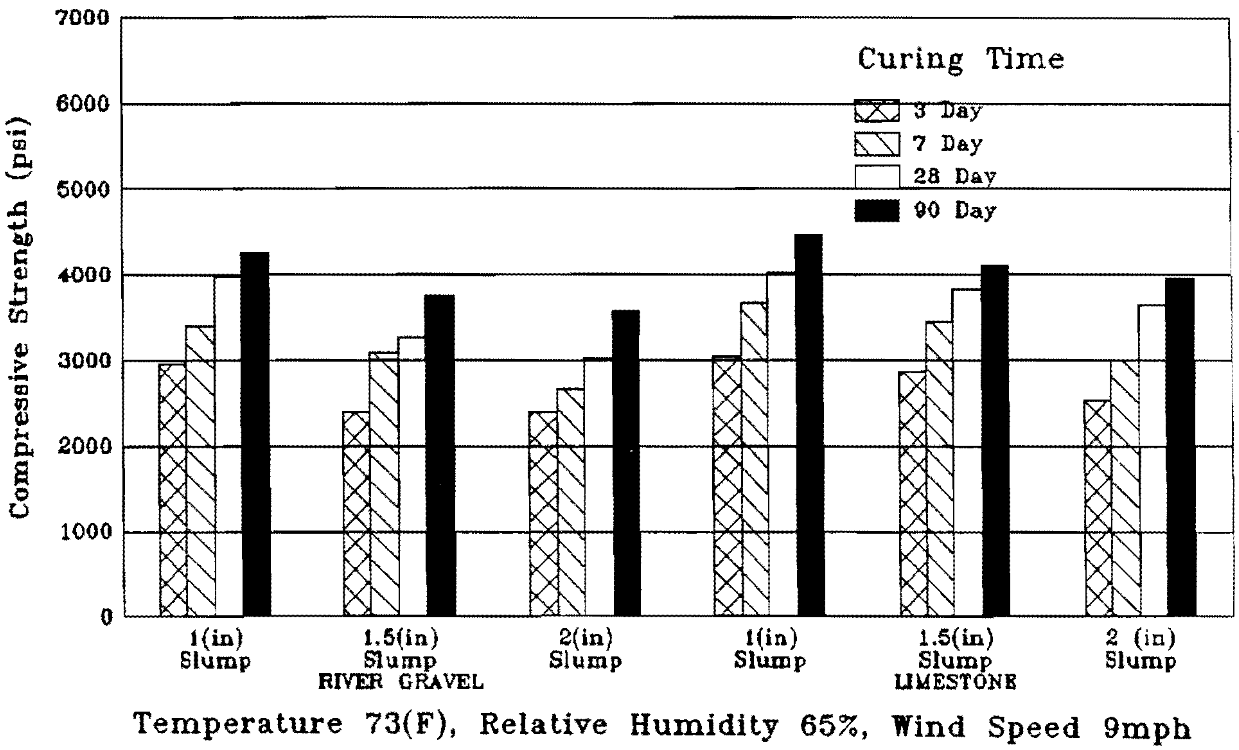


Figure 14. The effect of aggregate type and slump on compressive strength at 50°F; a) 65% RH and 9 mph wind b) 30% RH and 6 mph wind



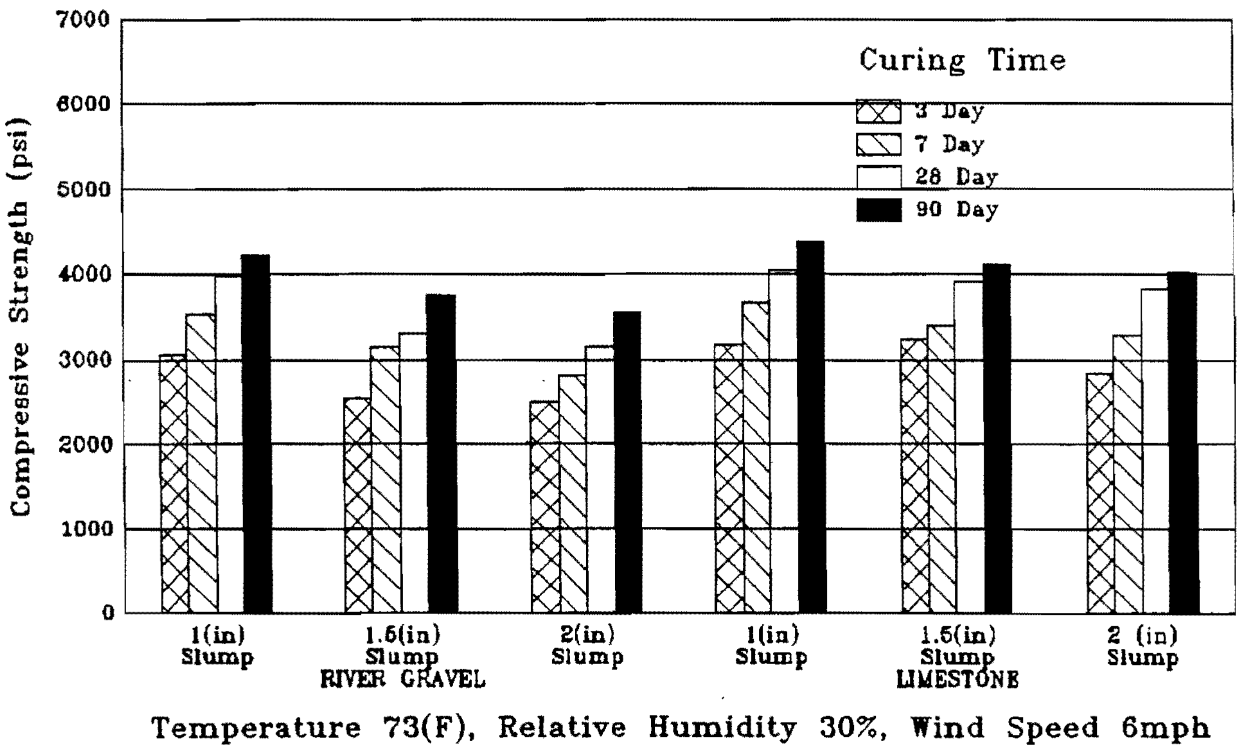
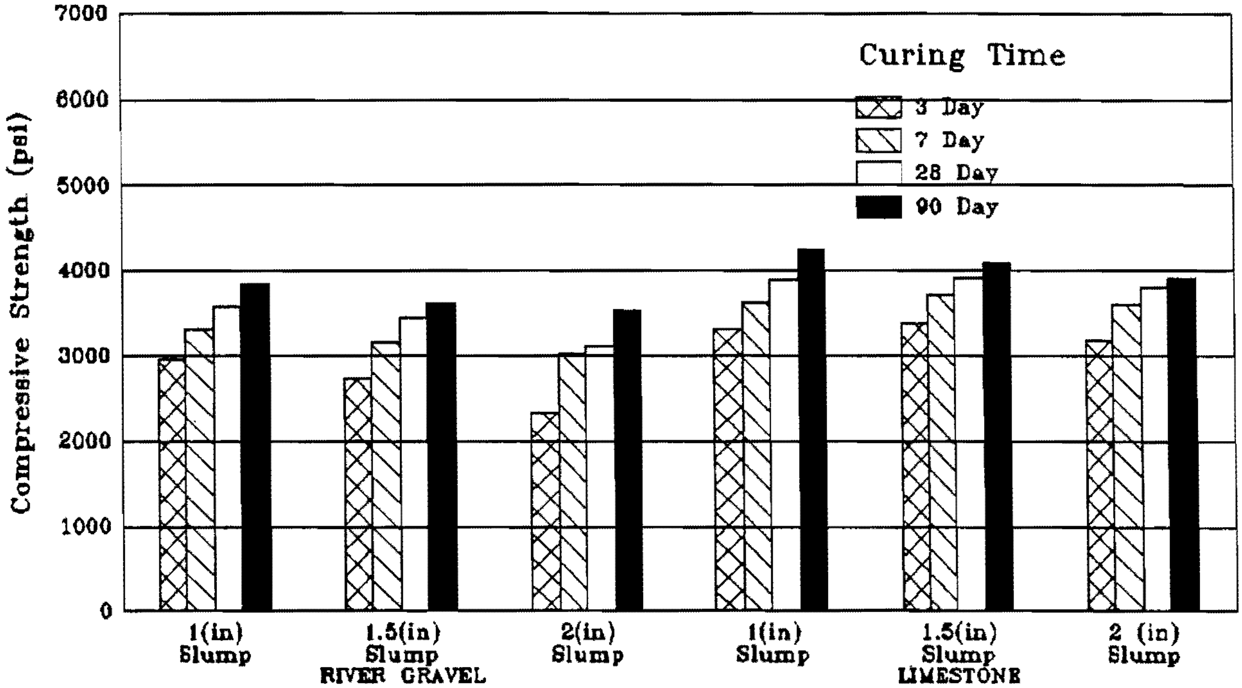
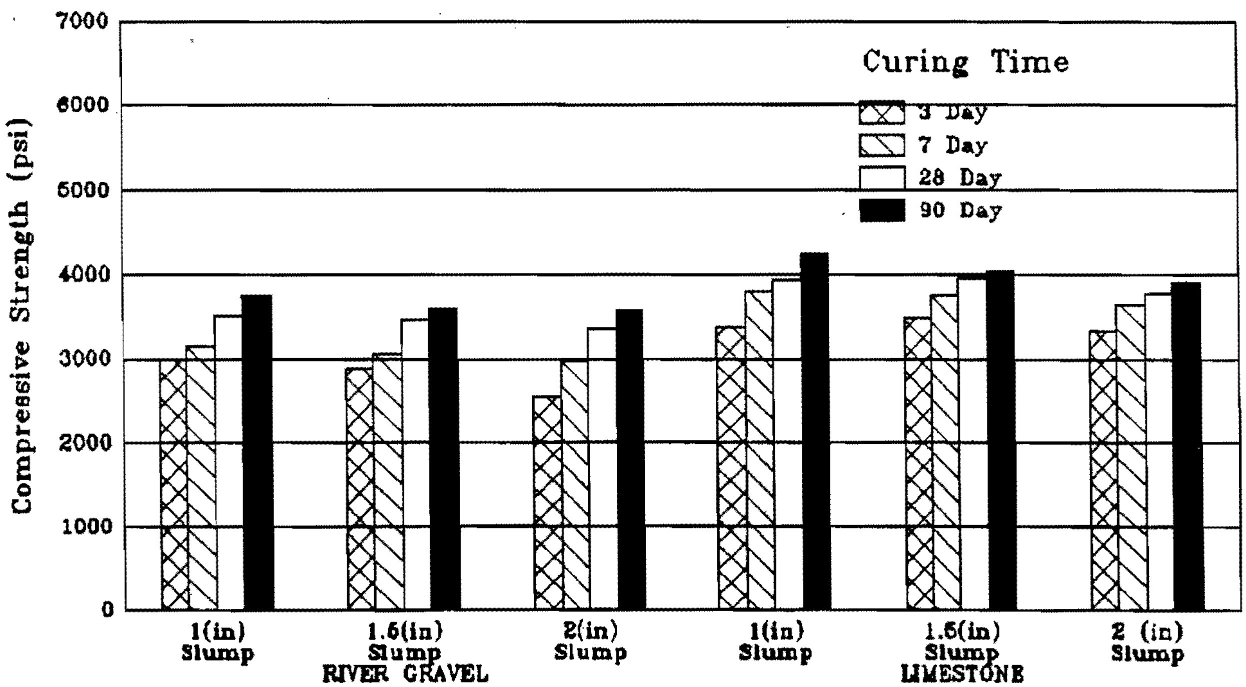


Figure 15. The effect of aggregate type and slump on compressive strength at 73°F; a) 65% RH and 9 mph wind b) 30% RH and 6 mph wind



Temperature 104(F), Relative Humidity 65%, Wind Speed 9mph



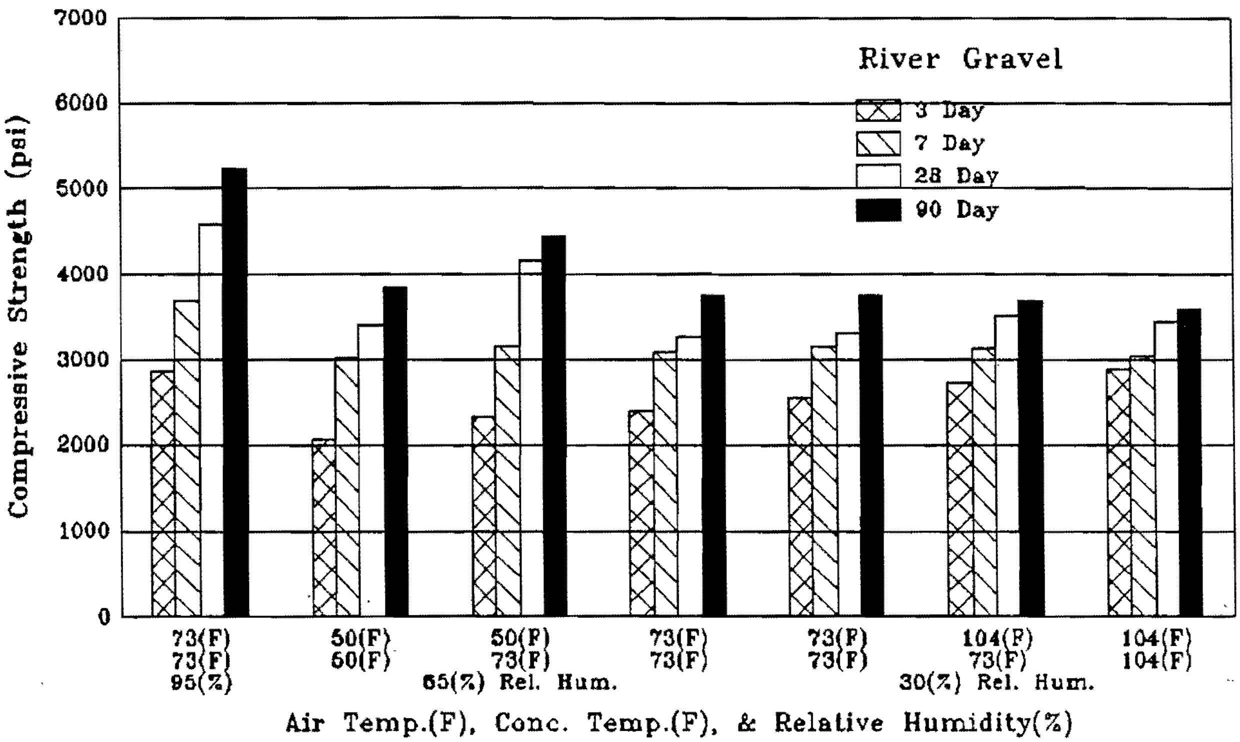
Temperature 104(F), Relative Humidity 30%, Wind Speed 6mph

Figure 16. The effect of aggregate type and slump on compressive strength at 104°F; a) 65% RH and 9 mph wind b) 30% RH and 6 mph wind

At low temperatures, the strength reduction upon an increase in slump is greater than the reduction at high temperatures. The reduction at low and high temperatures is about 20% and less then 10%, respectively. The smaller difference in the compressive strength at 104°F is caused by less availability of moisture. In the case of 104°F, the effect of slump on strength is quite small for the 90 day test results, and it is almost negligible for the concrete mixture containing limestone as coarse aggregate for all ages.

Figure 17 shows the effect of moist curing and controlling concrete temperature on the compressive strength. The environmental conditions increase in severity from left to right, with the continuously moist environment on the far left. Continuously moist cured concrete showed the greatest compressive strength at all ages. The strength at 90 days at 104°F was close to the strength obtained after 7 days of continuously moist curing. The rate of strength gain was the greatest for the moist curing condition and decreased with an increase in the severity of the climatic condition for both aggregate types. Concrete initially at 73°F showed greater strength gains than concrete initially at 50°F when the concrete was exposed to an air temperature of 50°F, a relative humidity of 65%, and a wind speed of 9 mph. The strength gain was greater for the limestone concrete than for the river gravel concrete, and the 28 and 90 day strength was equal to the strength obtained under continuous moist curing conditions. As a result, the differences of strength between moist cured concrete and air dried concrete became greater with time.

Using warm materials in a cold environment or cold materials in a hot environment helped the concrete strength development. Particularly the control of material temperature in a cold environmental condition caused a much greater strength gain and greater 90 day strength than the control of material temperature in the hot environment. In the cold environment, initial enhancement of hydration through heat treatment of the materials prevents severe temperature drops in the concrete. This helps formation of hydration products and decreases the pore sizes so that the evaporation through the concrete is reduced more effectively. In the hot environment, the reduction of the rate of hydration due to the cooling of the materials results in a more porous concrete. The slow rate of hydration results in a slightly lower 3 day strength; however, a higher later strength can be observed in the figure. The higher later strength might be primarily derived from the initial slower



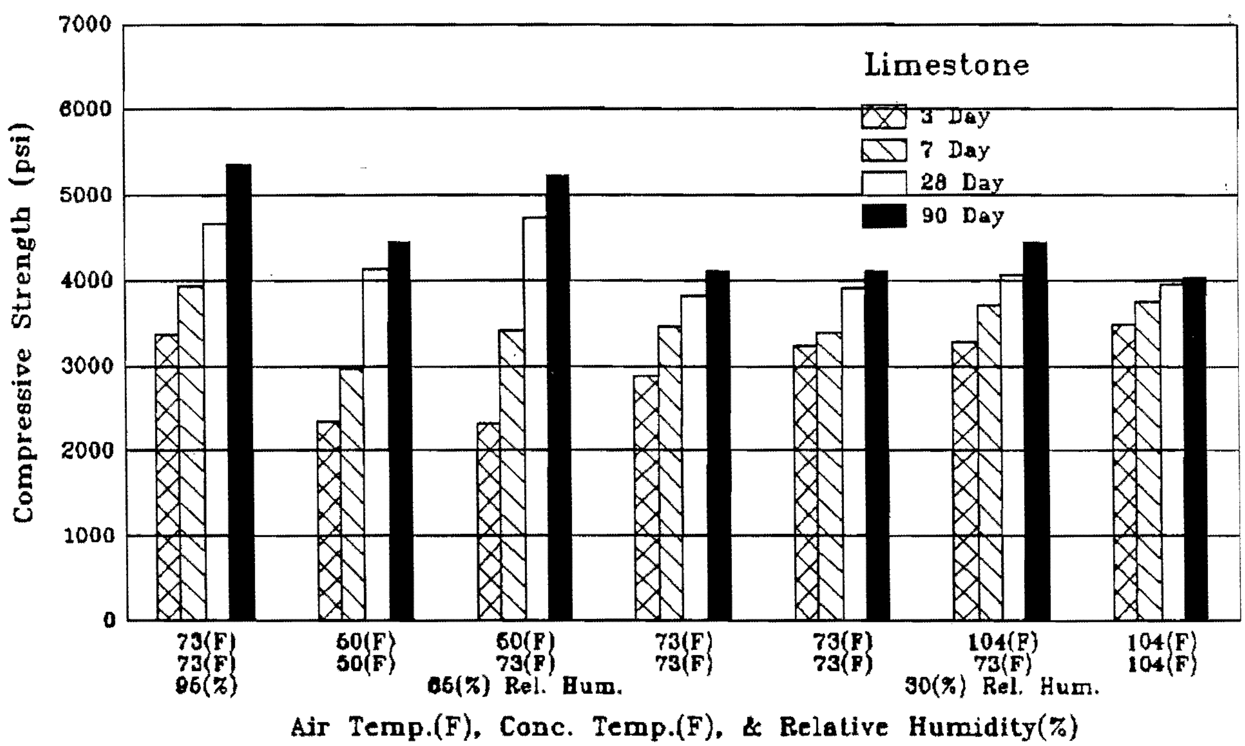


Figure 17. The effect of moist curing and controlling concrete temperature on the compressive strength of 1.5 inch slump concrete. For 30%, 65%, and 95% RH, wind speed 6, 9, and 0 mph respectively; a) River gravel b) Limestone

strength development. The faster rate of hydration in the hot temperature causes a weaker matrix structure to be formed as a result of a nonuniform distribution of hydration products (11).

When comparing the effect of aggregate type, the following can be observed from Figure 17. In general, the strength of the river gravel mixtures is less than for the limestone concrete mixtures. In particular, the strengths for the 50°F and 104°F environment with the materials heated or cooled to 73°F, respectively, increased more for the limestone mixture than the river gravel mixture when compared to the strengths obtained under continuous moist cure. This is attributed to the presence of larger amounts of water in the limestone aggregates and therefore a greater source of heating or cooling in the 50°F and 104°F environmental temperatures, respectively.

Figures 18 and 19 illustrate the effect of consolidation method on the compressive strength development for four different ages. The three different consolidation methods, spading, rodding and vibrating, were considered in this experiment. In most cases the vibrating method resulted in the greatest strength, followed by rodding and spading in that order. However, for the river gravel mixtures with 1.0 and 1.5 inch slump, the three consolidation methods produced about the same strength. For the 2 inch slump river gravel concrete, little difference in strength between the consolidation methods was observed at 3 days of curing. At the later ages, however, the previously stated trend is observed. For the limestone concrete mixtures, the difference in strength between the three consolidation methods appears to be the same for the different slumps. A similar pattern is seen for the river gravel mixtures. Furthermore, since the surface texture of the limestone concrete requires a larger energy to obtain liquefaction when compared to that of river gravel, a greater differentiation between the three consolidation methods is obtained with the limestone concrete.

The addition of fly ash to the concrete affected the compressive strength in two ways, depending on the aggregate type. With the exception of the results at 7 days, the fly ash mixtures with river gravel aggregates produced slightly lower strength than the plain concrete. For the limestone aggregate mixtures, the fly ash mixtures generally produced greater strength when compared to the strength obtained with the plain concrete. This difference in performance may be attributed to the greater

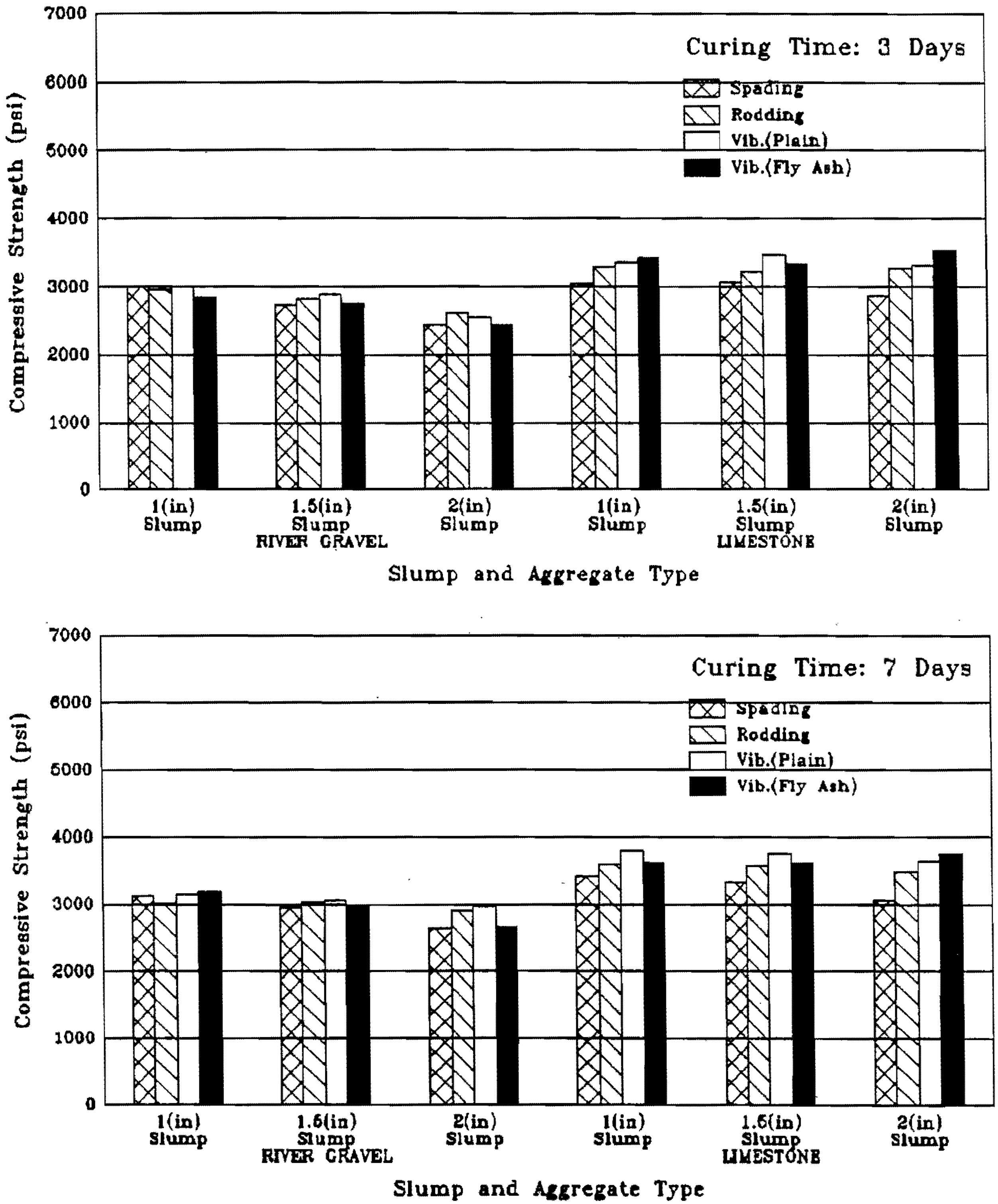


Figure 18. The effect of consolidation method on compressive strength; a) 3 days b) 7 days

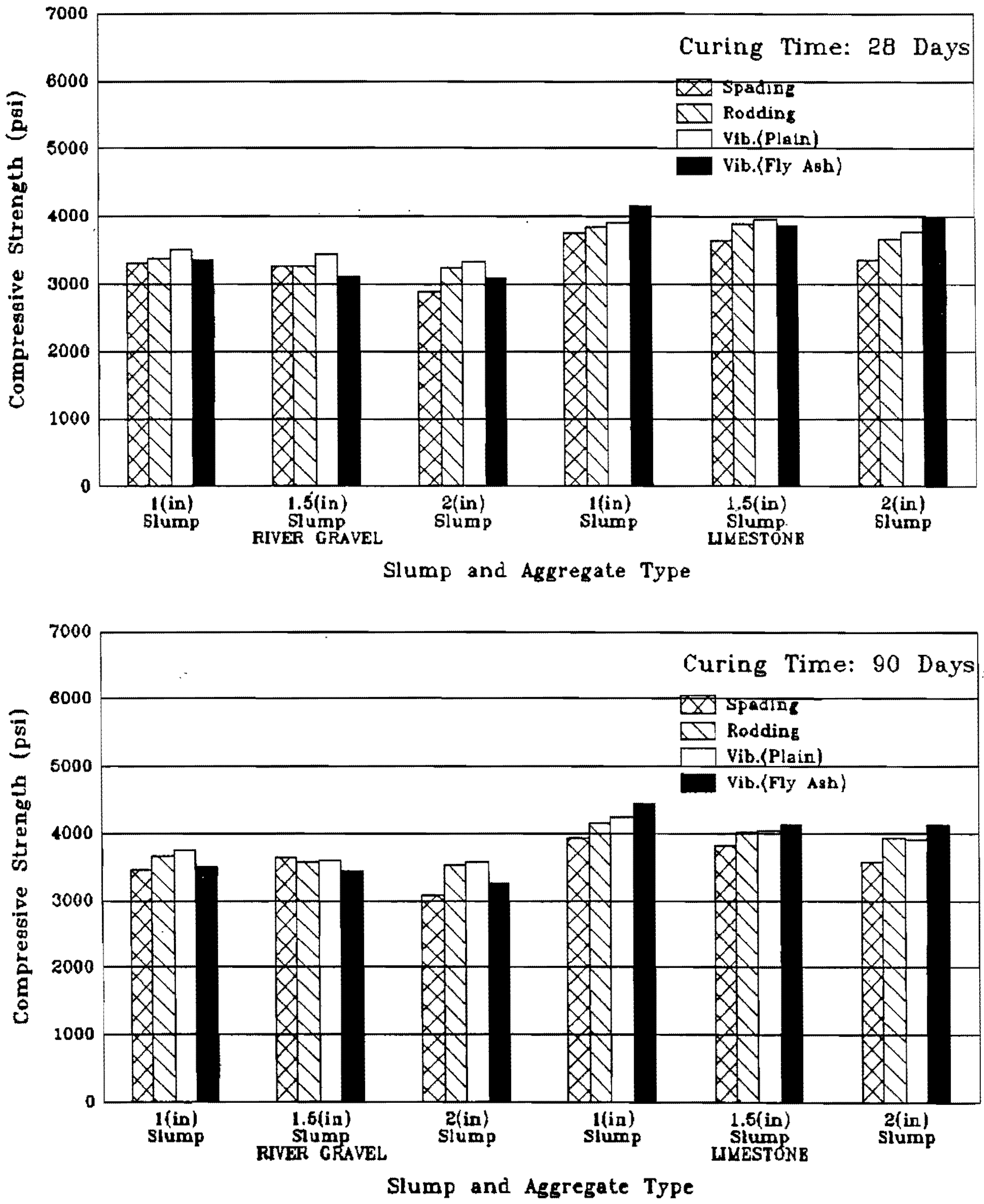


Figure 19. The effect of consolidation method on compressive strength; a) 28 days b) 90 days

ability of the fly ash to reduce the internal shear resistance of the limestone concrete than in the river gravel concrete during consolidation. Another possibility is the contribution of the fly ash to the amount of fines in limestone and river gravel. In river gravel, adequate fines are present, producing extra pore spaces when the fly ash is added. For the limestone, a lack of fines is corrected by the addition of the fly ash.

Since the results of pullout tests have to be correlated to either compressive or flexural strength for each individual mix design in order to be used for quality control purposes, the following analysis is offered. In this investigation, the flexural strength was only determined at 7 days as required by Item 366 (73), whereas the compressive strength was determined at 3, 7, 28, and 90 days. In order to assess the effect of age and environment on the beams normally used to determine the flexural strength, the pullout test was performed and the results correlated with the compressive strength. Figures 20 and 21 show the results of this correlation between compressive strength and pullout strength for the 50°, 73°, and 104° temperatures. From the plot, it can be seen that the slump changes did not affect the correlations between compressive strength and pullout strength for both aggregates investigated in this report. However, it can be clearly seen that the type of aggregate affects the correlations. Since slump changes affect the mortar strength, which affects both compressive strength and pullout strength, it is expected that the correlations are not affected by slump. Limestone concrete showed lower pullout strength than river gravel concrete for the same compressive strength. In pullout tests, the aggregates of smaller size than the diameter of the inserts are believed to affect the test results significantly when they are present on the failure surface. The failure surfaces of river gravel showed that most of the failure occurred between the mortar and the aggregate. On the other hand, many broken aggregates could be found on the failure surfaces of the limestone concrete. The strength of river gravel is greater than that of limestone, and that is the reason why smaller numbers of broken river gravel particles can be found on the failure surface. The failure cracks have to detour around the strong aggregates, which thus prevents cracks from propagating. The failure surfaces are increased by the detour, and the increased failure surface increases the pullout strength for the same compressive strength. Another observation from the figures is that the slope of the correlation

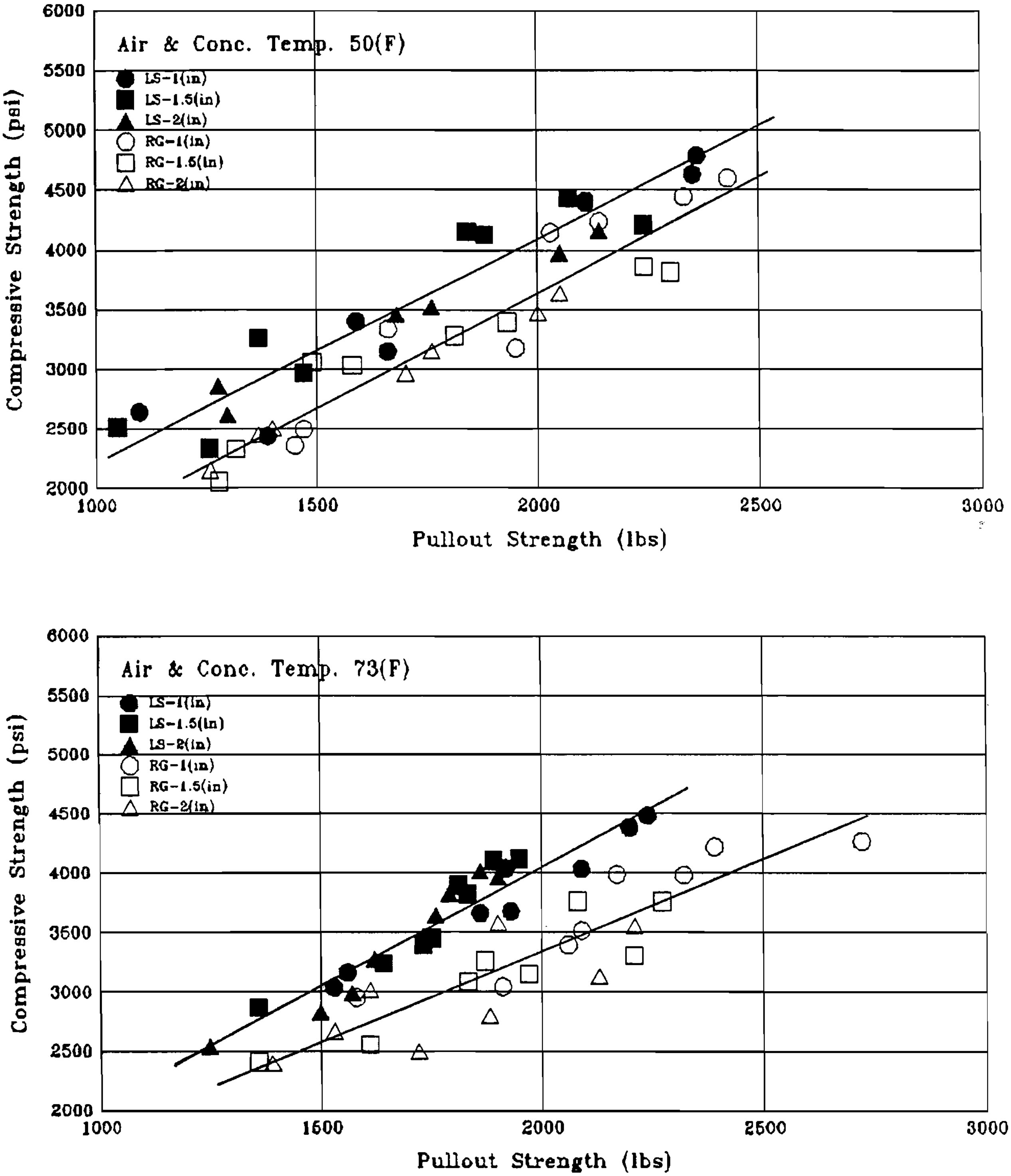


Figure 20. The correlations between compressive strength and pullout strength; a) 50°F b) 73°F

lines decreases as the temperature is increased from 50°F to 104°F. This indicates that the pullout strength is more sensitive to the change in temperature than the compressive strength and that the observed decrease in strength with temperature might be attributed to weak zones between the hydration products, as previously mentioned (11).

Moist Cured Condition The effects of mixing time on compressive strength are plotted in Figure 22 for 1.5 inch slump concrete. As the mixing time increased from 7 to 60 minutes, no significant changes in compressive strength occurred. Thus, the results indicate that the compressive strength was not affected by the extended mixing time for the standard conditions. A possible explanation for this observation is that the curing conditions after initial mixing provided adequate conditions for continued hydration.

Figure 23 shows the effect of consolidation method on compressive strength for different mixing times and a slump of 1.5 inches. The experiment was designed with the intention that the vibrating method had the highest consolidation energy and the spading method had the lowest consolidation energy. It was expected that the specimens that received the greatest amount of consolidation effort would yield the greatest strength. For 7 minutes mixing, this expectation was not met; even though the strengths at 3 and 90 days were the highest, the strengths at 7 and 28 days were not the highest values. Generally, the strengths were about the same. However, for 60 minutes mixing, the vibrating method showed the highest strength consistently, and almost the same strength was observed for the other two methods. The spading method gave slightly higher strength than the rodding method but not significantly higher. From these observations, we can conclude that the consolidation method did not affect the test results for 7 minutes mixed concrete, but the consolidation method affected the test results for 60 minutes mixed concrete. The 7 minutes mixed concrete had higher strength than the 60 minutes mixed concrete for most cases shown in Figure 23. The extended mixing time magnified the consolidation effects on the compressive strength.

Figure 24 illustrates the correlations between compressive strength and pullout strength. The vibrating and rodding methods show almost the same correlations. The spading method, however, showed a slightly different correlation from the other two methods. Both the spading and rodding methods show very good correlations

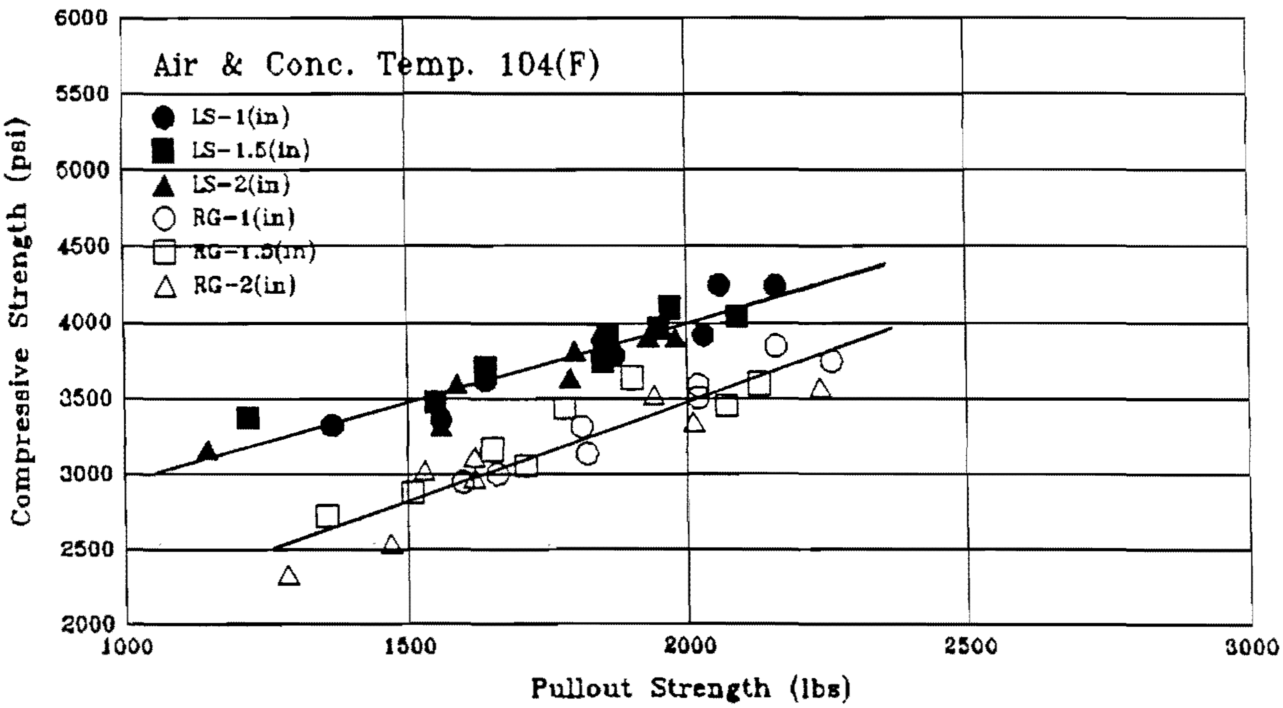


Figure 21. The correlations between compressive strength and pullout strength at 104°F

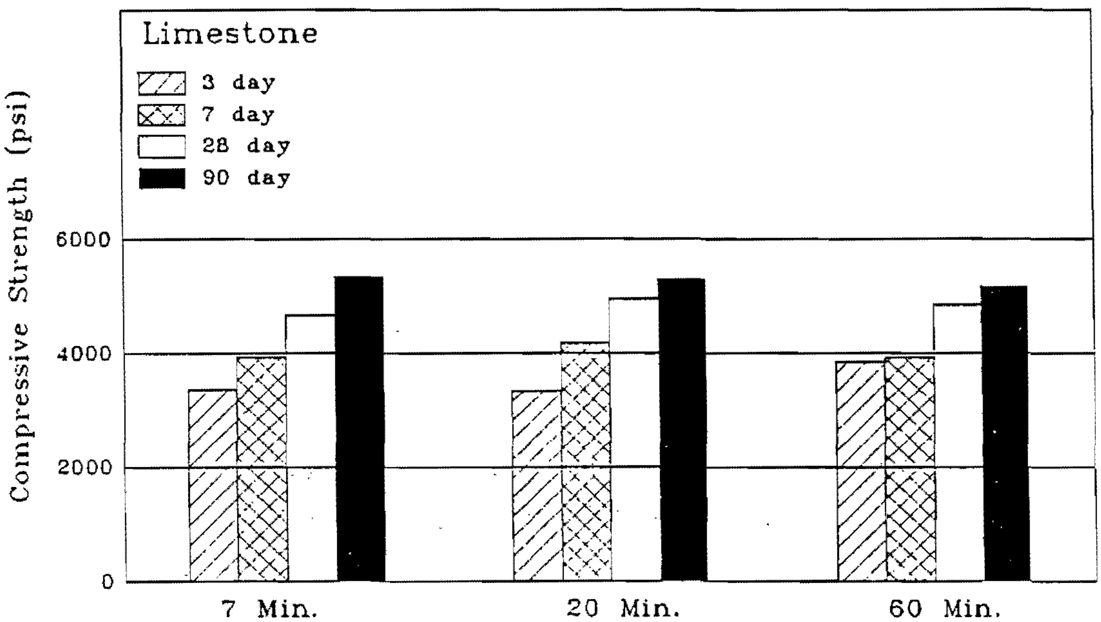
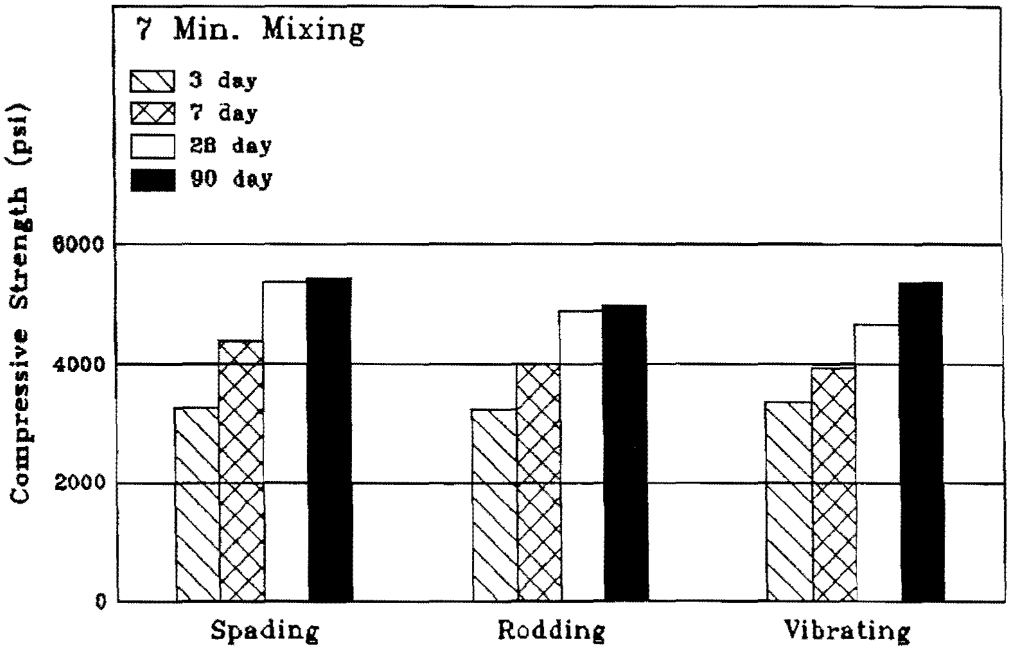


Figure 22. The effect of mixing time on compressive strength in moist cured condition for 1.5 inch slump concrete



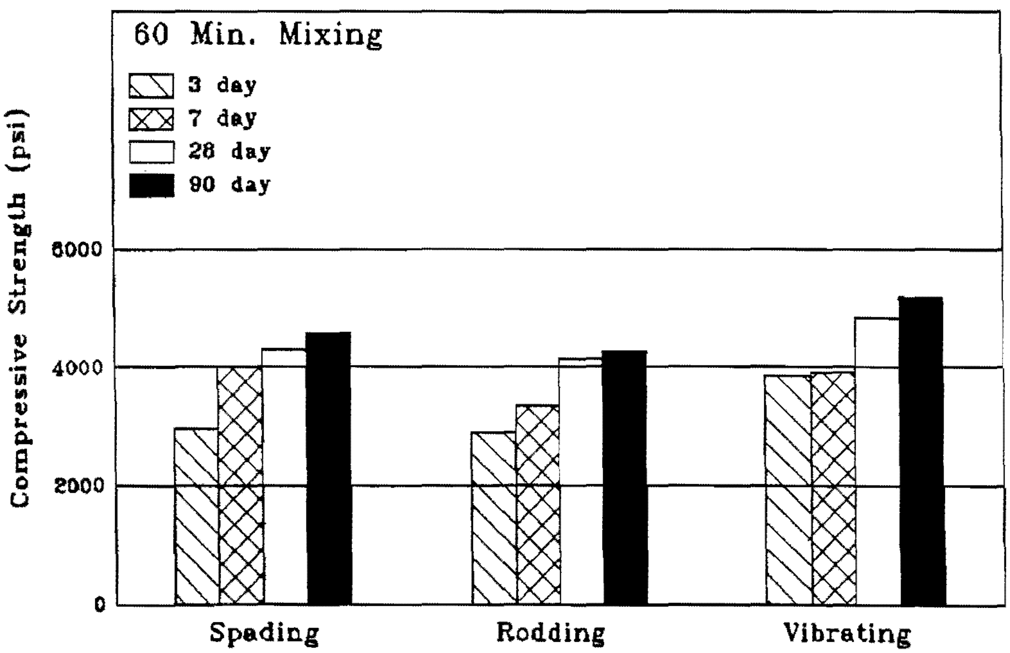


Figure 23. The effect of consolidation method on compressive strength in moist cured condition for 1.5 inch slump concrete

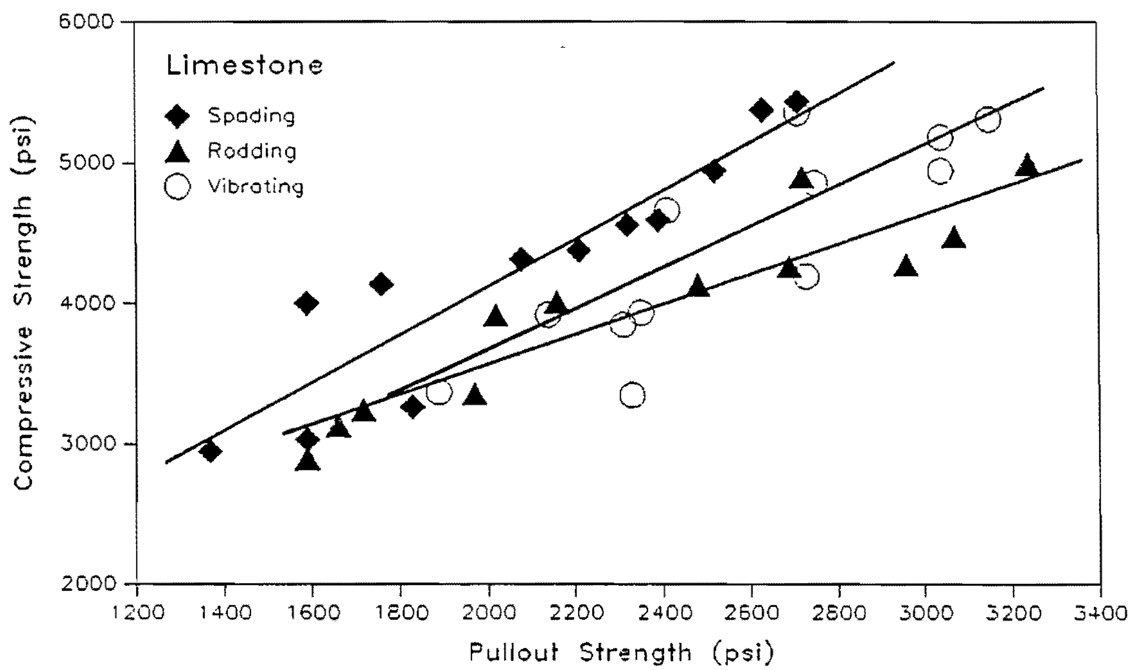


Figure 24. The correlations between compressive strength and pullout strength in moist cured condition

and fairly low variabilities. The vibrating method showed higher variabilities than the other two methods.

4.3.2 Flexural Strength and Modified Compressive Strength

During the initial trial mix design procedure, all of the beam samples were subjected to the center point flexural test. For the specimens that were moist cured, Table D2 in the Appendix shows that the flexural strength was greater than the minimum of 575 psi required by Texas Specification Item 366 (73). As seen from Figure 25, however, none of the simulated field environmental conditions tested here produced strengths greater than the required minimum strength. This implies that the curing treatment used can never be as effective as continuous moist curing, and significant strength reductions can be anticipated. The current pavement design procedures should consider this strength reduction rather than using the given minimum strength.

From Figure 25, the effect of evaporation rate on the 7 day flexural strength is also clearly seen. As the evaporation rate increases, again from left to right in the figure, the strength of river gravel concrete decreases more than 100 psi for all mixtures. Relatively smaller changes were observed for the limestone concrete. This smaller change of strength might be caused by the existence of pore water in the limestone aggregates. The pore water provides a source of water for hydration and reduces the effect of drying of the concrete. The continuous hydration reduces the rate of drying resulting in a reduction of the effect of the curing conditions on the flexural strength. At the low temperatures, with a low evaporation rate, the strengths of both types of concrete are almost the same. At the higher temperature with greater rate of evaporation, the differences between the strength of the mixtures becomes greater as the temperature increases. As these results show, evaporation is a restricting factor for the strength development, due to the removal of moisture needed for hydration. The temperature accelerates the chemical reaction by increasing hydration rate, but, as stated previously, high temperatures cause the formation of a nonuniform distribution of hydration products with weak zones. The decrease of strength as the slump increases can also be observed in Figure 25. From Figure 25a the results for 104°F and 65% relative humidity for the river gravel concrete indicate that the flexural strength for the 1.5 inch slump

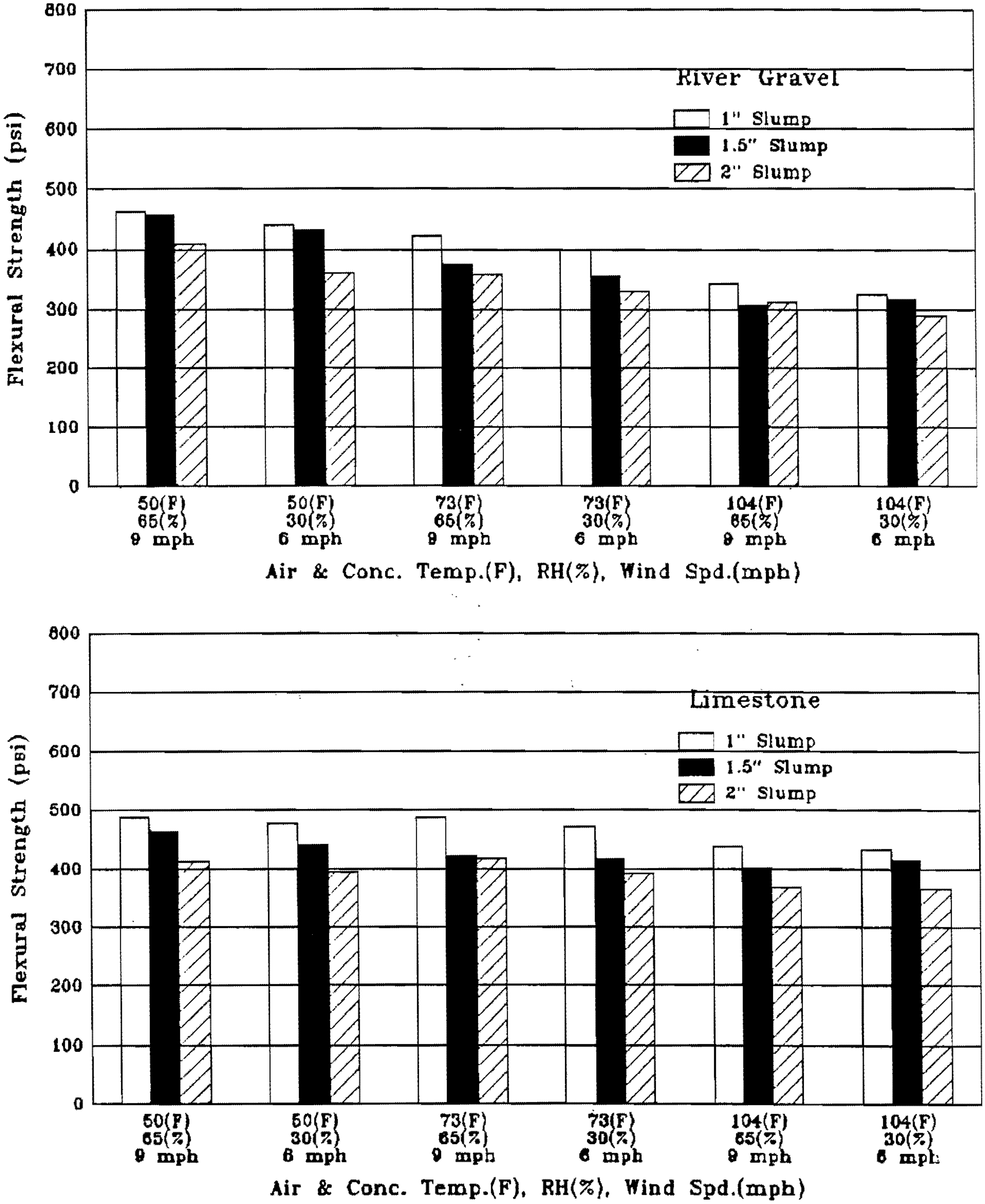


Figure 25. The environmental effects on the flexural strength; a) River gravel b) Limestone

mixture is lower than expected. This is attributed to the variability of the test, since only one beam was tested per data point. The decreases of strength due to slump changes are smaller than the changes due to the environmental changes investigated in this research. The observations imply that 7 days of evaporation is long enough to differentiate the effect of environmental changes on the flexural strength.

The delay of placement requires additional water to achieve proper workability, and causes a decrease in flexural strength. This is illustrated in Figure 26 where, for the same slump, the flexural strength decreases as the mixing time increases. However, this reduction in flexural strength can be avoided by controlling the initial slump. Even for 60 minute mixing, if the additional water is closely controlled within one inch slump, the flexural strength can be greater than that of 7 or 20 minute mixed concrete of higher slump. Reducing the initial slump, if delays in concrete placement are anticipated, can be helpful for recovering flexural strength. In other words, high slump has a worse effect on flexural strength than the delay of placement. Note that these results were achieved when retempering was administered after the end of the mixing time. If retempering is not administered, a permanent reduction in slump exists at the time of placement and difficulties in consolidating and finishing of the concrete will most likely occur.

The replacement of part of cement with fly ash slightly reduces the 7 day flexural strength. However, the effects of delays in placement and slump on flexural strength were not changed by the presence of fly ash. In this research, 20 % replacement of fly ash was used with a 1:1 ratio by weight of cement. If a 1:1.2 replacement ratio was used instead, the strength reduction might be reduced or eliminated.

For the limestone concrete, the absolute strength is about 100 psi greater than for the river gravel concrete. However, no large differences for the effect of mixing time and slump changes can be observed. Limestone concrete is more stable for the changes of the factors shown in Figure 26. The possible reasons for this phenomenon might be twofold: the rough surface of limestone might provide better bonds than river gravel concrete, or the greater absorption of the limestone compared to the river gravel might provide additional water for continuous hydration.

Figure 27 shows the effect of the consolidation method for both aggregate types for 1.5 inch slump concrete. The spading method is expected to yield the lowest

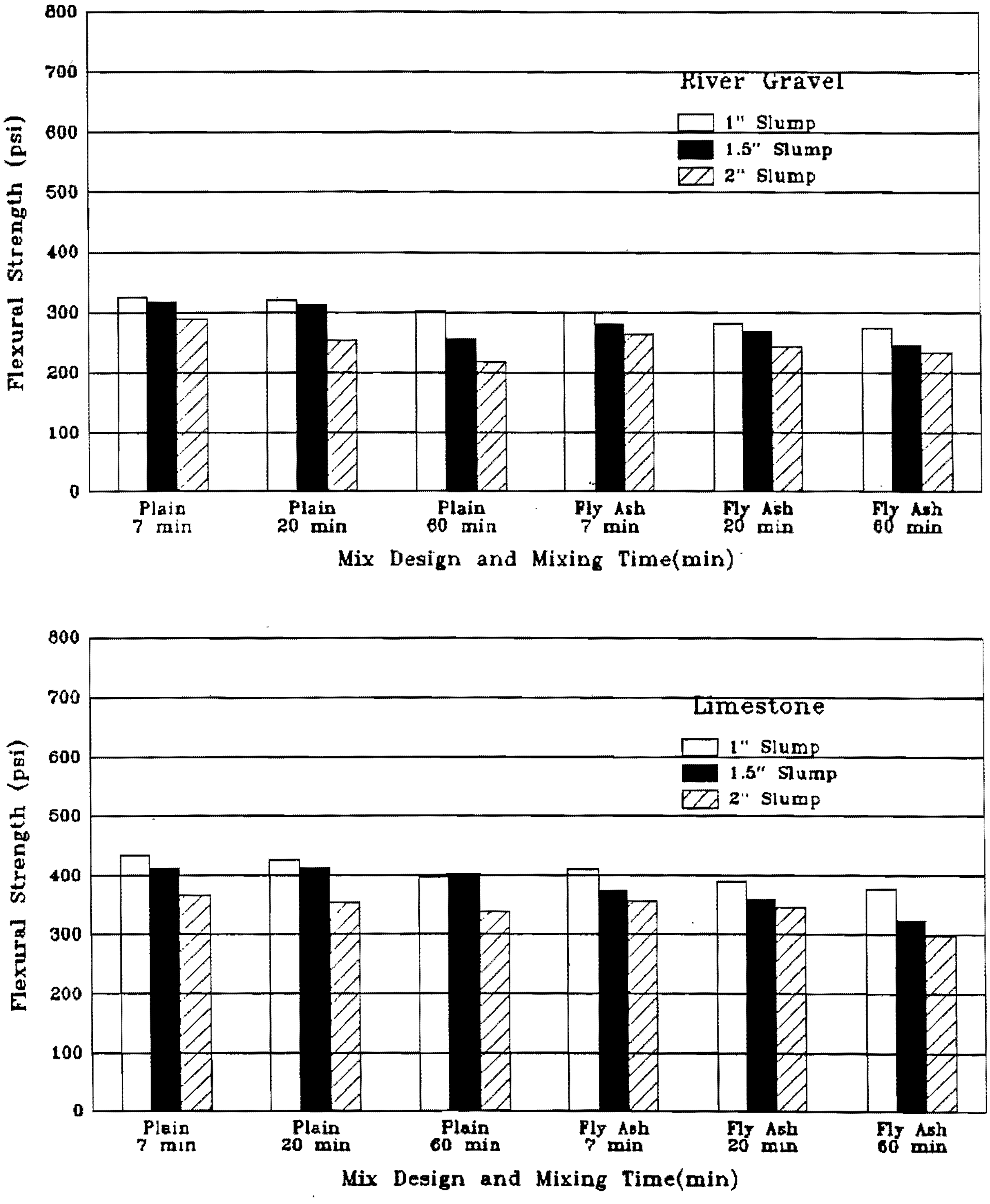


Figure 26. The effect of mixing time and fly ash on the flexural strength for 1.5 inch slump concrete ; a) River gravel b) Limestone

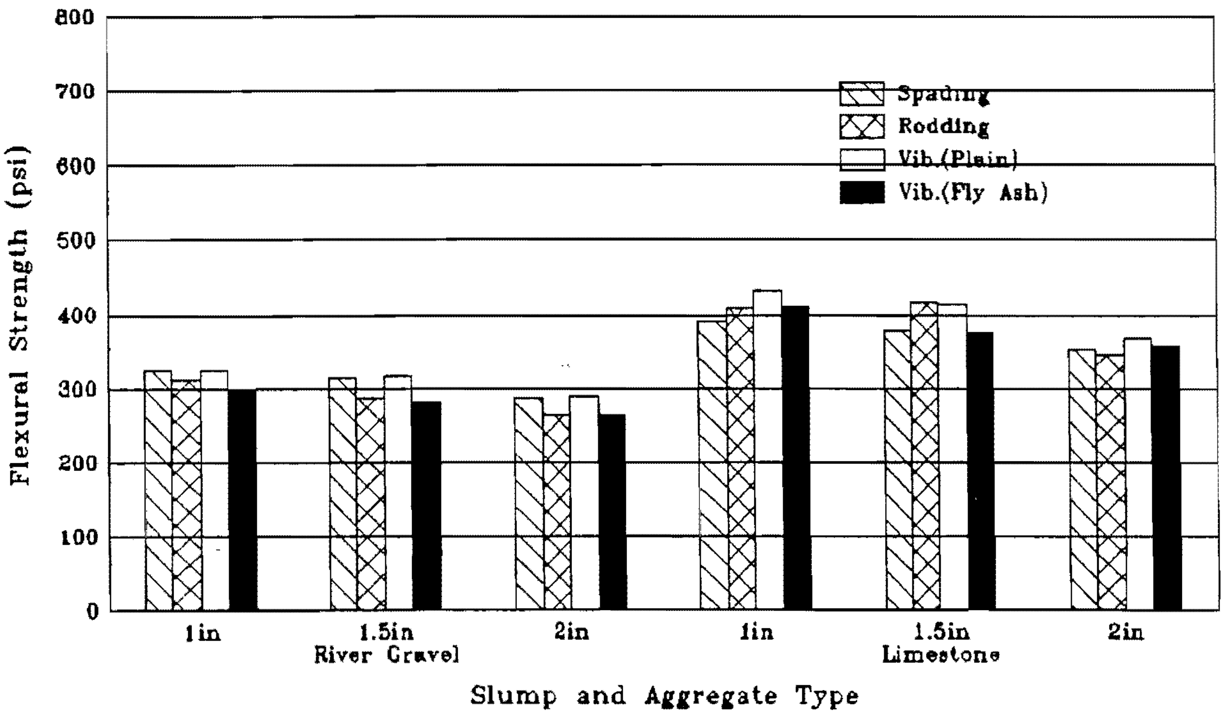
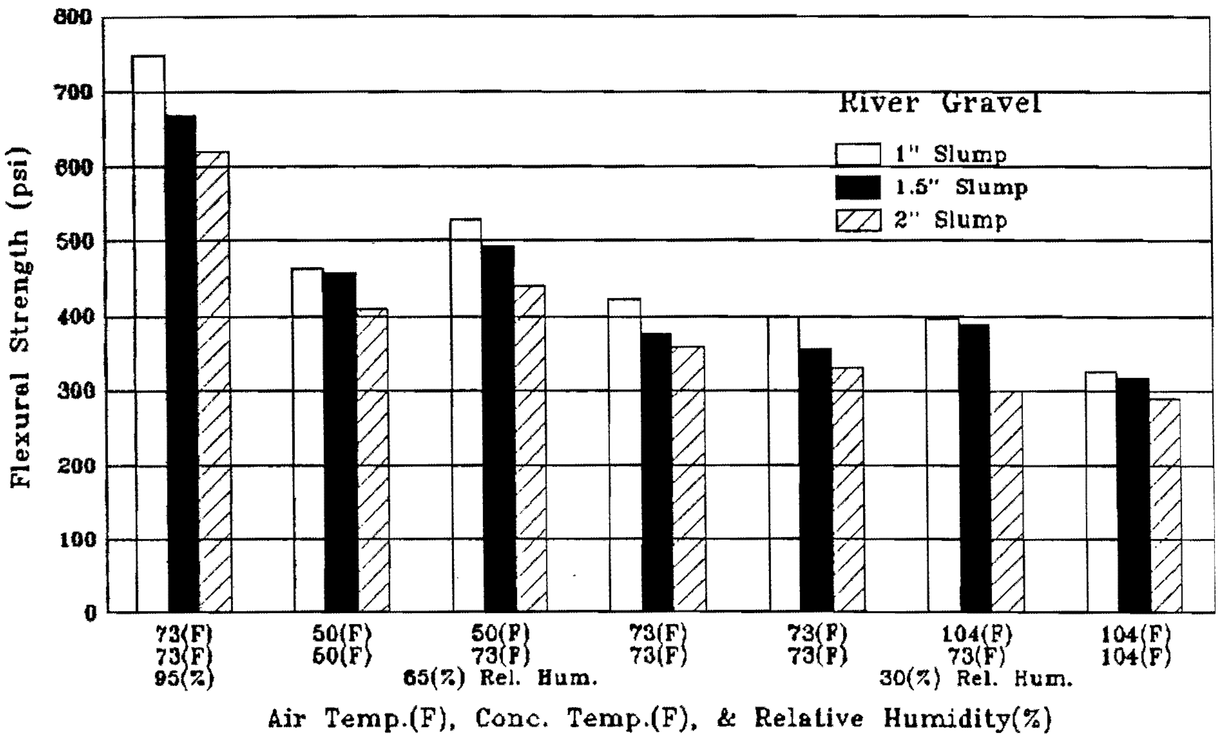


Figure 27. The effect of consolidation method on flexural strength for 1.5 inch slump concrete with river gravel or limestone aggregate

strength among the three methods because this method has the lowest consolidation energy. However, some of the spaded concrete showed higher strength than the rodded concrete and almost the same strength as the vibrated concrete. More than expected degree of consolidation must therefore have occurred with the achieved spading method. Even though the consolidation energy is not as high as the rodding method, the shape of the trowel used to consolidate the concrete by spading might have improved the efficiency of the consolidation. A long and narrow cross section of the trowel improves the penetration into the concrete mix and provides consolidation over a more wide area per stroke. Spading of the concrete with rounded river gravel particles appears to be as effective as vibration, but less effective for the crushed limestone concrete. In this case, the angular shape of limestone produced significantly lower strength for both the rodding and spading method compared to the vibrating method. The interlocking nature of angular aggregate particles thus limits the level of consolidation so that the vibrating method becomes more effective with angular limestone than the rounded river gravel in consolidating the concrete.

Figure 28 shows the effect of moisture curing and temperature control on the flexural strength. Moist cured concrete showed distinctly higher strength than the concrete exposed to other environmental conditions. All of the continuously moist cured samples resulted in greater flexural strengths than required by the Specifications of the Texas State Department of Highways (73). Most of the previous studies have reported that curing compounds were effective in retaining the moisture in concrete. Although the use of a curing compound generally has been found to be more effective than no treatment at all (5), Figure 28, however, clearly shows that the flexural strengths are significantly lower than for the continuous moist cured concrete. When a material temperature of 73°F was used instead of 50°F during the mixing in the 50°F environment, a significant increase in flexural strength was observed for the river gravel concrete. When this same temperature of the materials was used under the 104°F condition, a similar increase was observed. As in the case of the compressive strength, using warm materials in cold temperatures and cool materials in hot temperatures affects the flexural strength of the rivel gravel concrete beneficially. This is also the case for the limestone concrete, but to a lesser extent. These two observations indicate that controlling the material temperature is an effective way to overcome extreme temperature conditions for both river gravel and



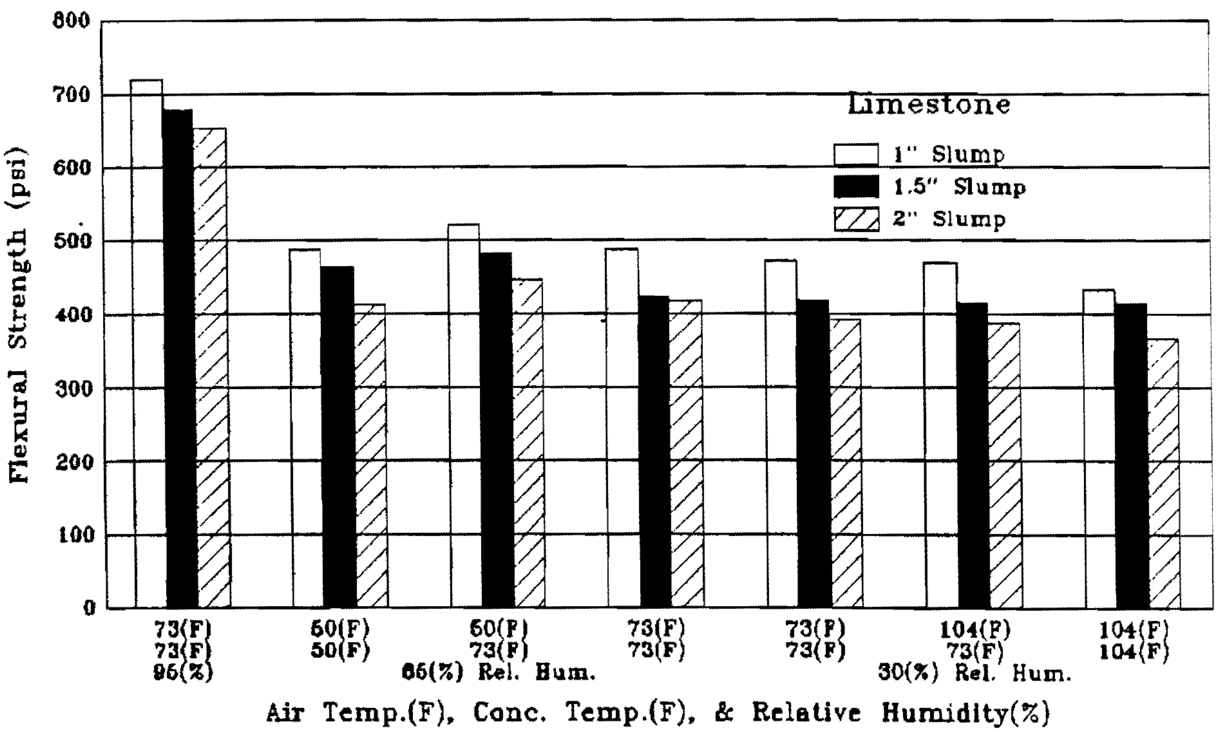


Figure 28. The effect of moist curing and controlling concrete temperature on the flexural strength. For 30%, 65%, and 95% RH, wind 6, 9, and 0 mph, respectively; a) River gravel b) Limestone

crushed limestone concrete. The beneficial effects are true regardless of the slump.

Figure 29 shows the correlations between flexural strength and modified compressive strength for different environments and types of aggregate. It can be recognized that the curing condition affects the correlations between the two strengths for the river gravel concrete and, to a lesser extent, for the limestone concrete. It can be seen that the dryer 104°F environment affects the flexural strength more significantly than the modified compressive strength. It is well known that when specimens are exposed to a dry environment, such specimens always have a nonhomogeneous moisture distribution, which produces nonunifom residual stress distributions across the cross section. As a result, tensile stresses are developed around the surface and compressive stresses in the center. The tensile stress in the surface layer decreases the flexural stength and helps to increase the compressive strength. Another possible explanation is that the flexural strength primarily depends on the bonding strength of the binder material, and that the compressive strengths are affected by bonding strength as well as shear friction between the constituents. As a result, compressive strengths are not as sensitive as flexural strength to changes in the distribution of residual stresses. As the specimens are exposed to drier conditions, this phenomenon becomes more distinct.

Figure 30 shows how the type of aggregate and the fly ash affect the correlations between the two different strengths. Limestone has higher flexural strength than river gravel for the same compressive strength. This is evidence of the advantage that the rough surface texture of limestone has over the rounded river gravel for flexural strength. The angular shape of limestone also may be increasing the bonding area. The flexural strength primarily depends on the bonding strength of the binder material, so the increase of the strength is more greatly affected by the bond strength than is compressive strength.

For both river gravel and limestone, the use of fly ash decreases flexural strength more significantly than compressive strength. The changes of correlations between the two strengths are due to the reduction of the bonding strength. For the same reason stated in the above paragraph, a decrease of bond strength decreases the flexural strength more significantly. The influence of the fly ash on the flexural strength, however, is less for the river gravel concrete, since the river gravel particles are well rounded, as are the fly ash particles.

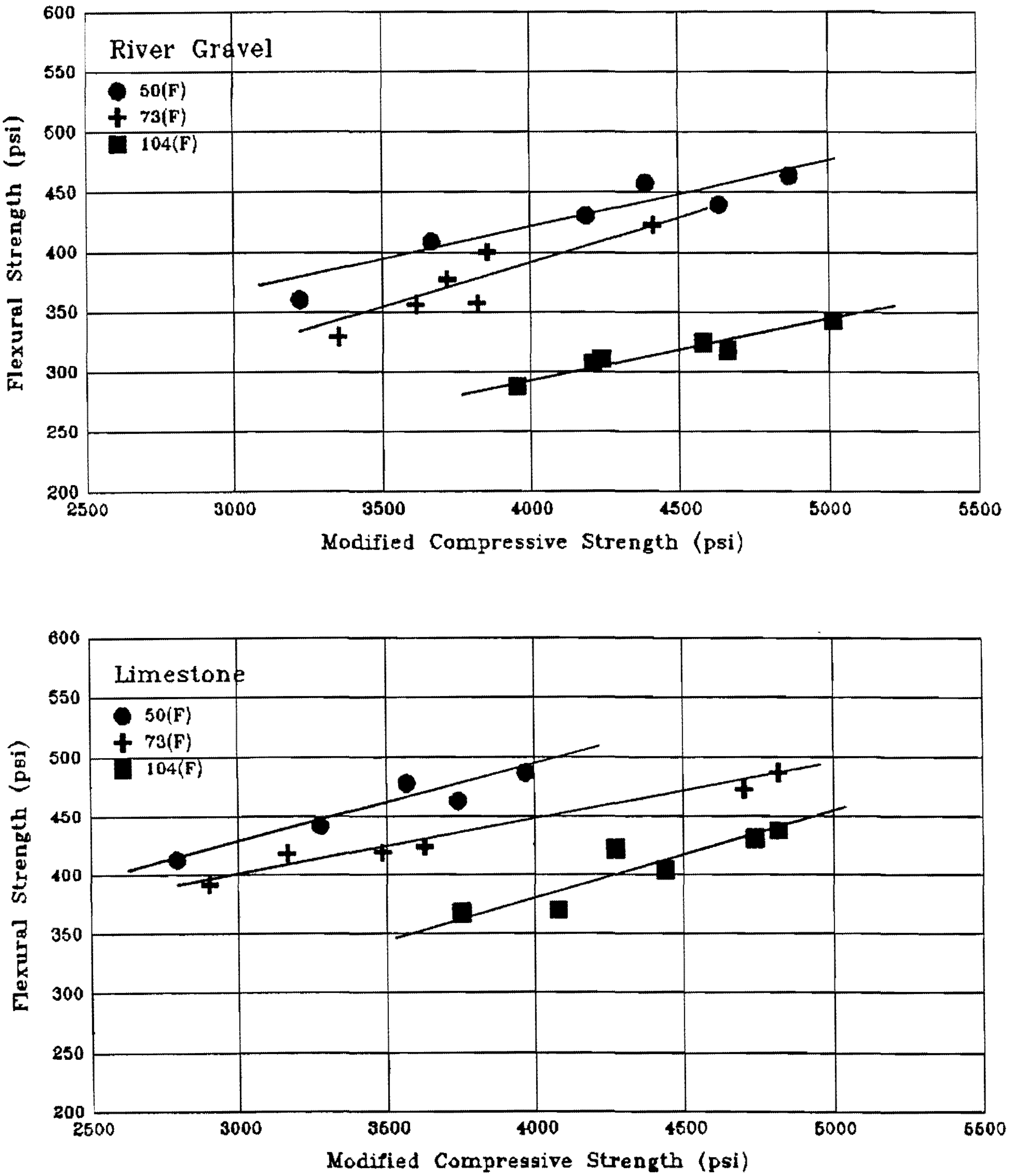


Figure 29. The correlations between flexural strength and modified compressive strength; a) River gravel b)Limestone

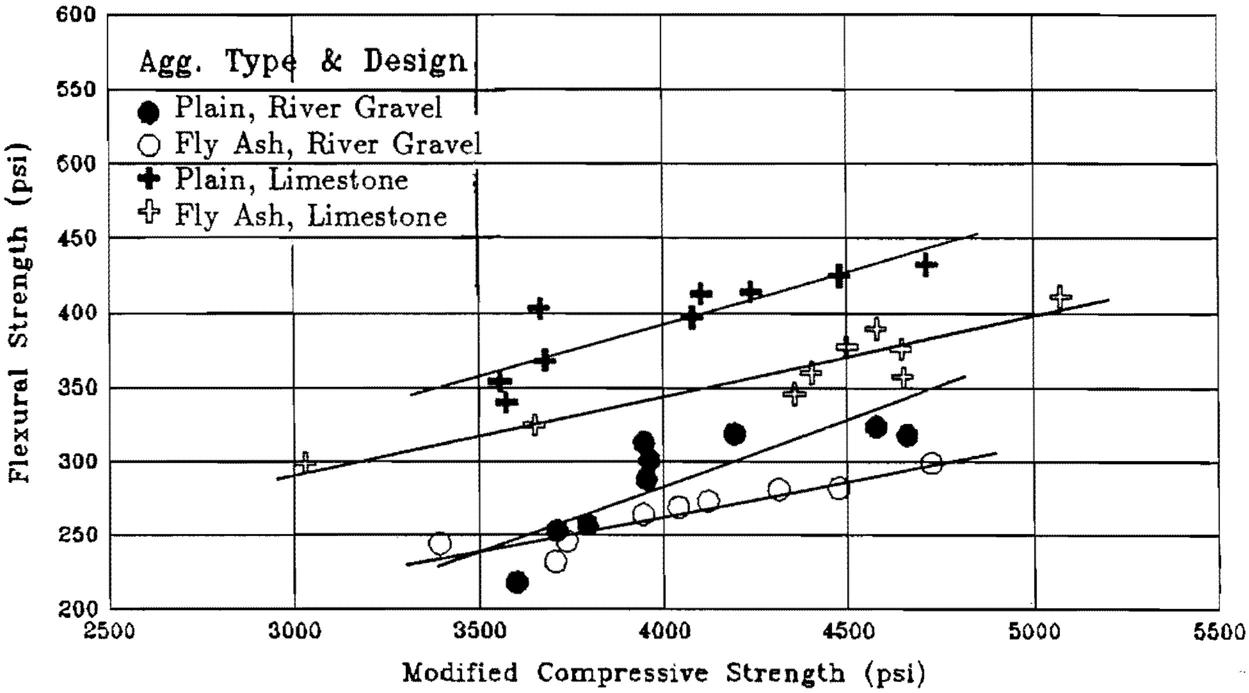


Figure 30. The correlations between flexural strength and modified compressive strength at 104°F

Moist Cured Condition The effects of mixing time and consolidation methods on flexural strength are plotted on Figure 31 for 1.5 inch slump concrete. All the flexural strengths were consistently greater than the construction requirement of 575 psi. An insignificant decrease of flexural strength can be observed with the increase of mixing time. However, the effect of consolidation is not as significant as mixing time.

Figure 32 shows the correlations between flexural strength and modified compressive strength for different consolidation methods. Both the rodding and vibrating methods showed good correlations, but the spading method showed odd correlations. More data points are needed to establish a better correlation for this method. Both the rodding and vibrating methods give almost the same correlations, whereas spading shows a different relationship.

4.3.3 Conclusion

The following conclusions are based on the results of the laboratory tests for the concrete strength. The conclusions are divided into two sections that refer to the results of the compressive and pullout strength data and the flexural and modified compressive strengths.

Compressive and Pullout Strength :

1. The strength at 3 days increases as the evaporation rate of the curing conditions investigated in this test increases; however, the amount of strength developed at 90 days decreases as the evaporation rate increases.
2. Extending the mixing time up to 60 minutes reduces the strength, regardless of the type of aggregate, the type of admixture and the age.
3. In the severe environment, the concrete mixtures containing fly ash developed about the same strength properties as the control mixture without fly ash.
4. The effect of fly ash addition on the compressive strength depends on the type of aggregate and aggregate gradation used in the mix.
5. With a few exceptions, as the amount of mixing water was increased, a strength reduction was observed, regardless of the type of aggregate and exposure conditions.

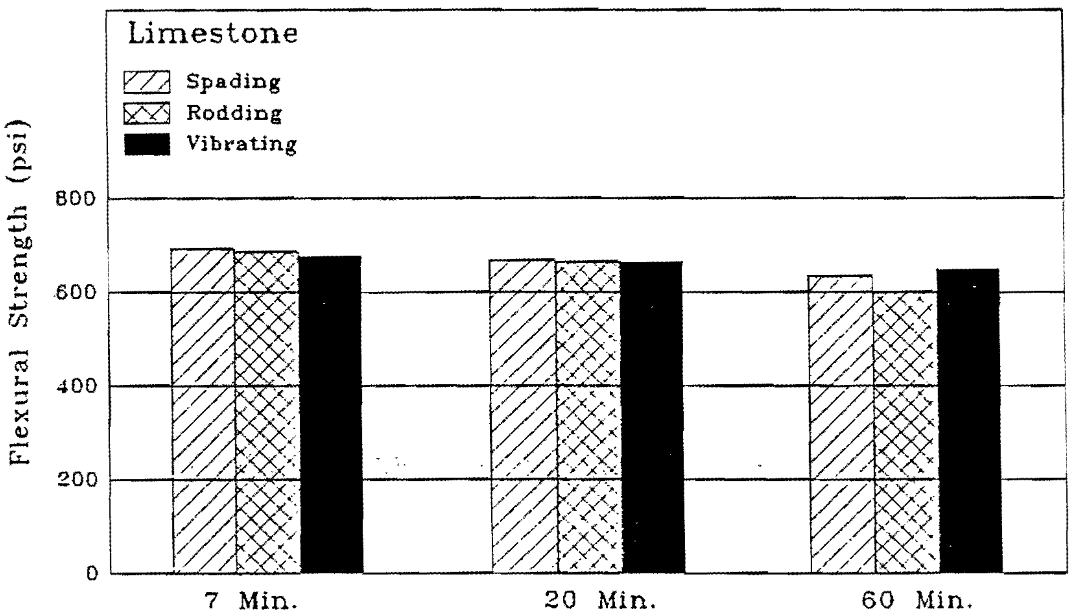


Figure 31. The effect of consolidation method on flexural strength in moist cured condition for 1.5 inch slump concrete

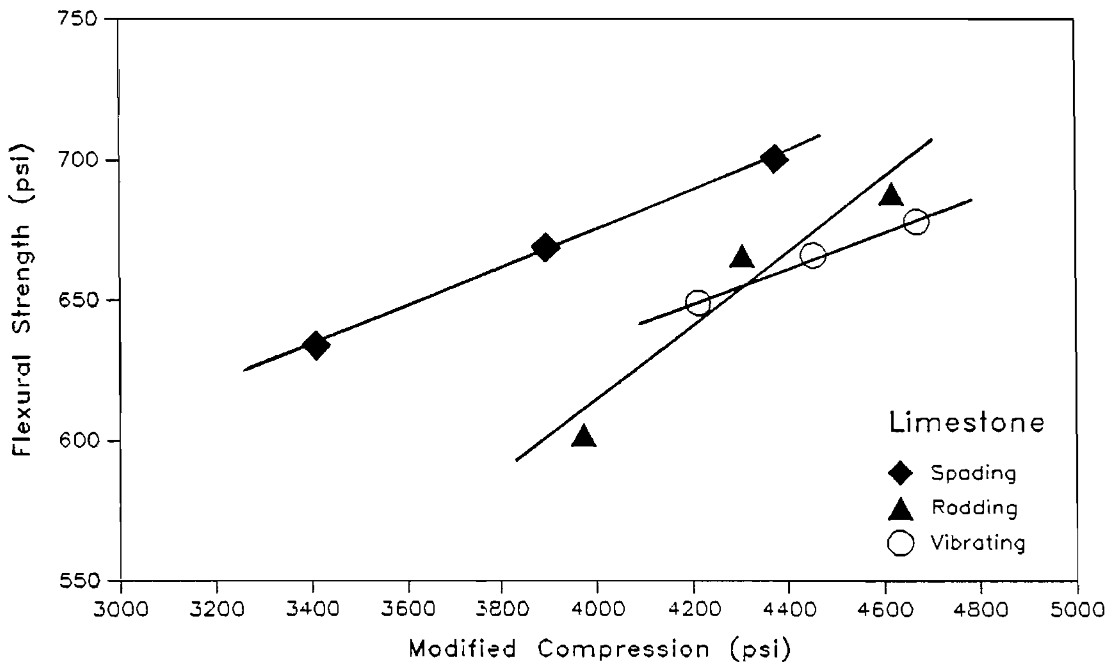


Figure 32. The correlations between flexural strength and modified compressive strength in moist cured condition

6. The effect of controlling the amount of mixing water was found to be more critical at the cold temperatures than at the hot temperatures within the temperature ranges investigated in this test.
7. The use of a curing compound produced concrete with lower strength than moist cured concrete at early ages. This strength difference increased with age.
8. Controlling the material temperature in a cold environment was found to be more effective than in a hot environment in increasing the compressive strength.
9. The effect of consolidation method on the compressive strength was not found to be significant. Although not statistically proven, the vibrating method produced the highest strength, and the rodding and spading methods produced the lowest strength.
10. The correlations between compressive strength and pullout strength are not affected by the slump changes, but are primarily affected by the type of aggregate and by the influence of the aggregate on the failure mechanism.

Flexural and Modified Compressive Strength:

1. All of the specimens treated with curing compound showed approximately 35% lower flexural strength than the specified 575 psi. For this reason, the value of 575 psi should not be used in the design procedure for CRC pavements unless the pavement is continously moist cured.
2. Continuously moist cured beams showed flexural strengths about 15% higher than the State's 575 psi minimum.
3. The 7 day flexural strength is affected by the evaporation rate. As the evaporation rate increases, the flexural strength decreases. The amount of reduction depends on other factors, such as type of aggregate.
4. The extended mixing time up to 20 minutes did not reduce the flexural strength; however, the 60-minute extended mixing reduced the flexural strength significantly for the river gravel concrete.
5. The limestone concrete has significantly higher flexural strength than river gravel concrete.
6. For the particular source of fly ash, a replacement of 1:1 by weight of cement with 20% fly ash causes a slight reduction in flexural strength.

7. The vibrating method gives the highest flexural strength in most cases. No significant difference in flexural strength was found between the rodding and spading compaction methods.
8. Controlling the material temperature in a cold environment produces greater strengths than in a hot environment.
9. The correlations between flexural strength and modified compressive strength are affected by the environmental conditions and type of aggregate. At high temperatures, slightly lower flexural strength can be observed for the same modified compressive strength.
10. Limestone concrete has higher flexural strength than river gravel concrete for the same modified compressive strength, but has almost the same range of modified compressive strength as river gravel concrete.

4.4 Shrinkage and Moisture Variation

4.4.1 Shrinkage and Weight Loss

The shrinkage of concrete is one of the most important properties of concrete and also one of the most difficult properties to measure and to predict. Moisture loss of concrete causes contraction of the cement paste and is directly related to the concrete shrinkage. Aggregates embedded in concrete provide restraint against volume changes due to either shrinkage or expansion. The amount of aggregate and the physical properties, such as modulus of elasticity and porosity, are important factors which determine the degree of restraint.

Figure 33 illustrates the effects of environmental conditions on the shrinkage of river gravel concrete with 1.5 inch slump. The average 90 day shrinkage at 50°F is about 210 microinches per inch. The average 90 day shrinkages at 73°F and 104°F are about 240 and 415 microinches per inch, respectively. The order of 90 day shrinkages corresponds well with the order of the evaporation rate for each environment. This was not the case for the early shrinkage results. In Figure 33, the early shrinkage at 50°F was greater than the early shrinkage at 73°F. The reversed order was, however, corrected at about 28 days. There is no reasonable explanation for this reversed order at early ages. It might be caused by the differences between the evaporation rates being smaller than the test variability. As the effects of evaporation rate accumulated with age, the environmental effects decreased the testing variability of the shrinkage data.

Figure 34 is a companion figure to Figure 33 showing the shrinkage of limestone concrete with a slump of 1.5 inch. The average 90 day shrinkages at 50°F, 73°F, and 104°F were about 460, 500 and 700 microinches per inch, respectively. The average values were about twice those obtained with the river gravel concrete. The 90 day shrinkages were arranged in increased order of evaporation rates. It is clearly seen that the environmental conditions of 104°F and 30% RH and 50°F and 65% RH give respectively the highest and the lowest shrinkages. For the limestone concrete, the lowest shrinkage was also obtained with 50°F and 30% RH.

Figures 35 and 36 illustrate the effects of mixing time and fly ash on the shrinkage of concrete with 1.5 inch slump. At early ages, the 7 minute mixed concrete showed the lowest shrinkage and the 60 minute mixed concrete showed

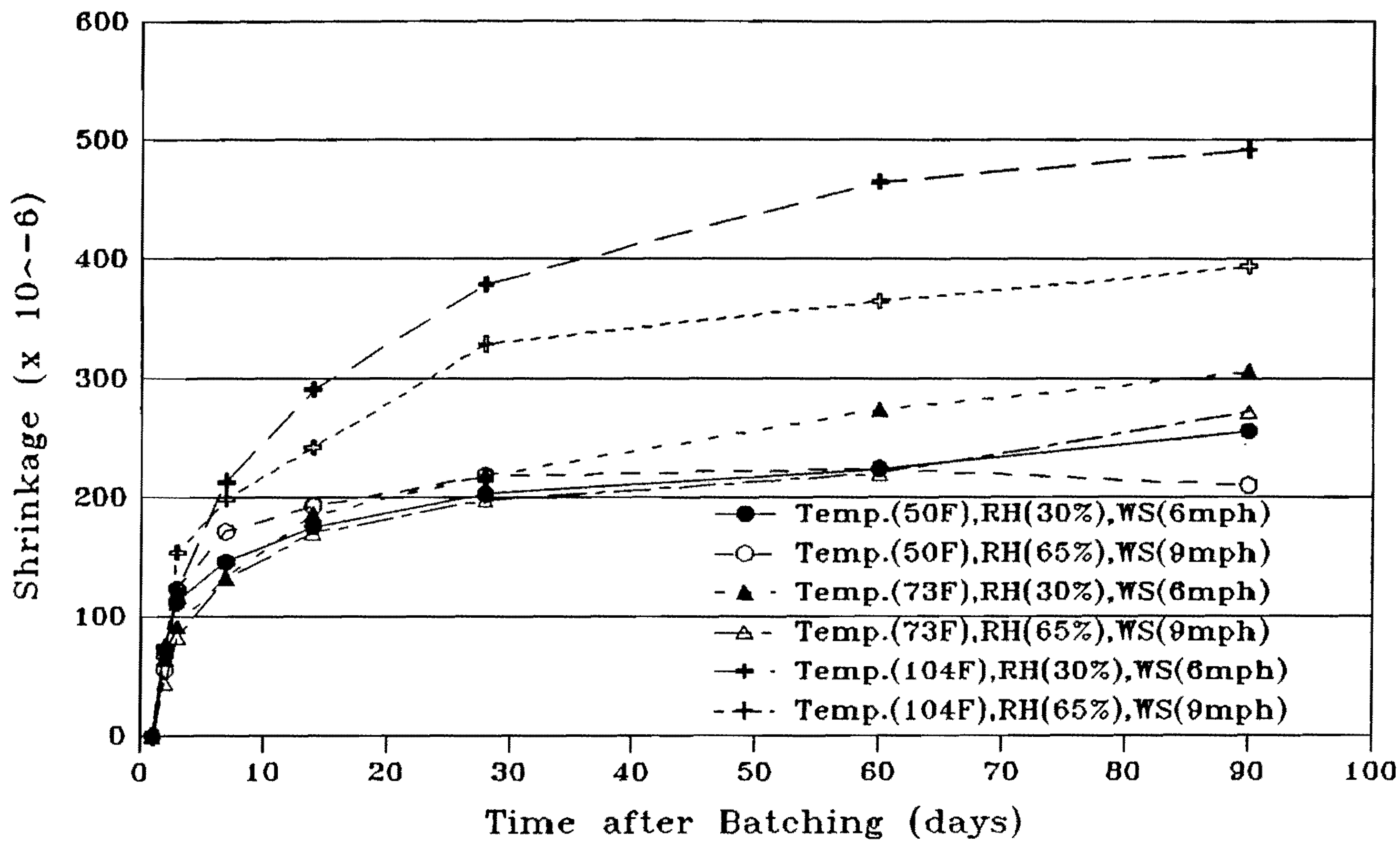


Figure 33. The environmental effects on the shrinkage of river gravel concrete with 1.5 inch slump

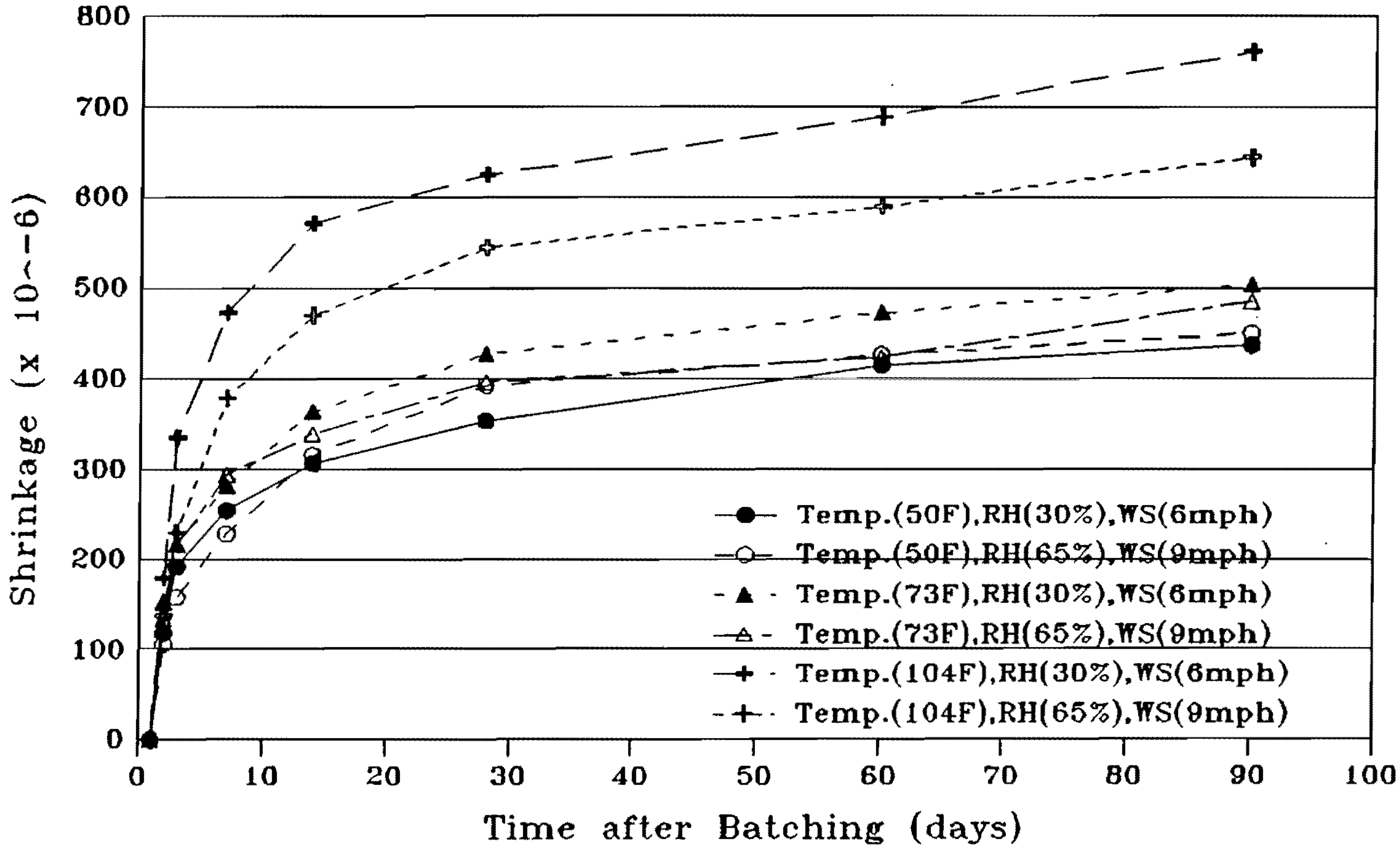


Figure 34. The environmental effects on the shrinkage of limestone concrete with 1.5 inch slump

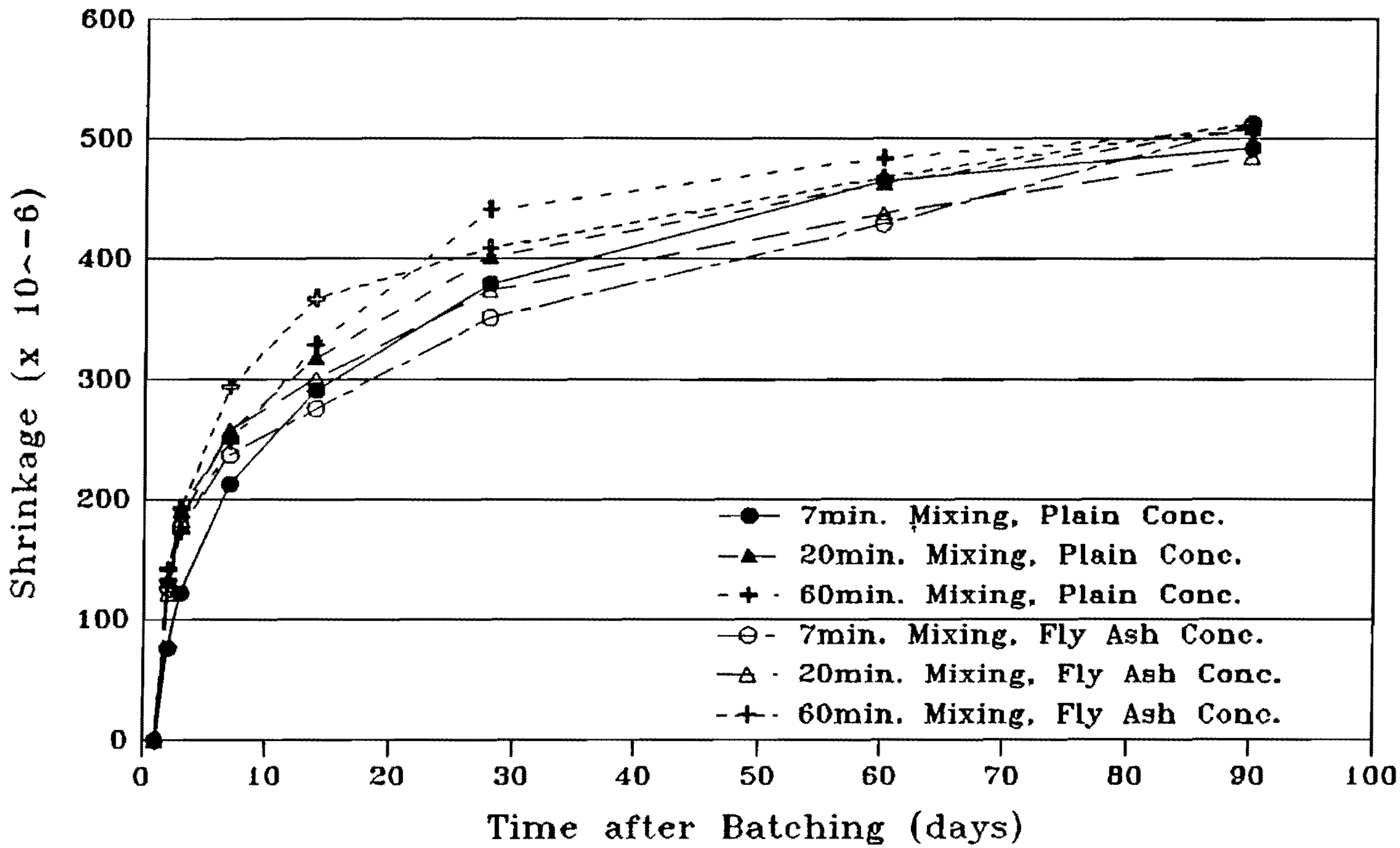


Figure 35. The effects of mixing time and fly ash on the shrinkage of river gravel concrete with 1.5 inch slump

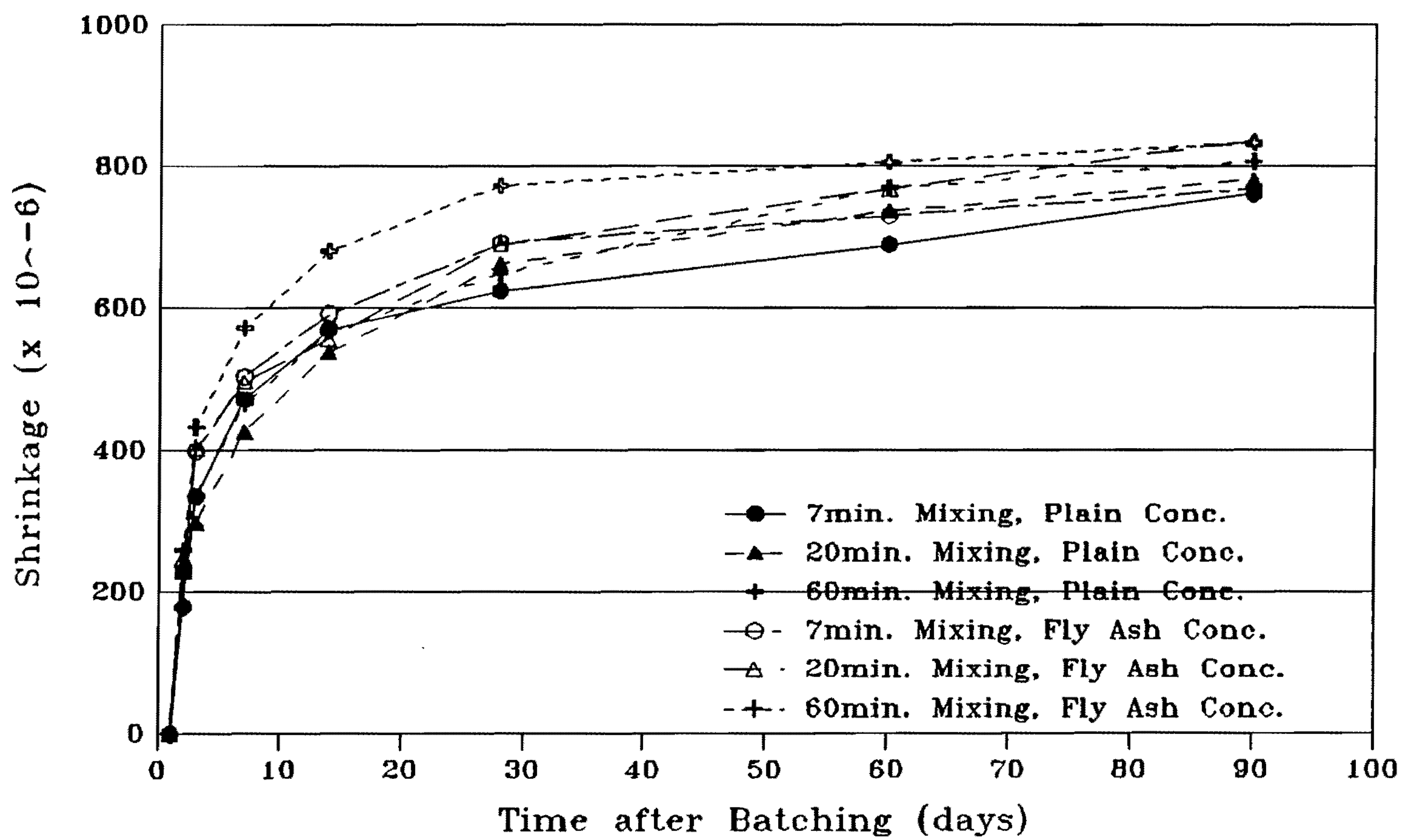


Figure 36. The effects of mixing time and fly ash on the shrinkage of limestone concrete with 1.5 inch slump

the highest shrinkage. The effects of mixing time on shrinkage were influenced by the amount of initial mixing water. The extended mixing time affects both the amount of initial mixing water and the early shrinkages. The effects of mixing time were quite obvious at early ages, but by 90 days most of the shrinkage data converged. Whether this tendency would remain at later ages is not known, based on the data available in this test. As for the reasons why the convergence is taking place, one explanation might be that with the increase in mixing time, more water was used to retemper the concrete mix before it was placed in the forms. This extra water evaporates quite easily from the concrete at ages less than 14 days and increases the rate of shrinkage. However, the amount of water does not appear to contribute to the long-term shrinkage that is affected more by the aggregate type and environmental condition.

With respect to the influence of fly ash on the shrinkage of concrete, Figures 35 and 36 show that for river gravel concrete, fly ash reduces the early shrinkage, whereas the opposite is found for limestone concrete. This apparent contradiction is attributed to the difference in water requirements for the fly ash concretes. In the initial trials, a SSD water content of 228 lbs for the river gravel concrete and 232 lbs for the limestone concrete was found for a one-cubic-yard batch. The same SSD water content did not change for the plain concretes. In general, however, the changes in shrinkage, due to the use of fly ash, are reduced between the ages of 60 and 90 days and are 75 microstrain or less in value between 3 and 60 days. Therefore, these changes in shrinkage due to fly ash might not influence the performance of CRC pavements significantly.

Figures 37 through 42 illustrate the effect of slump and type of aggregate on shrinkage. Figures 37 and 38 are for 50°F, and 65% RH and 30% RH environmental conditions, respectively. Figures 39 and 40 are for 73°F, and for the same relative humidities. Figures 41 and 42 are for 104°F. Clearly, aggregate type is a very important factor in shrinkage. Limestone concrete shows almost twice as much shrinkage as river gravel concrete. A difference of 25 to 50 microinches per inch in shrinkage is observed for each half-inch change in slump at all concrete ages. The effect of a change in slump on the shrinkage of limestone concrete is greater than for the river gravel concrete. From Figures 37 through 42, it is apparent that the change in shrinkage with a change in slump is independent of the environmental

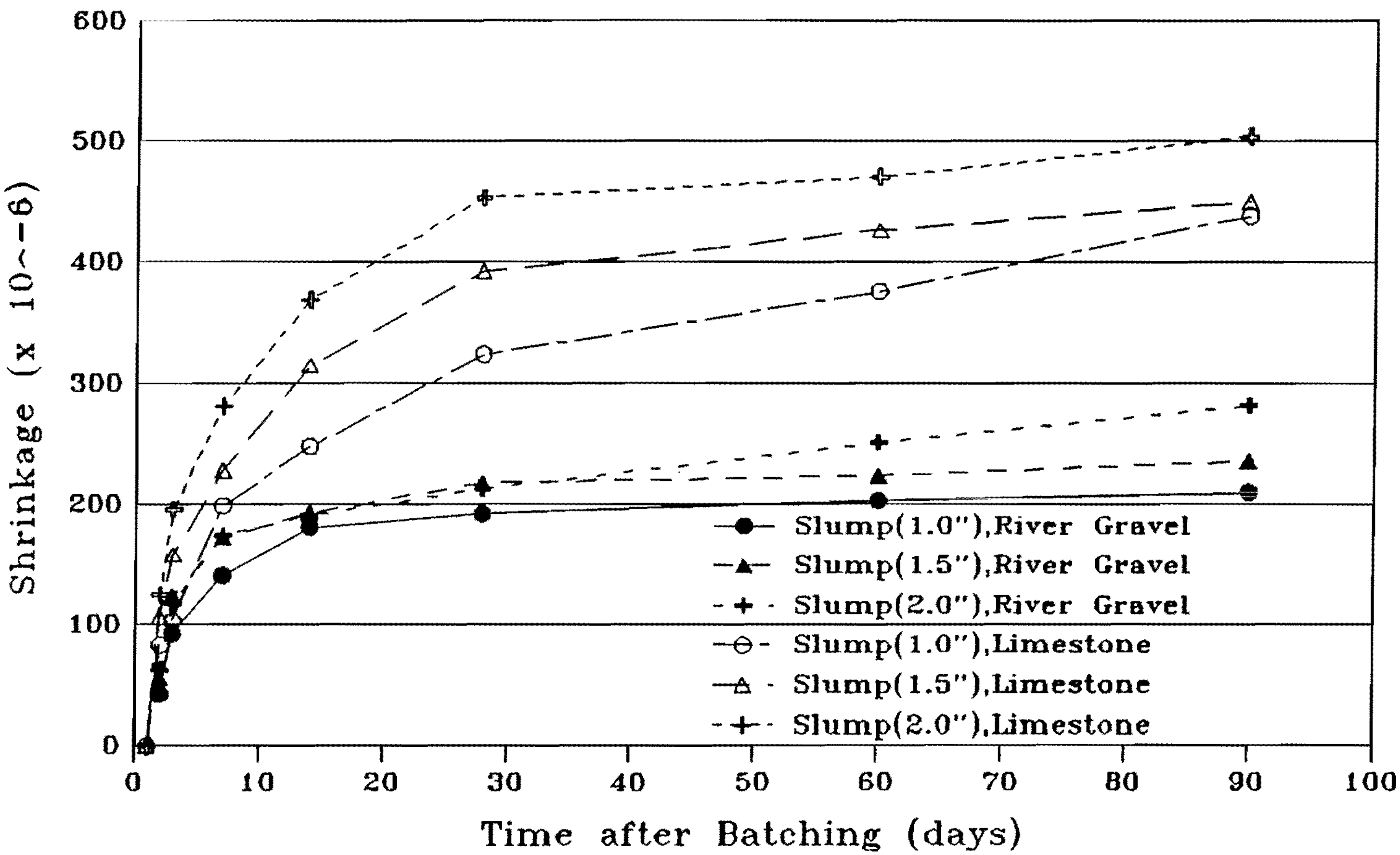


Figure 37. The effect of slump and type of aggregate on shrinkage, at 50°F and 65% RH

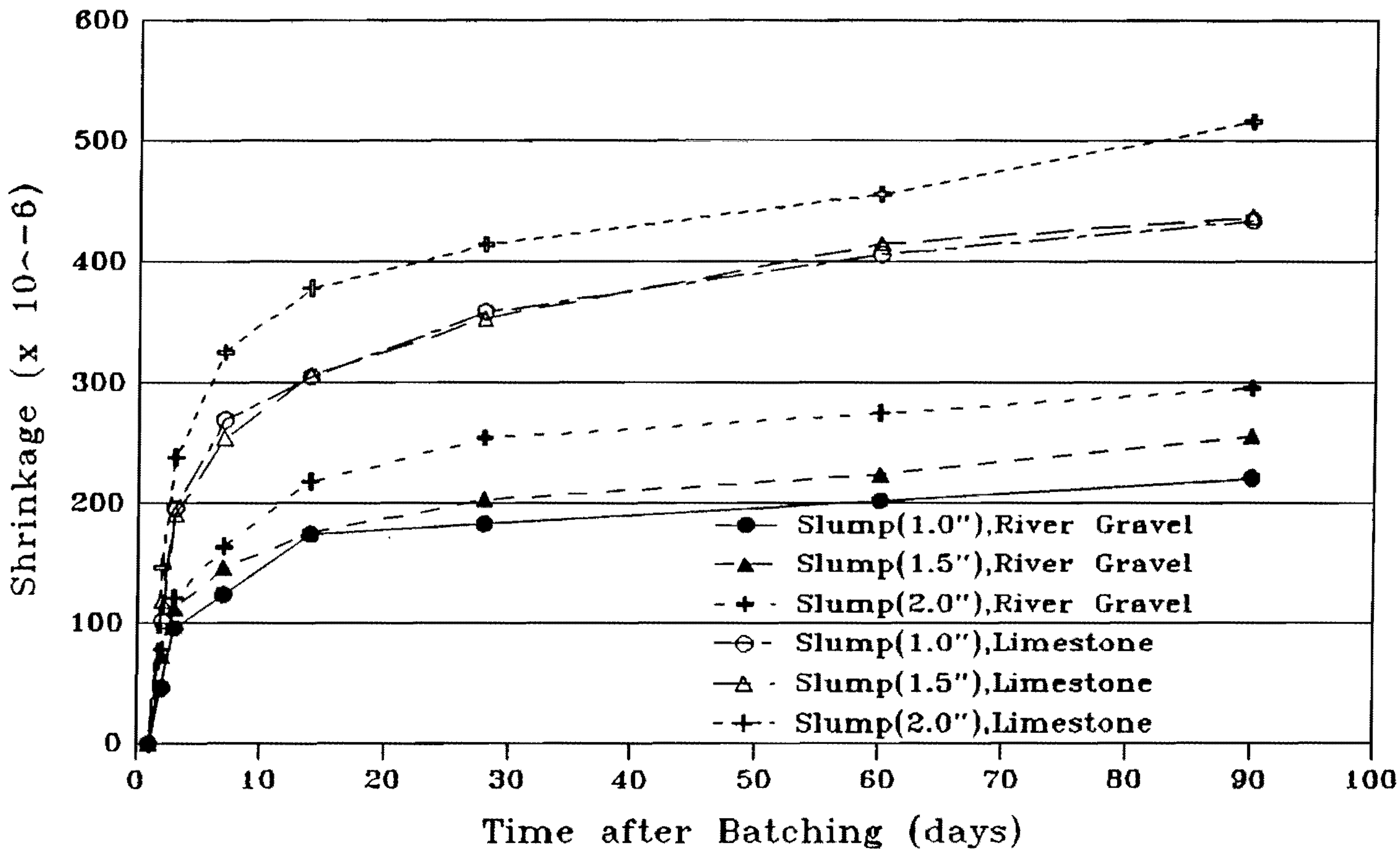


Figure 38. The effect of slump and type of aggregate on shrinkage, at 50°F and 30% RH

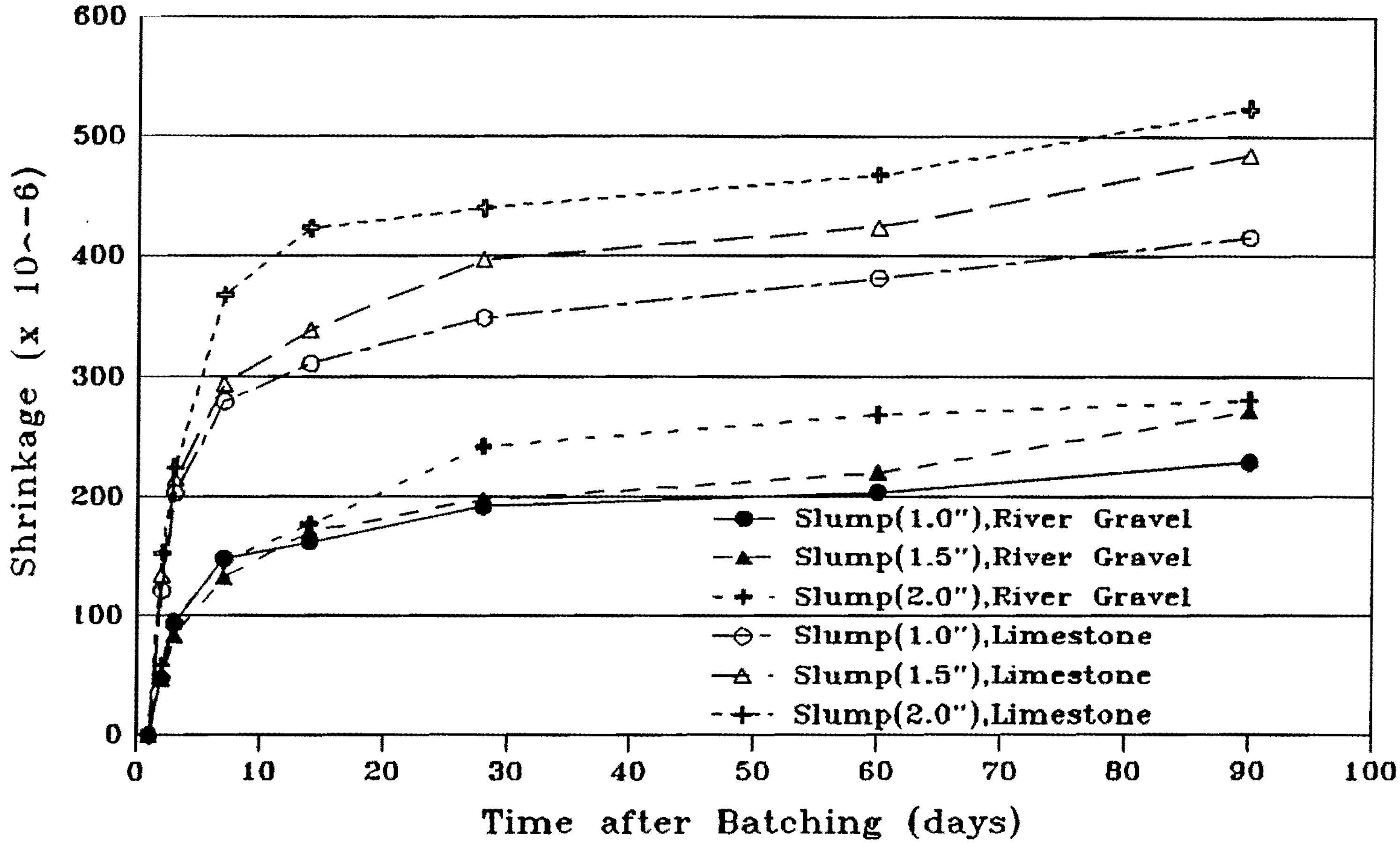


Figure 39. The effect of slump and type of aggregate on shrinkage, at 73°F and 65% RH

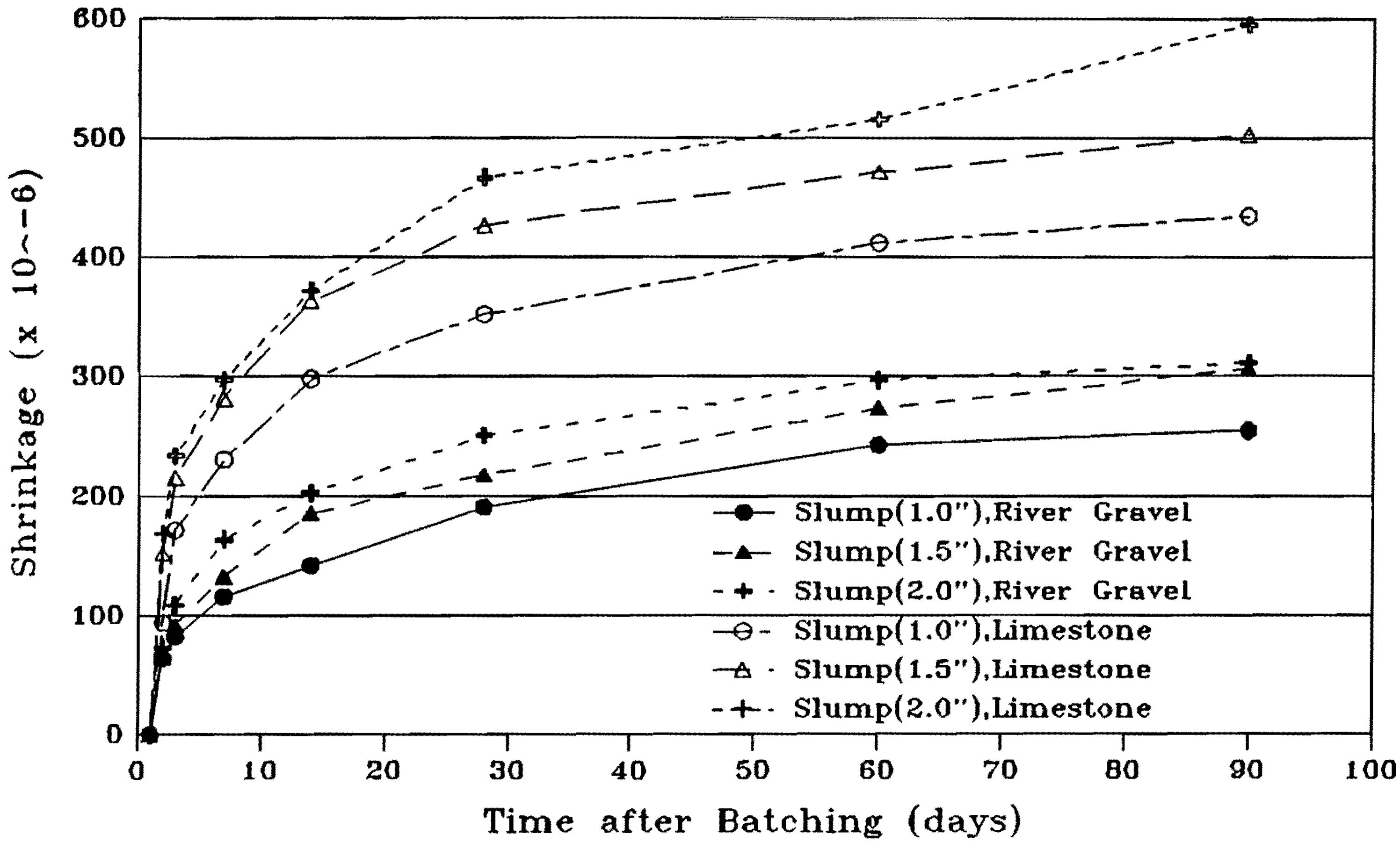


Figure 40. The effect of slump and type of aggregate on shrinkage, at 73°F and 30% RH

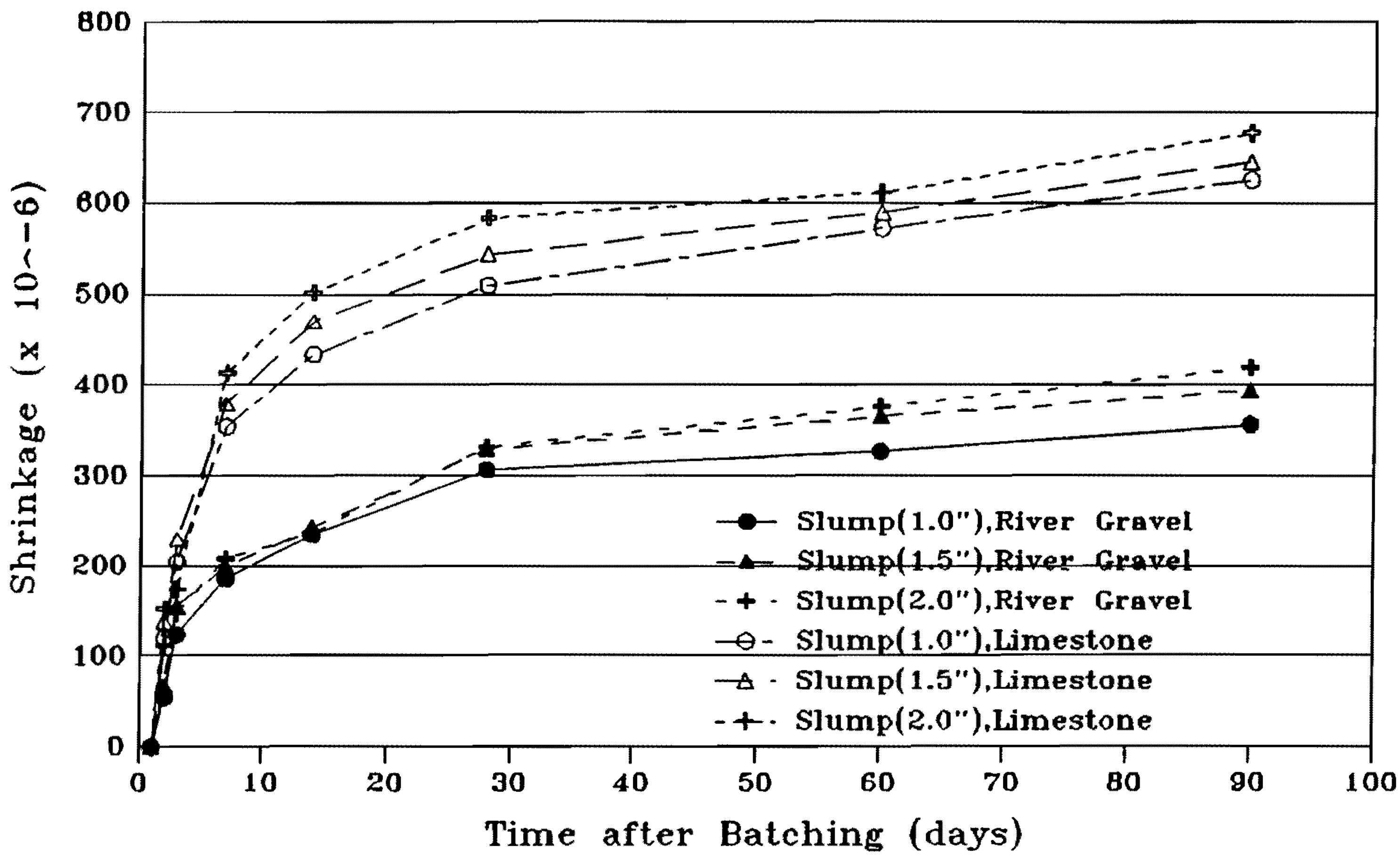


Figure 41. The effect of slump and type of aggregate on shrinkage, at 104°F and 65% RH

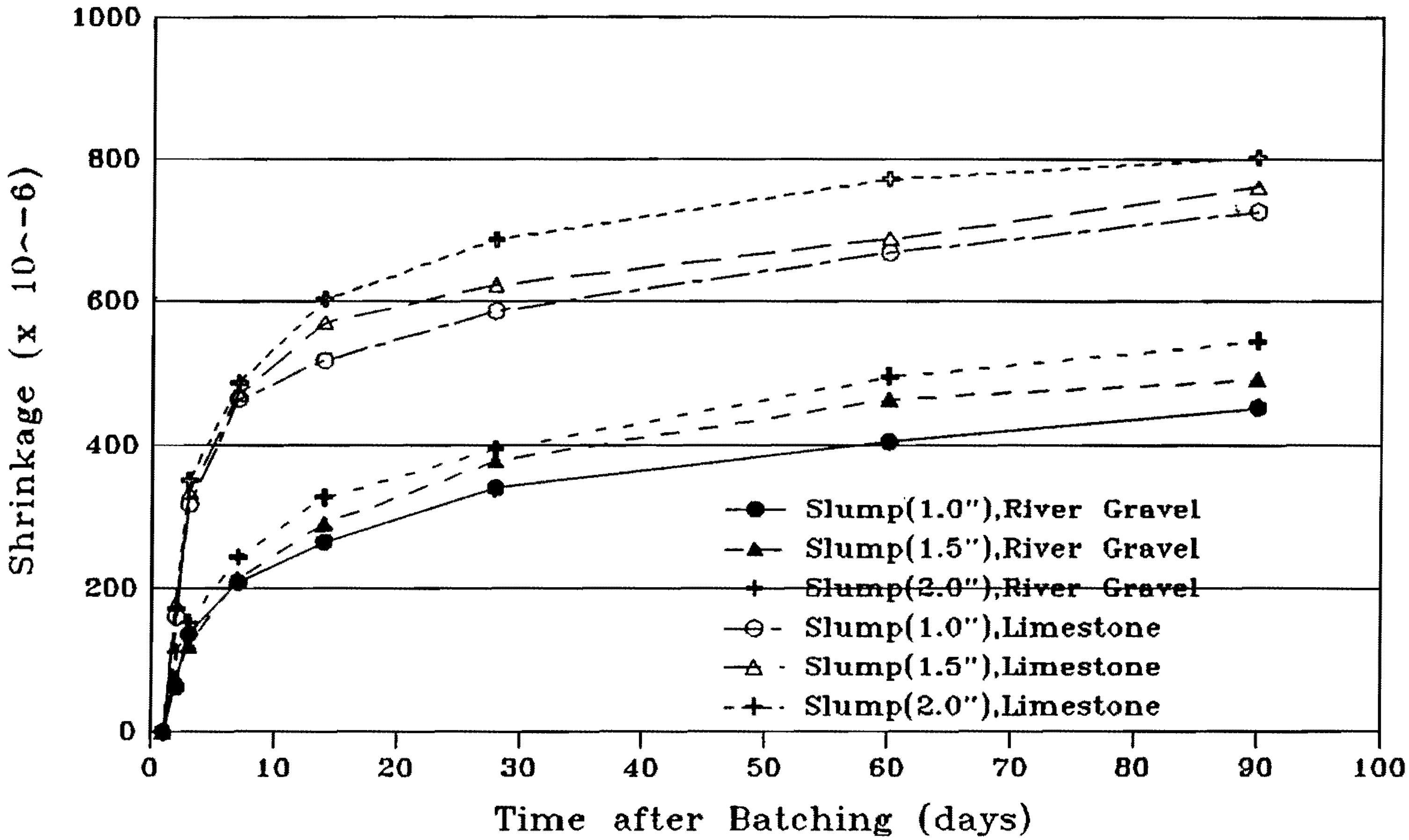


Figure 42. The effect of slump and type of aggregate on shrinkage, at 104°F and 30% RH

conditions. This behavior is to be expected since the change in slump is primarily influenced by the aggregate type and initial amount of water in the cement paste.

Figures 43 and 44 illustrate the effect of initial material temperature on shrinkage of concrete with 1.5 inch slump. As the figures show, using warm material in cold temperatures or cool material in hot temperatures did not affect the shrinkage significantly. This can be attributed to the small changes in the amount of initial mixing water.

Figures 45 and 46 illustrate the effect of consolidation method on shrinkage of concrete with 1.5 inch slump. This effect is not large enough to be distinctly observed in the shrinkage test results for either the limestone concrete or the river gravel concrete.

Figure 47 shows the effects of environmental conditions on the correlations between shrinkage and weight loss for 1.5 inch slump concrete. Different environmental conditions investigated in this study are designated with different symbols shown in the figure. Almost linear correlations between shrinkage and weight changes can be observed for both river gravel and limestone concretes. The line of correlation for limestone concrete shows a steep slope, whereas that for river gravel concrete shows a shallow slope. For the same amount of weight loss, which is primarily caused by moisture loss, limestone concrete shrinks more than river gravel concrete. The greater shrinkage of limestone concrete for the same amount of moisture loss is caused by the lower stiffness of aggregate used in the concrete; that is, the limestone has a lower modulus of elasticity so that it shrinks more than river gravel when it is subjected to the same confining force. The data for all the environmental conditions tested in this study fall in one line, which implies that the shrinkage depends on the amount of moisture loss occurring in the curing conditions. The different pore structures which might be developed in the different environmental conditions at early ages are not significant enough to affect the correlations.

Figure 48 shows the effects of mixing time and fly ash on the correlations between shrinkage and weight loss for concrete with 1.5 inch slump. The replacement of fly ash with cement affects the correlations and shifts the correlation curve slightly. Fly ash concrete looks to be more stable to the deformations for the given moisture changes than plain concrete. Fly ash differs from cement in two aspects: particle size and chemical reactivity. Especially, different chemical reactivity affects

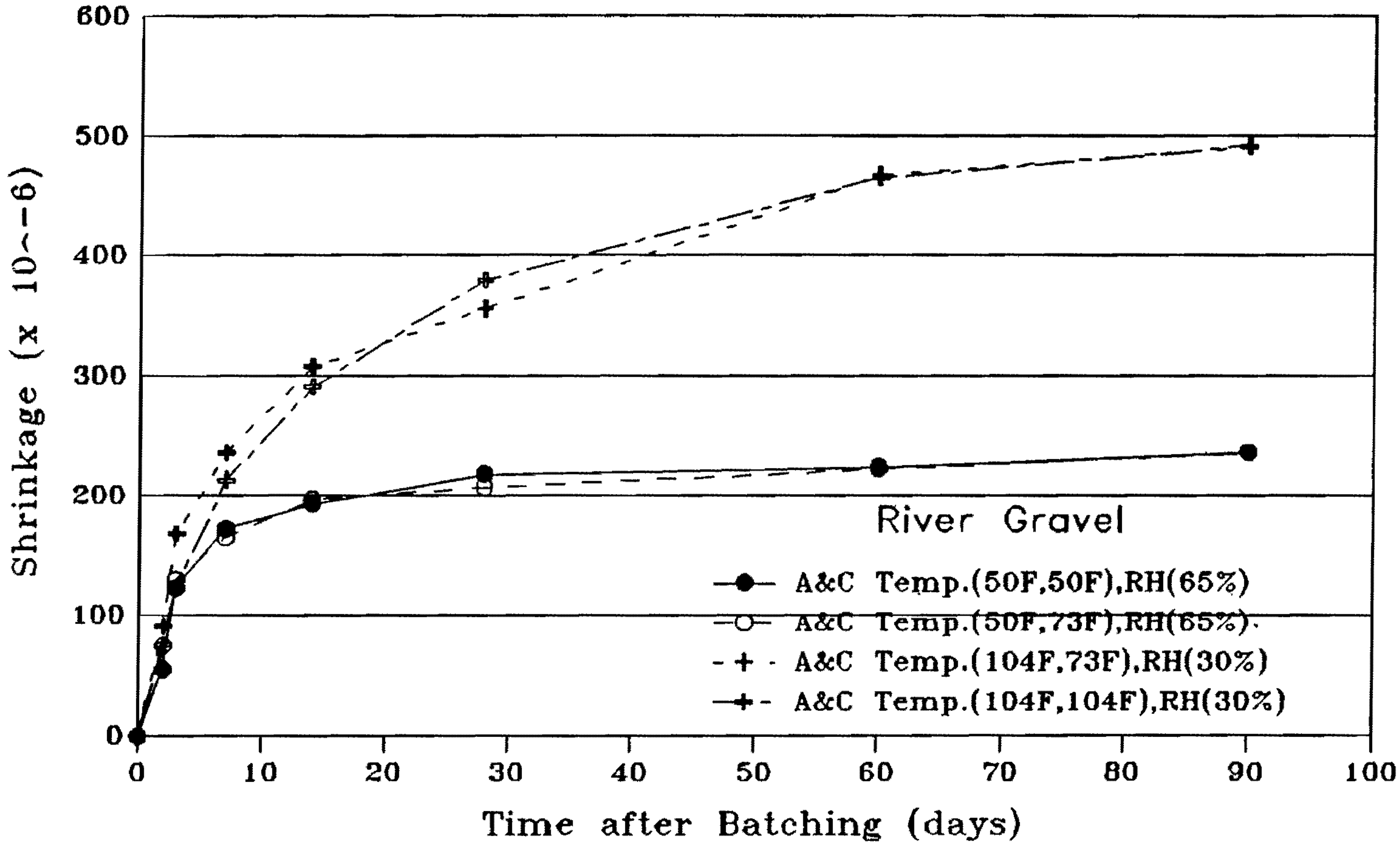


Figure 43. The effect of controlling material temperature on the shrinkage of river gravel concrete with 1.5 inch slump

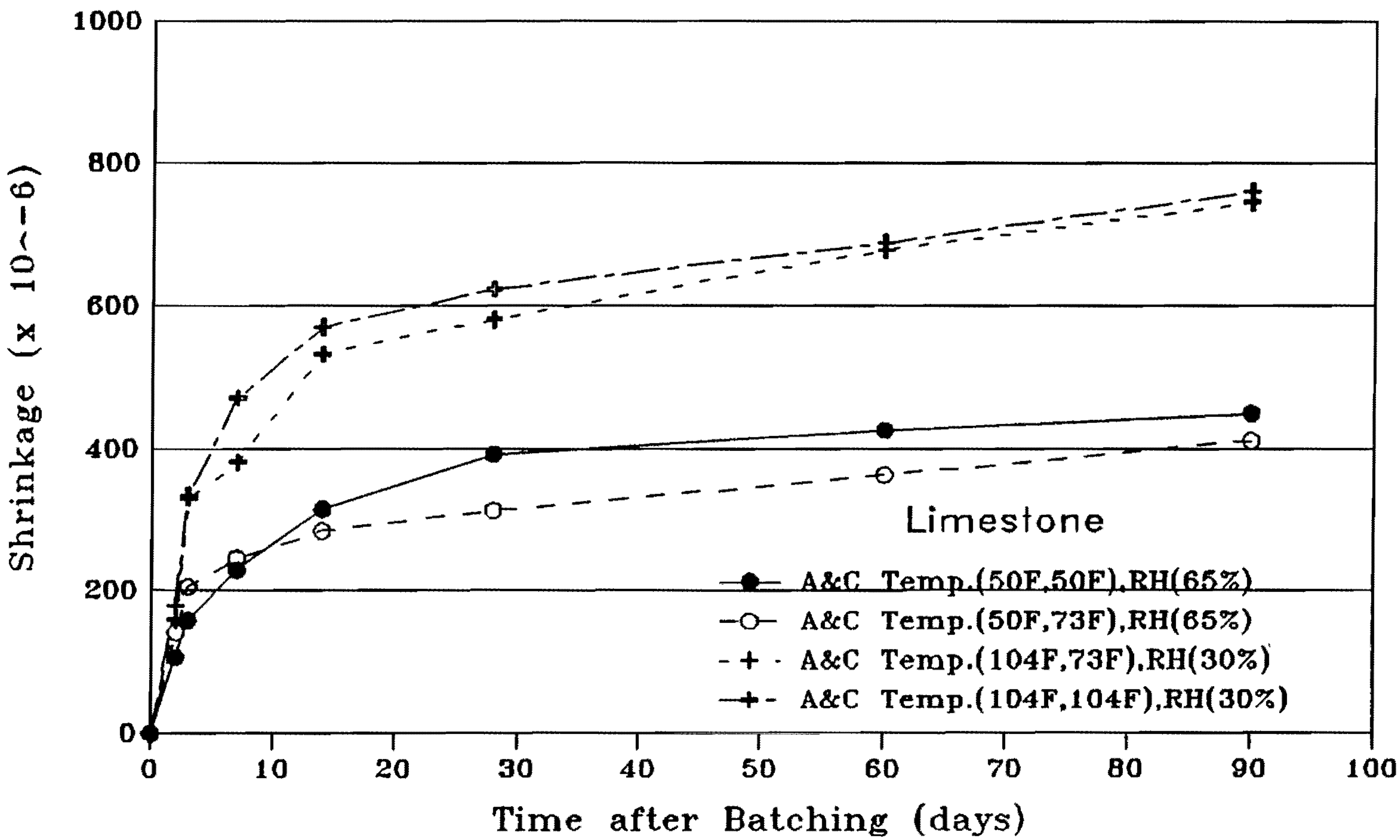


Figure 44. The effect of controlling material temperature on the shrinkage of limestone concrete with 1.5 inch slump

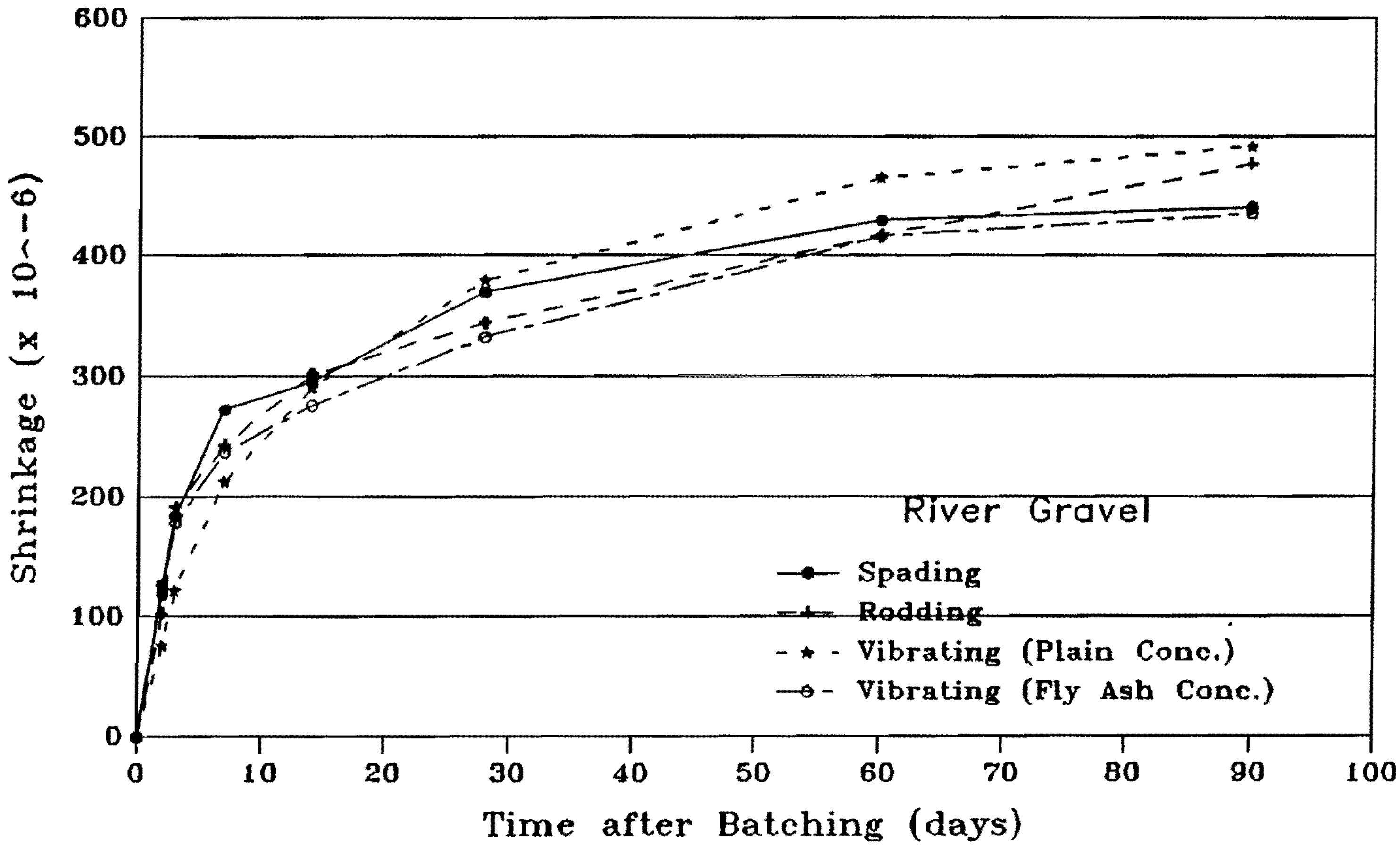


Figure 45. The effect of consolidation method on the shrinkage of river gravel concrete with 1.5 inch slump

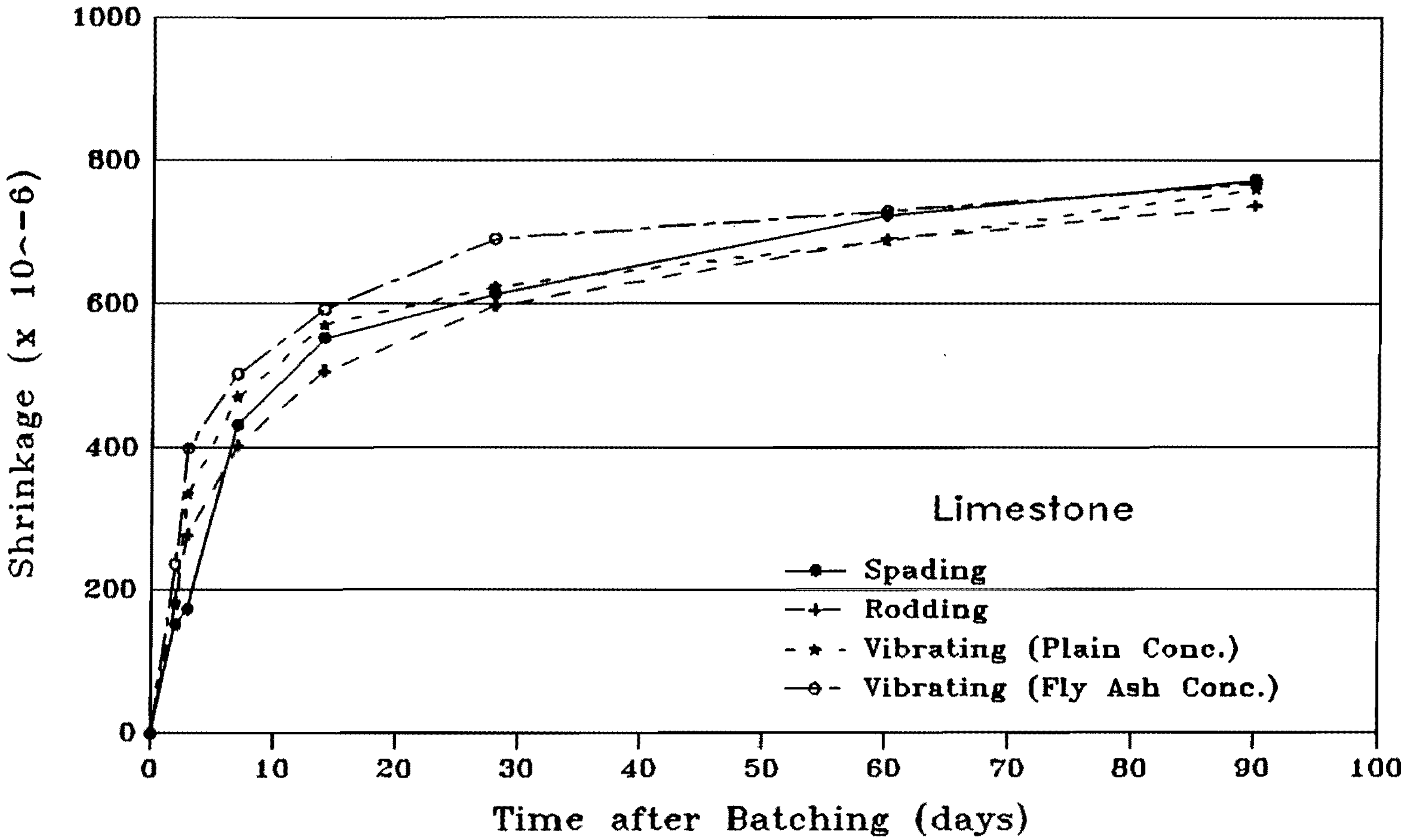


Figure 46. The effect of consolidation method on the shrinkage of limestone concrete with 1.5 inch slump

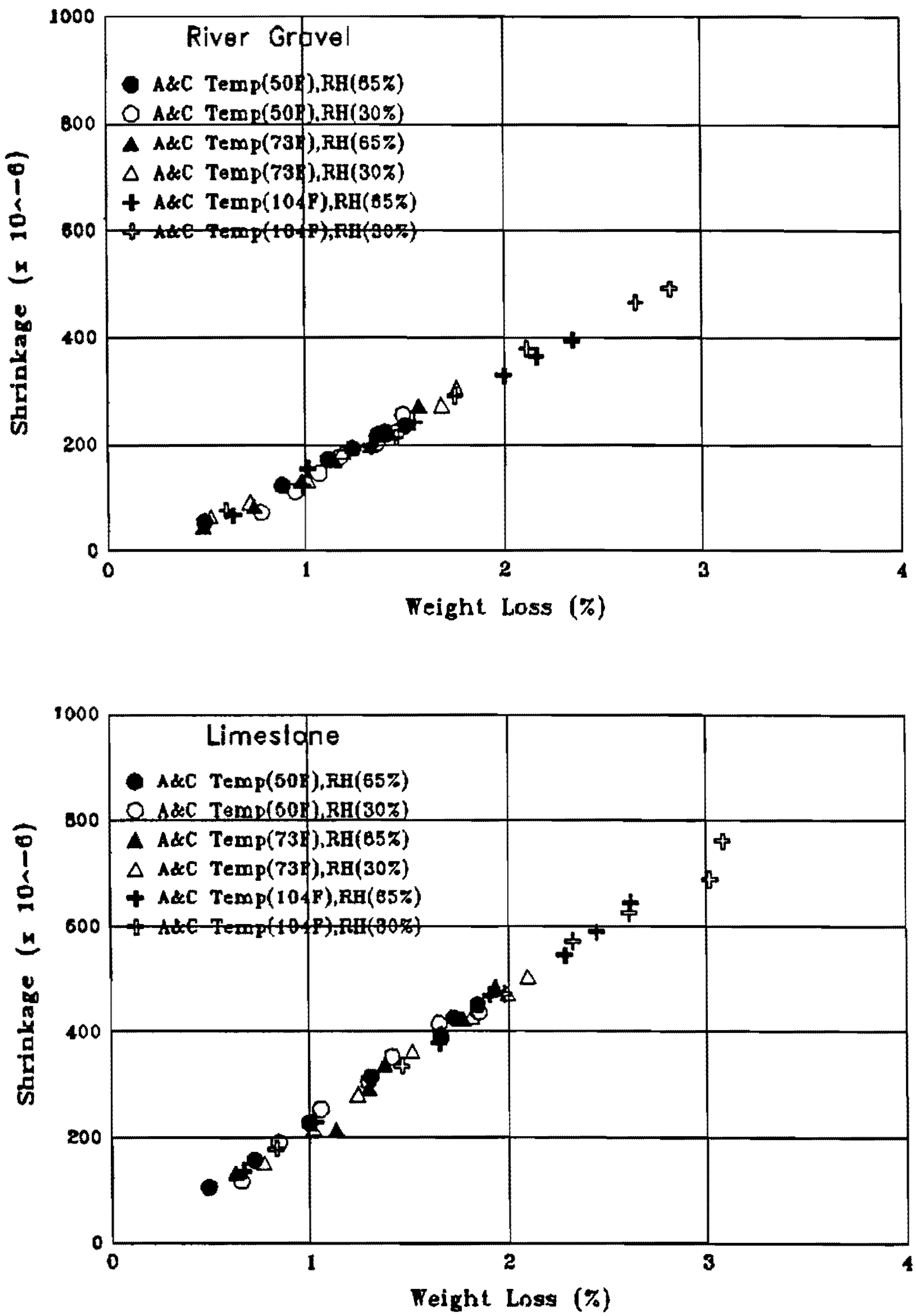


Figure 47. The correlations between shrinkage and weight loss for different environmental conditions and 1.5 inch slump concrete. For 30% and 65% RH, wind speed 6 and 9 mph respectively; a) River gravel b) Limestone

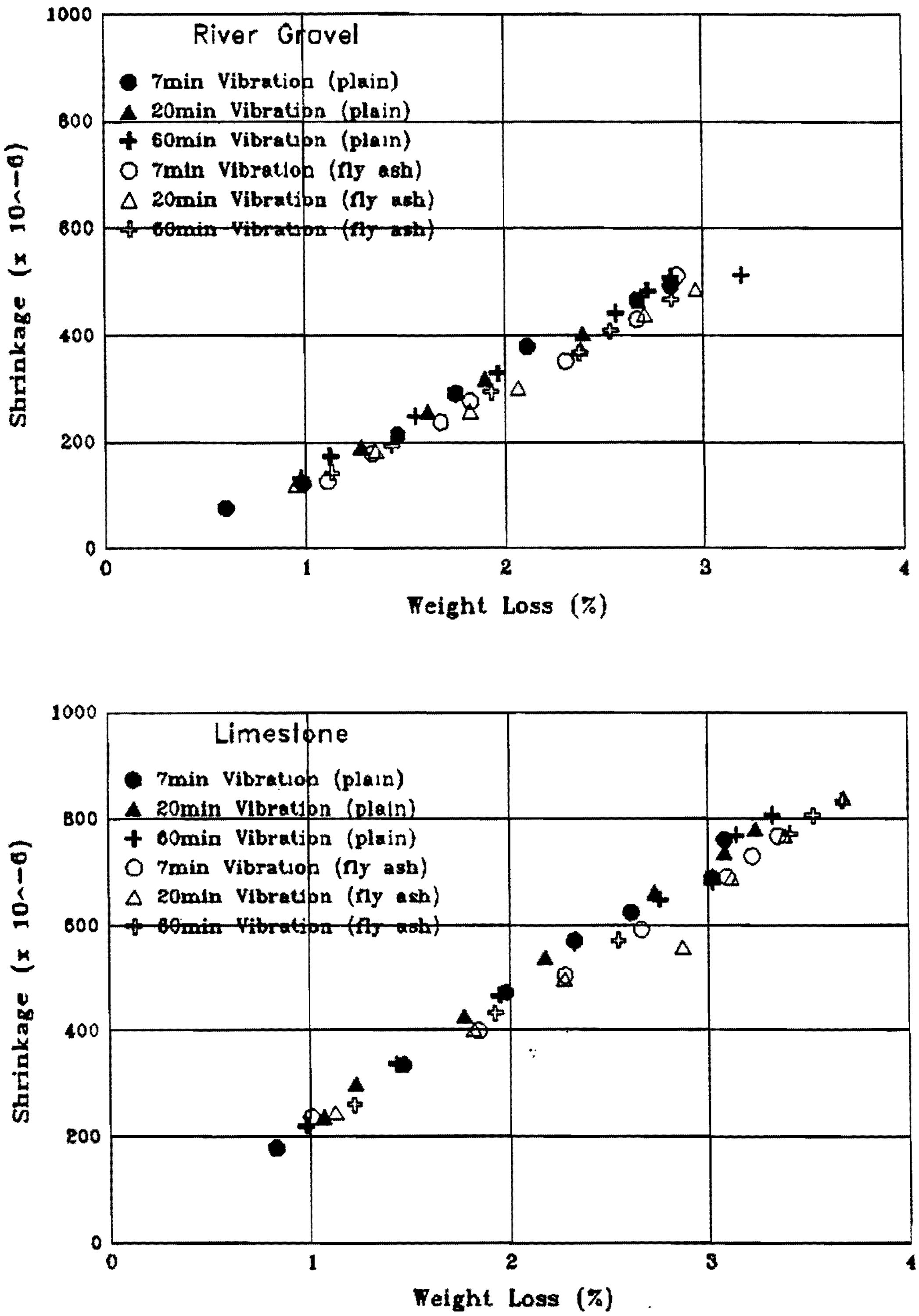


Figure 48. The correlations between shrinkage and weight loss for different mixing time and fly ash and 1.5 inch slump concrete in the environment with 104°F, 30% RH, and 6 mph; a) River gravel b) Limestone

the pore structure which changes the correlation curve. Similar observations can be found for both river gravel and limestone concrete. Two extended mixing times were plotted in the same figure. The extended mixing time did not affect the correlations between shrinkage and weight loss. The different mixing time is not enough to change gel pore structure.

Figures 49, 50, and 51 illustrate the effect of slump and aggregate on correlations between shrinkage and weight loss for different environmental conditions and concrete with a slump of 1.5 inch. Figure 49 represents the temperature of 50°F and two relative humidities of 65% RH and 30% RH. The other two figures are for 73°F and 104°F temperatures, respectively. Two very distinct facts can be observed which explain why limestone shrinks more than river gravel. First, limestone concrete shrinks more than river gravel concrete for the same amount of weight loss, and limestone concrete loses more weight than river gravel concrete. At 50°F and 73°F, limestone concrete loses a weight of more than 2%, whereas river gravel concrete loses less than 2%. At 104°F, the weight loss has increased to 3% or more for limestone concrete and less than 3% for river gravel concrete. The greater shrinkage is occurring not because of differences in shrinkage mechanism, but rather because of greater amounts of moisture weight loss.

Moist Cured Condition The effect of mixing time on shrinkage of 1.5 inch slump concrete is shown in Figure 52. Because of the wet curing condition, the results indicate that expansion is occurring rather than shrinkage. Figure 52 shows that, as the mixing time increases, the amount of expansion increases.

Figure 53 shows the effect of consolidation method on shrinkage of concrete with 1.5 inch slump for 7 and 60 minutes mixing. For both mixing times, vibrated concrete shows the lowest expansion, and rodding shows the greatest expansion. The shrinkage specimens were smaller than the strength specimens, causing the spading and rodding methods to be inadequate to consolidate the concrete in the narrow and shallow shrinkage molds. The spading method yielded smaller expansion than the rodding method. This may be caused by the shape of the compaction tool.

Figure 54 shows the correlation between weight loss and shrinkage for moist cured condition. Since concrete expands rather than contracts in the moist curing environment, a negative weight loss (i.e., weight gain) is observed. The effects of weight loss on shrinkage were almost identical to that observed for weight gain on

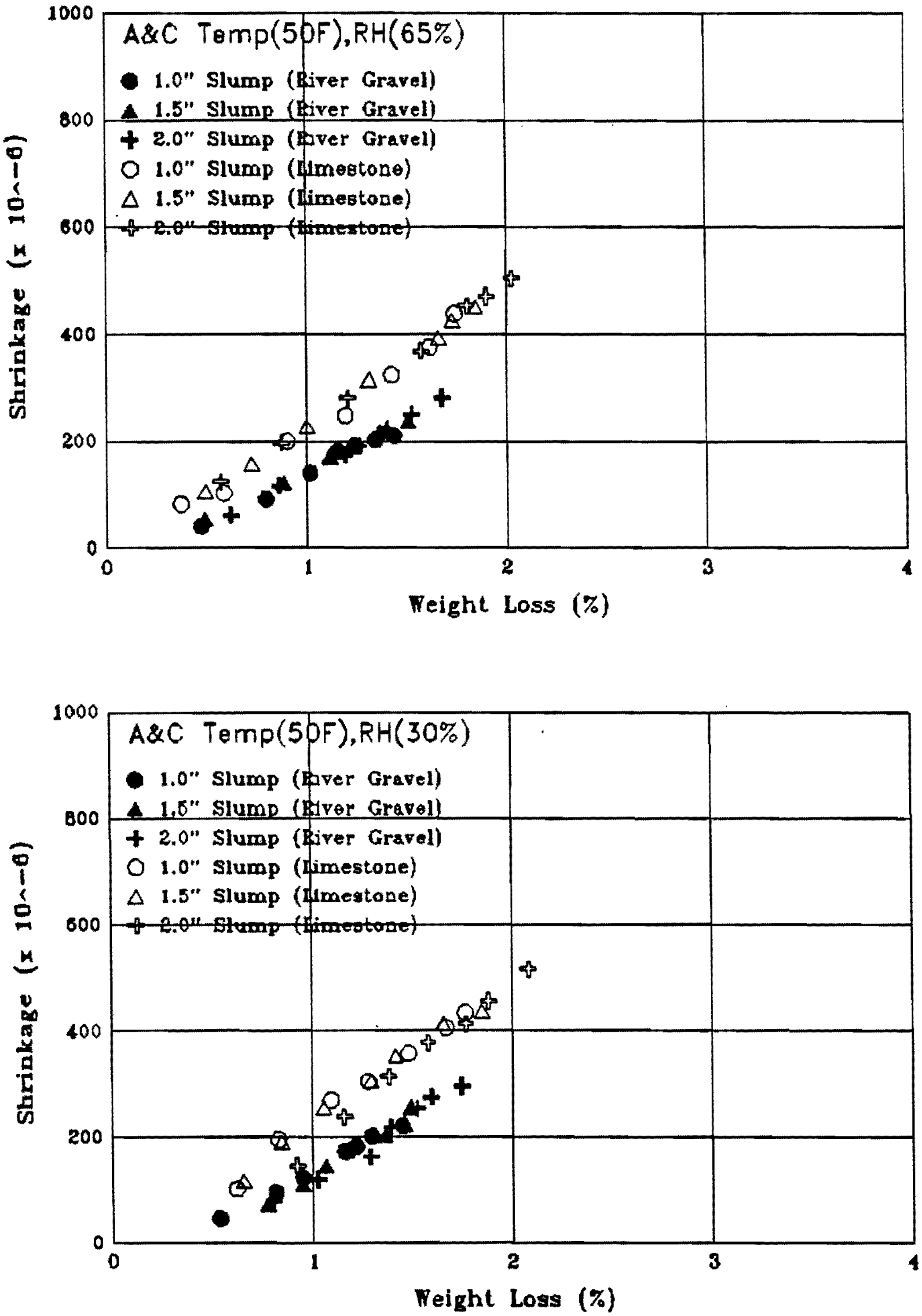


Figure 49. The correlations between shrinkage and weight loss for different type of aggregate at 50°F; a) 65% RH and 9 mph wind b) 30% RH and 6 mph wind

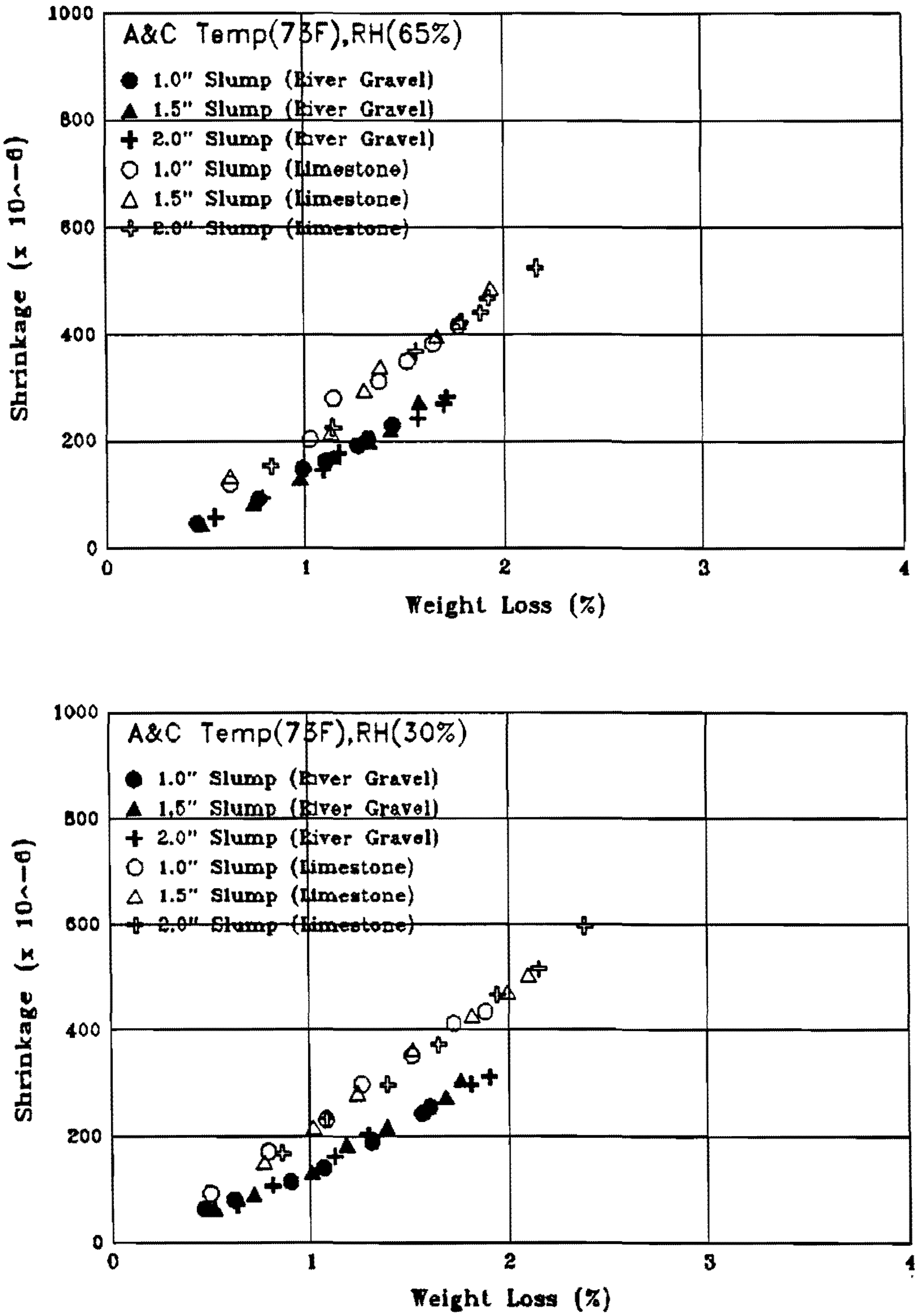
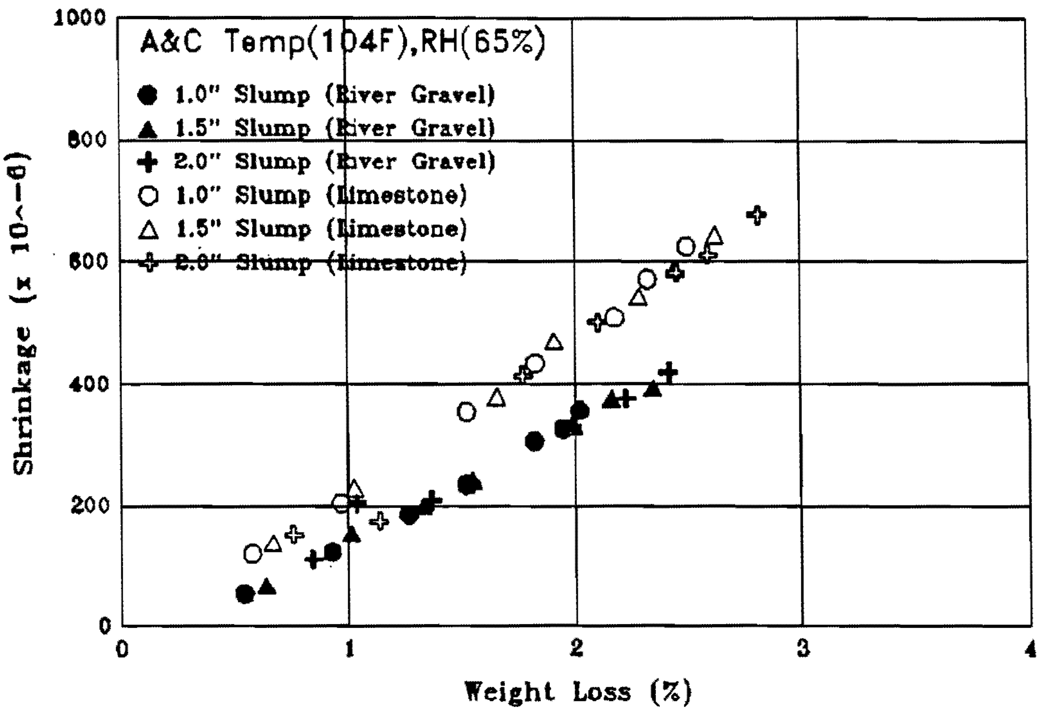


Figure 50. The correlations between shrinkage and weight loss for different type of aggregate at 73°F; a) 65% RH and 9 mph wind b) 30% RH and 6 mph wind



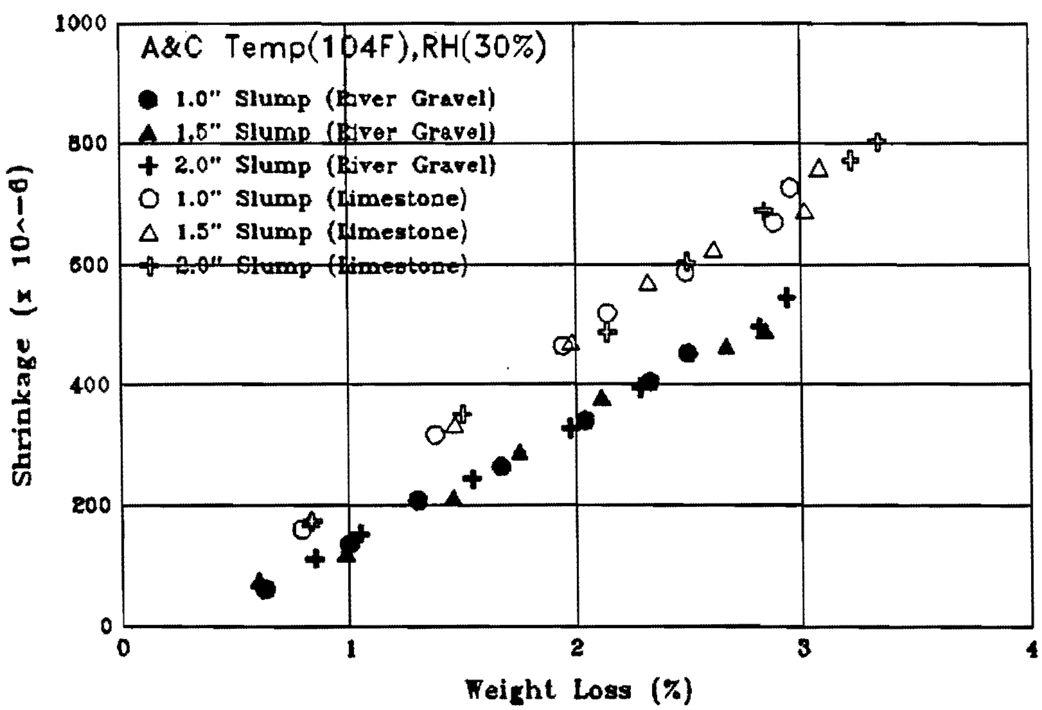


Figure 51. The correlations between shrinkage and weight loss for different type of aggregate at 104°F; a) 65% RH and 9 mph wind b) 30% RH and 6 mph wind

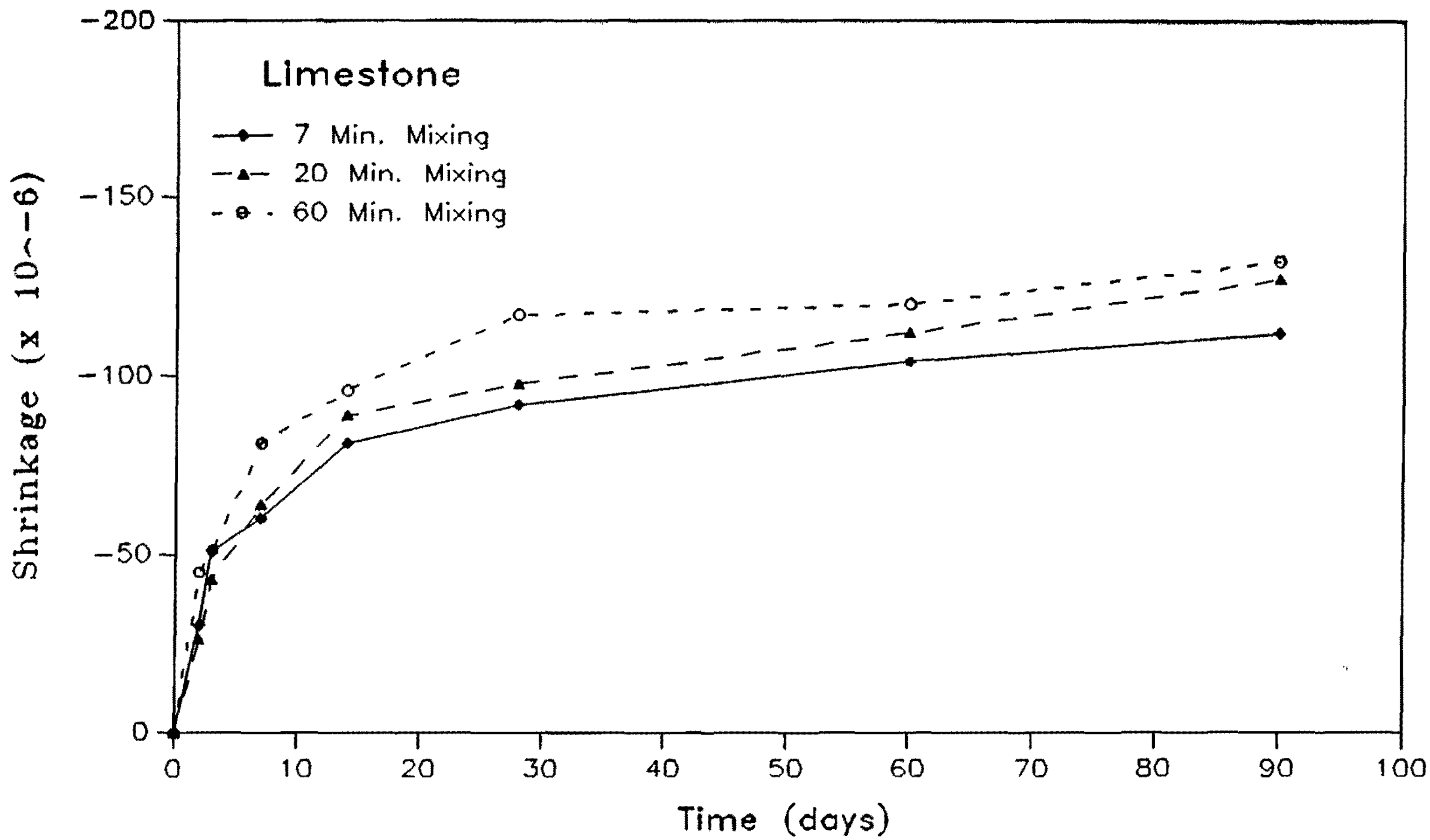
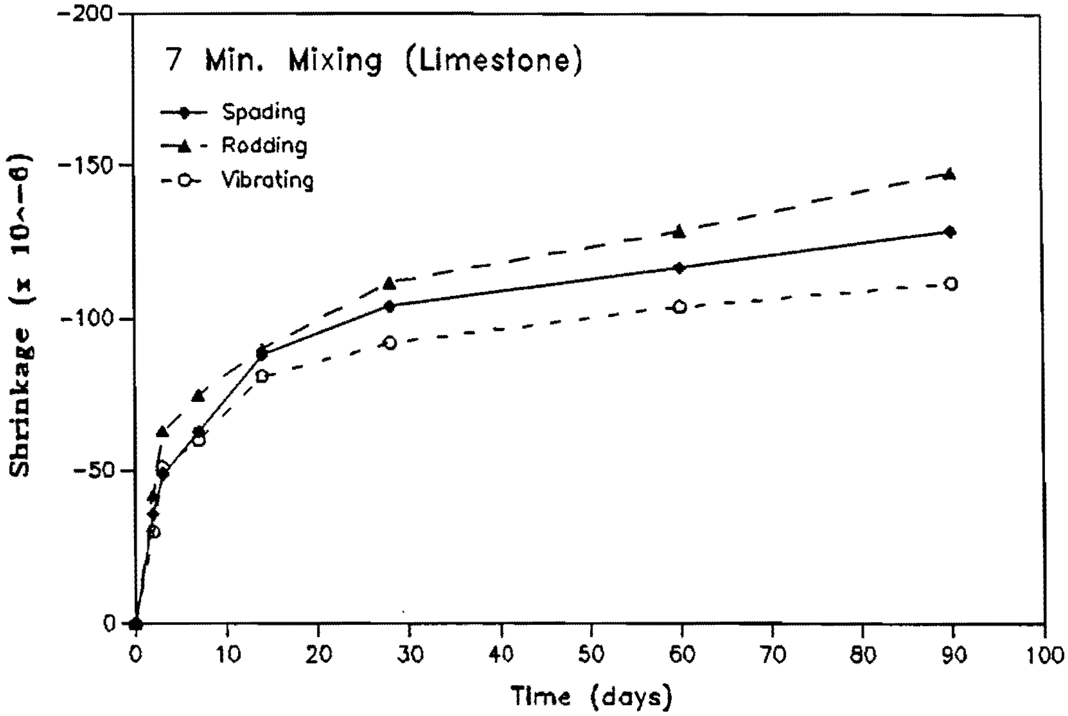


Figure 52. The effect of mixing time on shrinkage in moist cured condition for 1.5 inch slump concrete



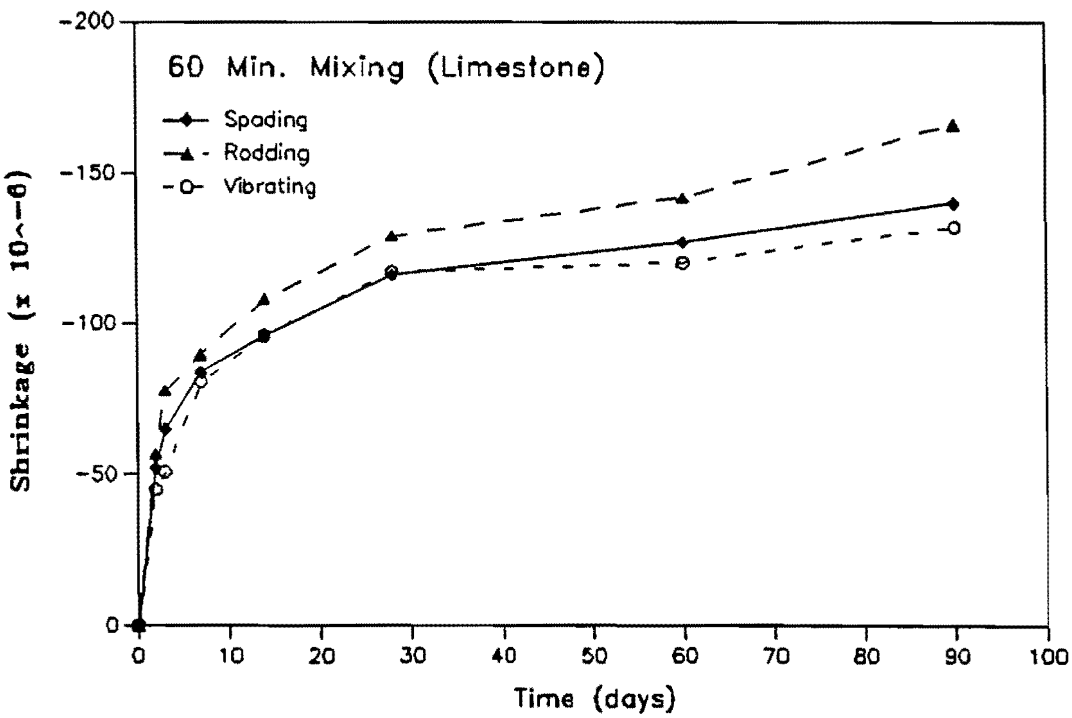


Figure 53. The effect of consolidation method on shrinkage in moist cured condition for 1.5 inch slump concrete; a) 7 min. mixing b) 60 min. mixing

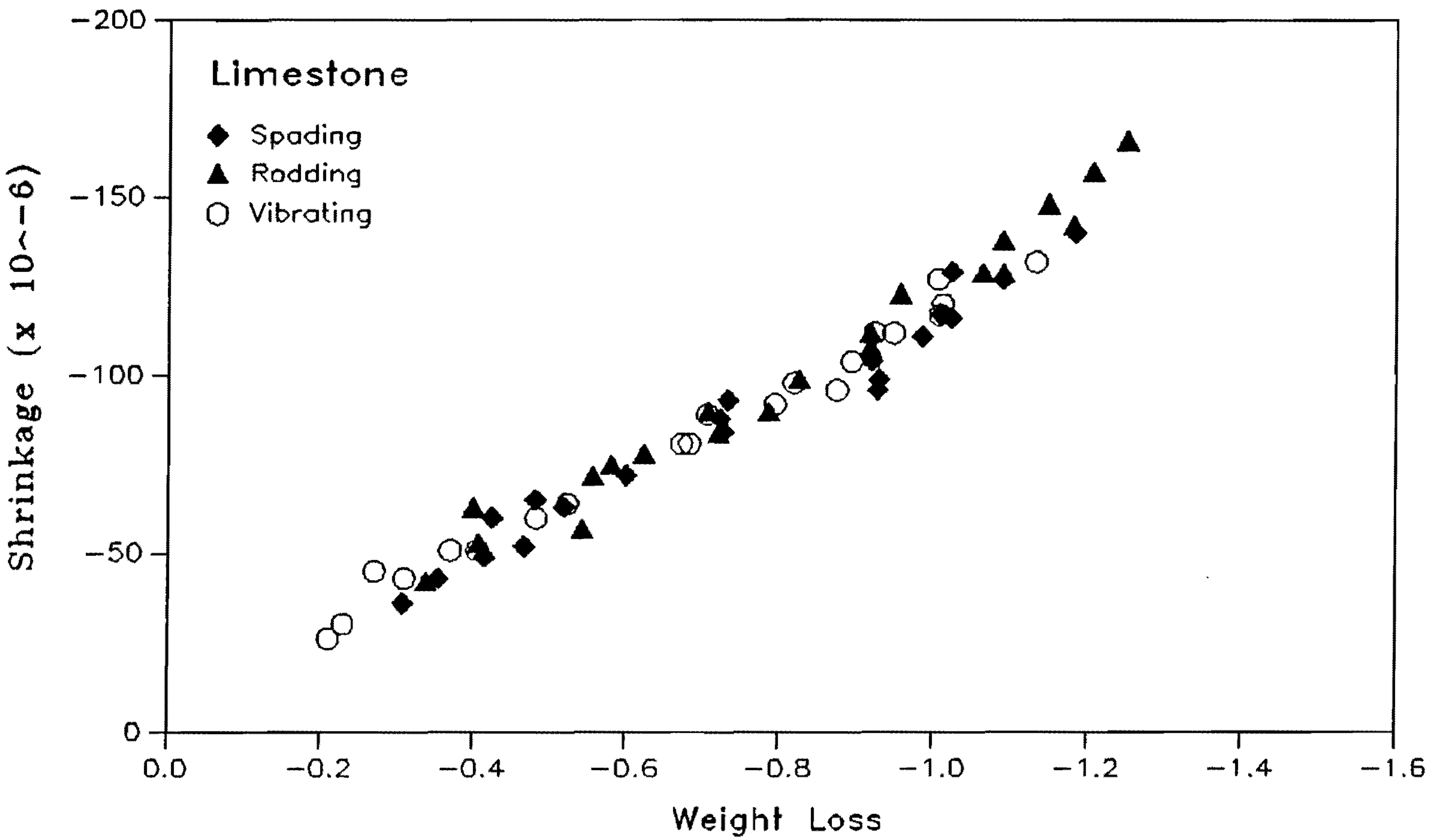


Figure 54. The correlations between shrinkage and weight loss for moist cured condition

expansion. Figure 54 shows that the correlation is not affected by the consolidation method or the mixing time.

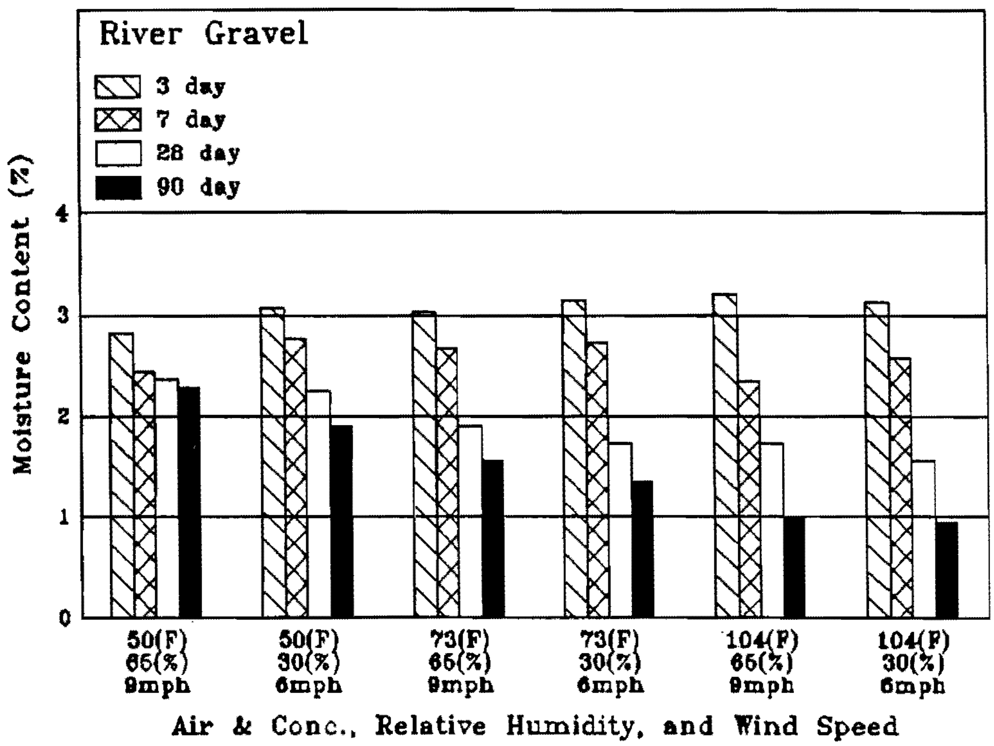
4.4.2 Moisture Content and Moisture Loss

Moisture is a constituent which is absolutely needed for hydration, since the degree of hydration is determined by the availability of water. By measuring the moisture content at different ages of the concrete, a qualitative idea of how the hydration is progressing can be deduced. The moisture content can be determined through drying at 105°C and one atmosphere of pressure (oven drying), at ambient temperature and vacuum over dry ice at -78°C (D-drying), and at ambient temperature and vacuum over a salt solution (P-drying). Of these three methods, the first one is the most common and was therefore used in this research. The other two methods are only used in more detailed pore structure studies, which are beyond the scope of this study.

Higher levels of moisture content are needed to ensure continuous hydration, and rapid changes of moisture content can result in either rapid hydration or rapid loss of moisture, depending on the curing conditions. In conjunction with moisture content, moisture loss measurements provide a means of differentiating between the above changes. The moisture loss is, furthermore, directly related to the change in shrinkage.

Figure 55 shows the moisture content at each different age and environmental condition for the concrete mixtures with a slump of 1.5 inch. At 3 days, the moisture content is almost the same for all conditions with a slight increase as the temperature increases. The increase of moisture content with temperature is not caused by the environmental conditions during curing but reflects the different amounts of mixing water introduced during batching. As the temperature increased, more water was required to achieve the same workability. This is a consequence of the increase of moisture loss with an increase in evaporation rate as the environmental condition becomes more dry. Both the increased amount of mixing water and the increased water loss are the reasons why the 3 day moisture content increases slightly with the severity of the environment.

In limestone concrete, the 3 day moisture content increases as the environmental condition becomes drier. This tendency is more distinct than for the river



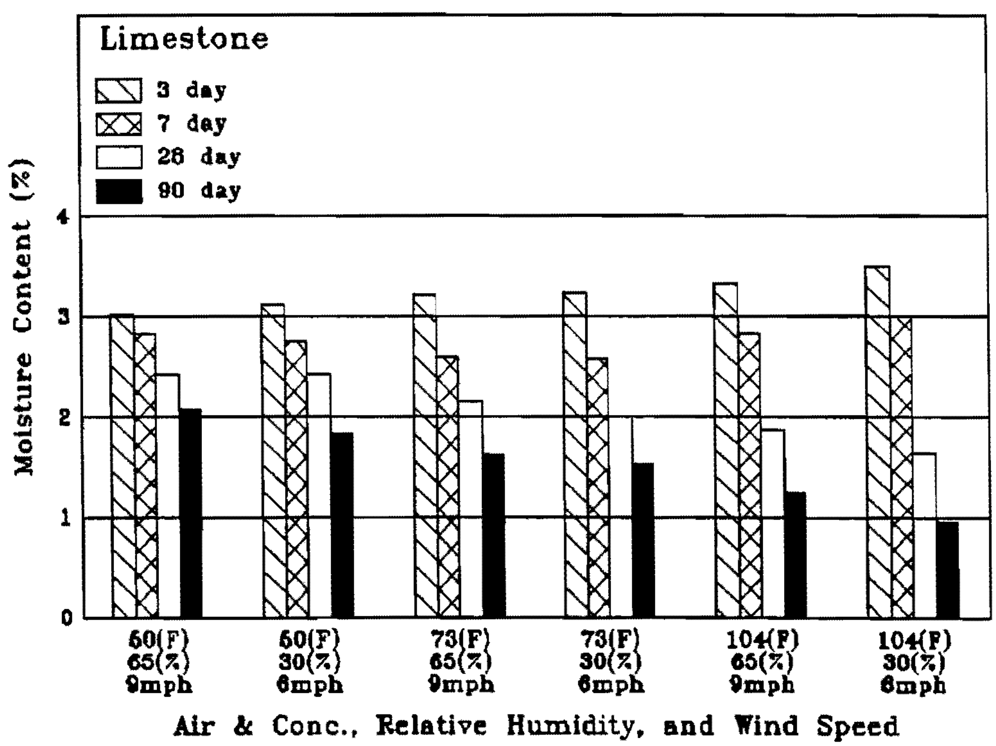


Figure 55. The environmental effects on moisture contents for 1.5 inch slump concrete; a) River gravel b) Limestone

gravel concrete. The changes in moisture content with time, at all temperatures investigated in this test, are greater in the limestone concrete than that in river gravel concrete. Therefore, limestone concrete has a greater rate of moisture loss than river gravel concrete. However, despite this greater rate of moisture loss, limestone concrete has a significantly higher initial moisture content because there is more extra initial moisture in the pores of the aggregates. The extra moisture keeps limestone concrete wetter than river gravel concrete at the age of 3 days even with the faster moisture loss rate for the limestone concrete.

Seven-day data varies quite randomly. Drying at the age of 7 days is primarily controlled by diffusion through the tortuous capillary pores formed in the concrete. The moisture loss rate decreases exponentially and is primarily controlled by the amount of remaining water in the concrete, rather than by a change in diffusivity. Drying for 7 days is long enough to evaporate most of the excess water, but not long enough to compensate for the increased initial mixing water. As a result, the moisture contents at 7 days are quite variable and independent of the environmental conditions.

The 28 and 90 day moisture contents are decreasing in order as the rate of evaporation increases. The rate of evaporation at these ages is much smaller and more stable than the rate of evaporation at early age. In the concrete specimens with limestone, the change in water content between 28 and 90 days is slightly larger than for the river gravel mixtures. The difference is attributed to the greater porosity of the limestone, which can contain more water and continuously supply water for evaporation.

At low temperatures, slow hydration helps to produce a dense and less porous internal structure which decreases the rate of water loss. On the other hand, rapid hydration at high temperature forms loose and more porous internal structures, which enhance later loss of water. The amount of water which is present in concrete depends on the size of the pores and the relative humidity. When concretes are exposed to the same relative humidity and temperature, the internal water can be assumed to have the same surface tension. The radius of meniscus formed in a pore under the given relative humidity depends on the pore size. If the overall size of pores is large, the number of pores which can hold water under the given condition is reduced. The same is also true for the moisture contents. The long-term, equilibrium water content depends on the size of pores formed in the concrete. The moisture content in a low temperature environment is low but becomes larger as the temperature of the environment increases. Drying for 90 days in the hot and dry condition is long enough for the evaporation process to be considered to have reached quasi-equilibrium; in that state the moisture content depends on the internal pore structure of the concrete, and its values are an indication of the size of the pores. A low moisture content at higher temperatures is caused by the large and coarse pore structure formed in the concrete. Even though specimens cured at low temperatures are moved to a higher temperature environment with the same relative humidity, the moisture content will not be as low as in specimens continuously cured under high temperatures. Because of different curing conditions, different internal pore structures were formed. The difference of moisture content is due to the difference of internal pore structure of the concrete mixtures.

The effects of mixing time and fly ash on moisture content for the mixtures with a slump of 1.5 inches are shown in Figure 56. In general, the longer the mixing time, the greater the moisture content is at later ages. The observation is valid for different ages, different types of aggregates, and the presence of fly ash. The loss of water due to evaporation reduced the workability of concrete. The degree of moisture loss and the loss of workability depend on the mixing time. Some additional water was introduced after the mixing time to restore the original workability. The added amount was about equal to the amount of water loss. However, just compensating the water loss is not enough to recover the workability. Additional water is needed to compensate for the increase in viscosity and reduction in workability due to the formation of cement hydration products. From Figure 56 it can furthermore be observed that the increase in moisture content with an increase in mixing time is present at all ages, even though the differences are reduced with age. The effect of high initial moisture content lasts throughout the 90 day period investigated.

The effect of introducing fly ash on the moisture content can also be observed in Figure 56. The fly ash concrete showed quite different moisture characteristics from the plain concrete. The fly ash concrete had about 50 percent less moisture content than plain concrete at all ages. Fly ash replacement slightly reduced the amount of initial mixing water, as shown in Appendix C. In the opinion of the authors, the shape and relative small size of the fly ash particles combined with the additional

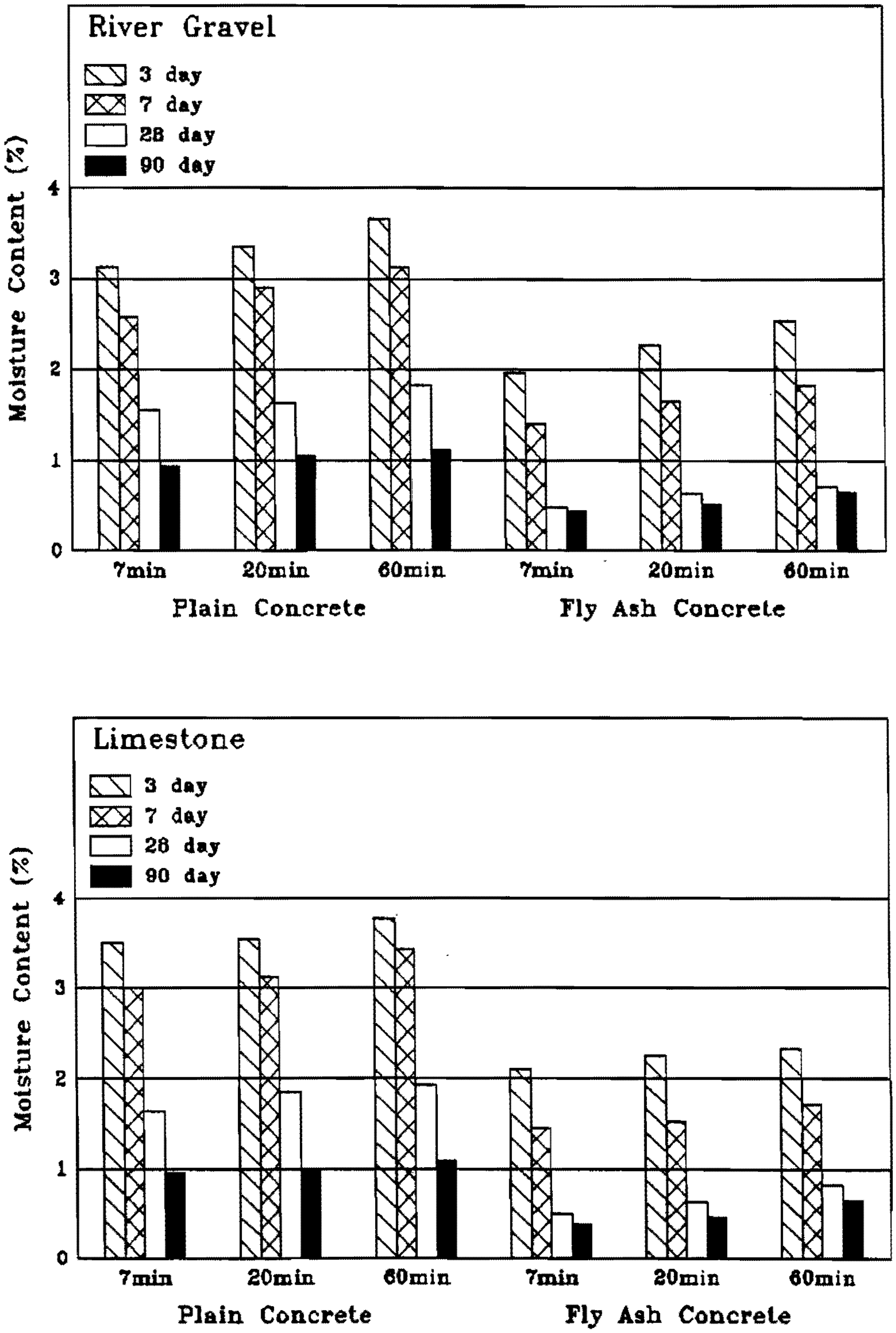
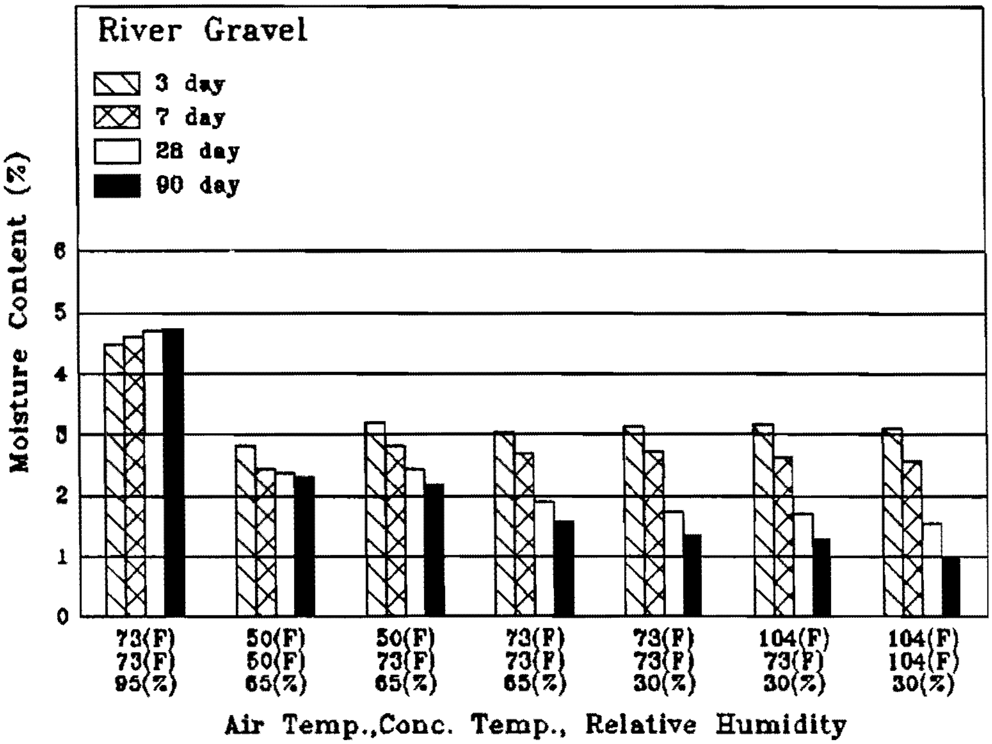


Figure 56. The effect of mixing time and fly ash on moisture contents for 1.5 inch slump concrete; a) River gravel b) Limestone

chemical reactivity of the particular type C fly ash used are responsible for the reduction in both initial mixing water content and subsequent moisture contents. From the results shown in Figure 56, the internal pore structure of fly ash concrete might not be drastically different from plain concrete because the moisture loss for these mixtures remained almost in the same order as for the plain concrete mixtures up to 28 days. This implies that the pores in the two types of concrete had almost the same characteristics, same sizes and same distributions. During the first 28 days, most of the evaporable water in the fly ash concrete was lost, and therefore, no further significant moisture losses occurred at ages greater than 28 days. This observation implies that the fly ash concrete almost reached equilibrium after about 28 days of curing.

Figure 57 shows the effects of continuous moist curing and initial material temperature on the moisture content of 1.5 inch slump concrete. Continuously moist cured concrete has twice the amount of moisture content as any other concrete stored in dry air. The specimens cured in the moist room showed an increase in moisture content, whereas the specimens stored in dry air showed a decrease in moisture content. If concrete is cured in sealed condition, thus preventing evaporation of part of the moisture to the environment, the moisture content must be decreased because the chemical reactions in concrete consume the water to form hydration products. The increase in moisture content is an indication that the amount of absorbed moisture is greater than the amount of hydrated water. The changes in moisture content with age are, however, not as significant as the changes under dry conditions.

When the material temperature is controlled to overcome the cold air temperature, a slightly higher moisture content can be observed at the age of 3 days, and almost the same moisture content can be observed for the later ages. The high moisture content is a result of the high initial mixing water. At low air temperatures, the warmer materials needed more water than the cooler materials, and the moisture loss of the warm material was also greater than evaporation from the cool material at the same air temperature. The initial mixing water was increased to compensate for this loss, and the increased water affected the 3 day moisture content. However, the effect of using warmer materials lasted for a short period — generally within a day — and the immediate decrease in temperature was observed during the mixing



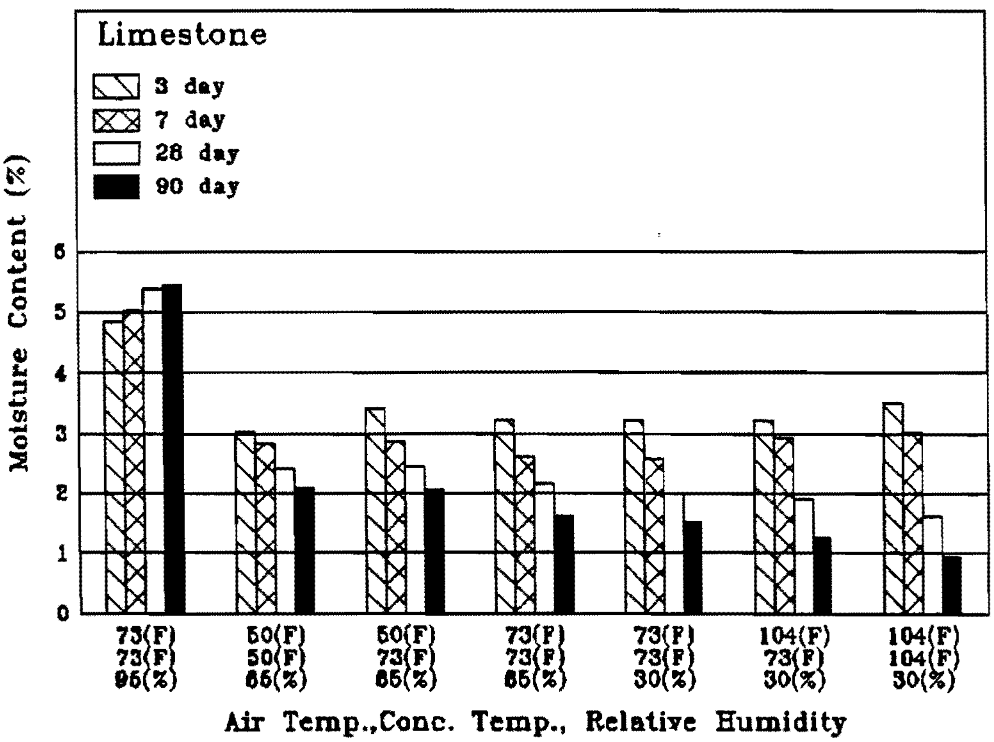


Figure 57. The effect of moist curing and controlling concrete temperature on moisture content for 1.5 inch slump concrete; a) River gravel b) Limestone

of the concrete. When cooler materials were used in the hot temperature environment, similar behavior was observed with slightly lower moisture content at the age of 3 days.

Figures 58 and 59 show the effect of temperature and slump on the moisture content at different ages for the relative humidity and wind speed of 65% and 9 mph, and 30% and 6 mph, respectively. At 3 days of curing, the specimens stored in a high temperature environment have a greater moisture content than specimens stored in a low temperature environment. For the 7 day test, this pattern did not exist, indicating the existence of a transient period where the effect of environmental factors exceeds the effect of the initial mixing water. For river gravel, the moisture content in the hot environment has the lowest value. For the limestone, on the other hand, the moisture content at 73°F showed the lowest value. It is difficult to explain what causes these differences between the two aggregates. For the rest of the curing periods, the moisture content is in reverse order. In the hot environment, the high moisture content at an early age is due to the effect of the greater amount of initial mixing water, and the low moisture content at a later age is caused by a greater loss of water to the environment. The effect of slump lasts throughout the period of 90 days. The different initial slump might cause structural differences which were not changed later. The effect of initial slump was not different from that of the environmental conditions at early ages. However, whereas the effect of slump remained almost constant throughout the testing period, the effect of environmental conditions was increasing with time. At 28 and 90 days, the differences in moisture content due to the environmental conditions were much more significant than that due to slump.

Figure 60 shows the effect of consolidation method and the presence of fly ash on the moisture content. The effect of consolidation is not as clear as the other factors investigated in this report. The differences are small enough to be considered as testing errors, and the orders are changing with time. One obvious observation is that the vibration method yields the highest moisture content in many cases. This indicates that well consolidated concrete might have a denser pore structure, so that the moisture loss rate is lower than in under-consolidated concrete. The effect of initial slump on the moisture content can also be observed in this figure. The specimens with greater slump and consolidated by vibration had

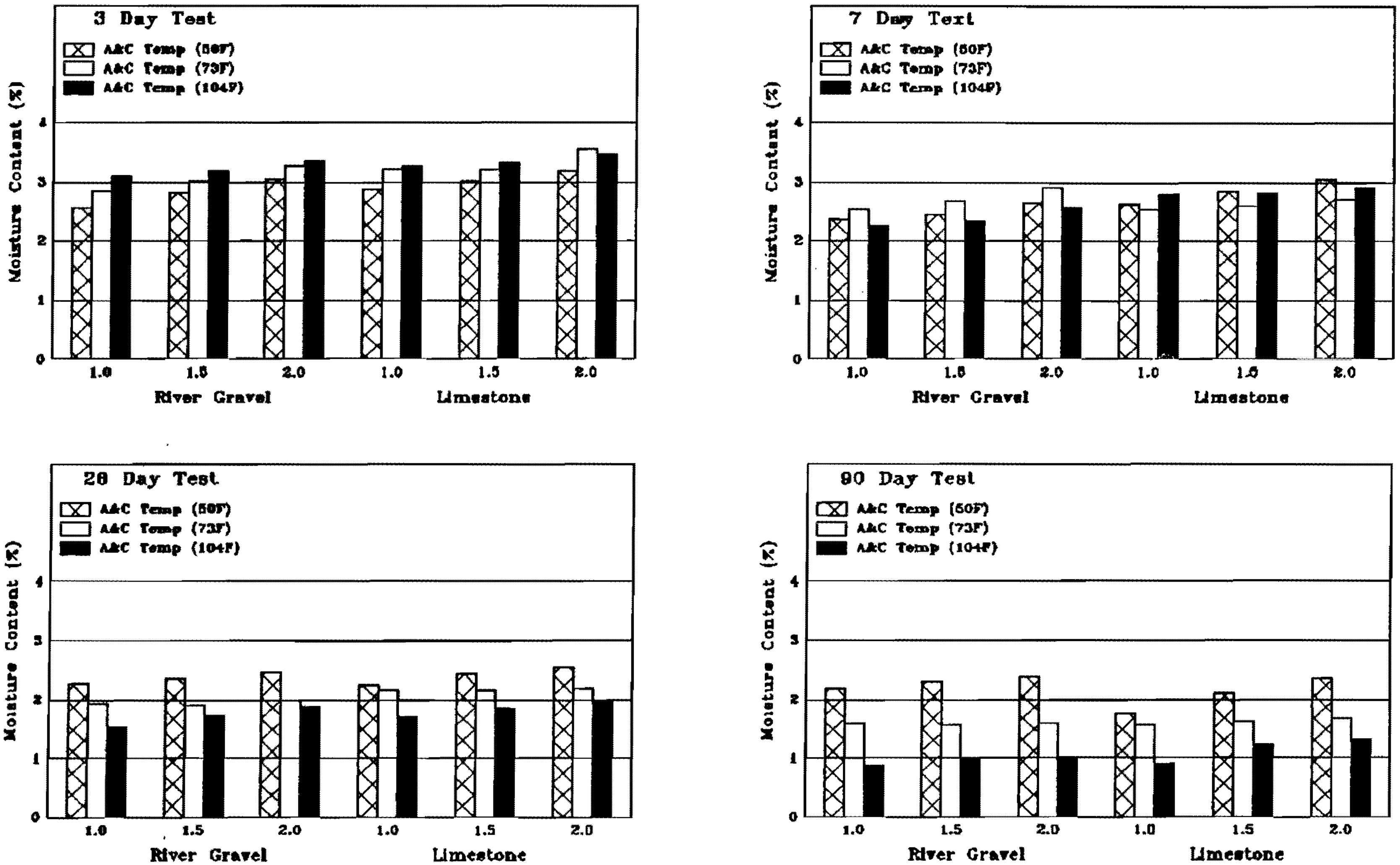


Figure 58. The effect of temperature and slump on the moisture contents at different ages, 65% RH and 9 mph wind

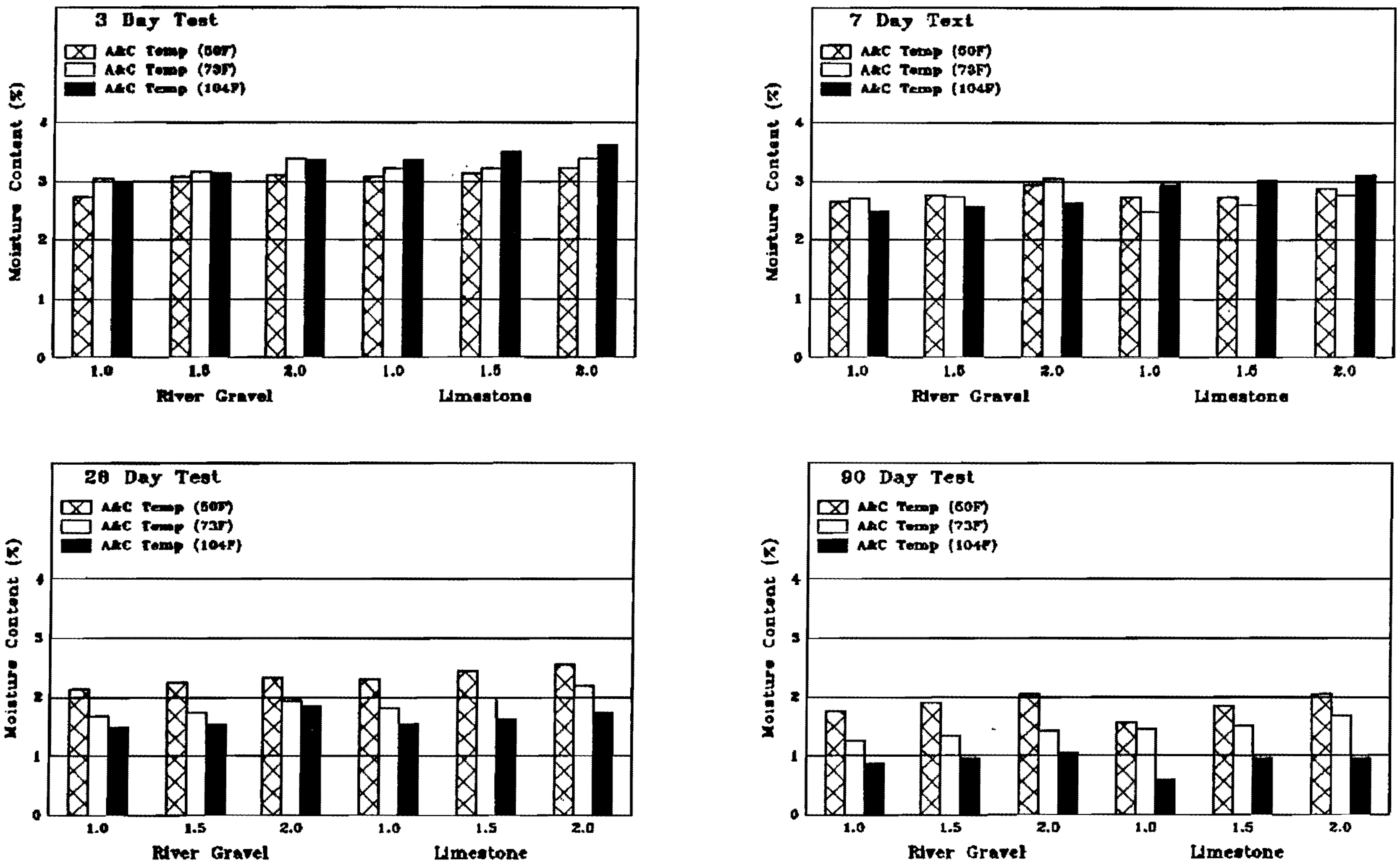


Figure 59. The effect of temperature and slump on the moisture contents at different ages, 30% RH and 6 mph wind

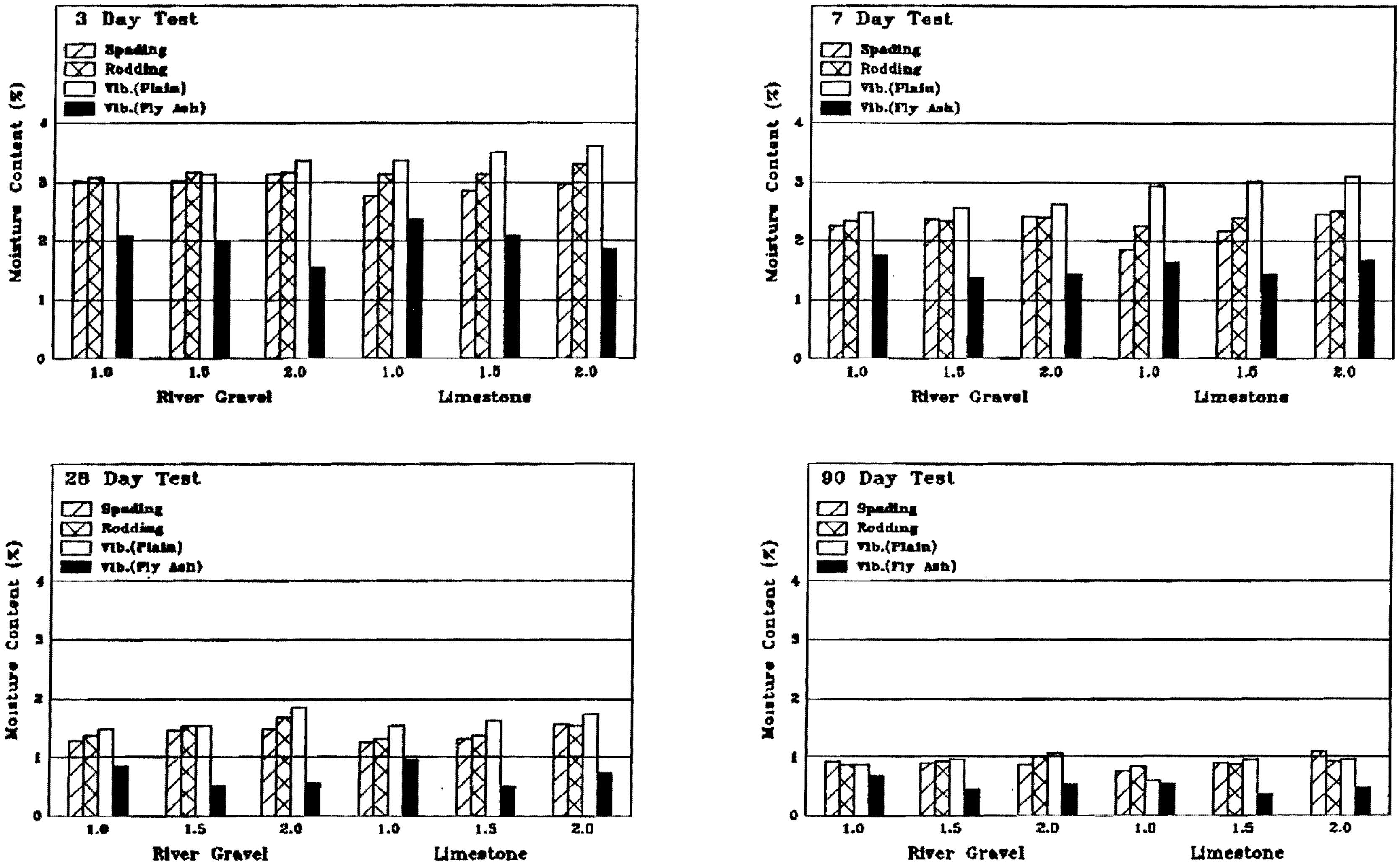


Figure 60. The effect of consolidation method and fly ash on the moisture content

higher initial moisture content and a constant rate of moisture change. Consistently the specimens with the highest moisture content at any age are the specimens with the greatest slump. However, for the other two consolidation methods, spading and rodding, the effect of slump on moisture content varies with time. The specimens made with these two methods might be consolidated less uniformly than specimens made with the vibrating method. Moisture content tests were performed with the specimens made separately, not with one specimen, so that the test variabilities per each specimen were large enough to include the effects of both consolidation methods. As was mentioned in a previous section, replacement of fly ash for a portion of the cement reduced the moisture content to almost half that of plain concrete.

In Figure 61, percent moisture loss, based on the specimen weight after removal of the forms at 24 hours, is plotted against the environmental conditions at 3, 7, 28, and 90 days of age for concrete with a slump of 1.5 inch. As expected, moisture losses increase when specimens are exposed to an environment with a higher evaporation rate. The tendency is very obvious for long-term measurements, but the difference is not distinct after only 3 days. This is attributed to the time dependent influence of the environmental effects and the effect of curing compound, which is believed to be effective for early ages. As long as the treatment is effective, the moisture loss is confined within a limited range. The curing compound used in this test can be concluded to be effective for a short period. The limestone concrete mixture lost more water than the river gravel concrete. There are two plausible reasons for this: first, the amount of mixing water for the limestone concrete was larger than for river gravel concrete; and second, the greater porosity of limestone might help transport moisture to the surface of the concrete.

Figure 62 shows the effect of mixing time and fly ash on the moisture loss characteristics in 1.5 inch slump concrete. Extended mixing time requires additional water, and most of the additional water was lost to the surroundings by evaporation. That is the reason moisture loss increases with mixing time. In the hot environments, most of the initial and final set occurred within 3 hours, whereas, in cooler conditions, the setting times extended up to 15 hours (see section 4.5.1 for more information). During the setting time tests, the concrete was covered to prevent excessive evaporation except when measurements were taken. To the

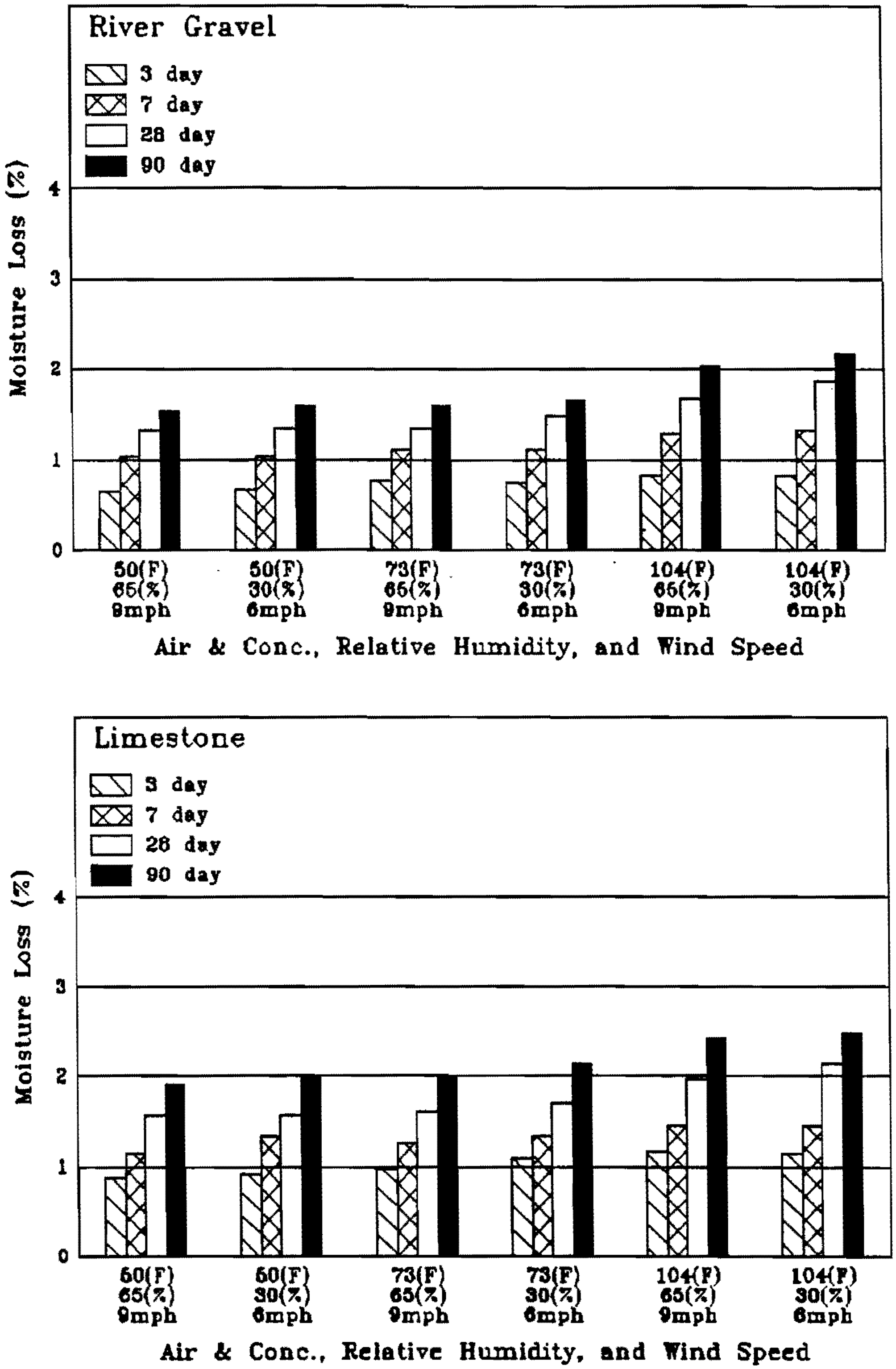
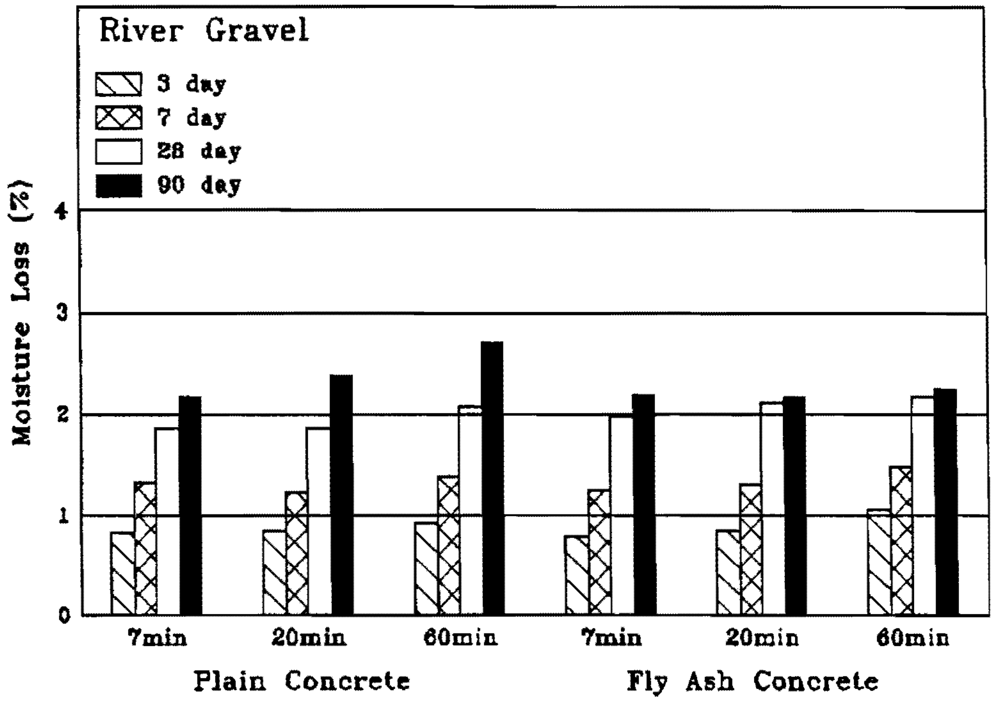


Figure 61. The environmental effects on moisture loss for 1.5 inch slump concrete; a) River gravel b) Limestone



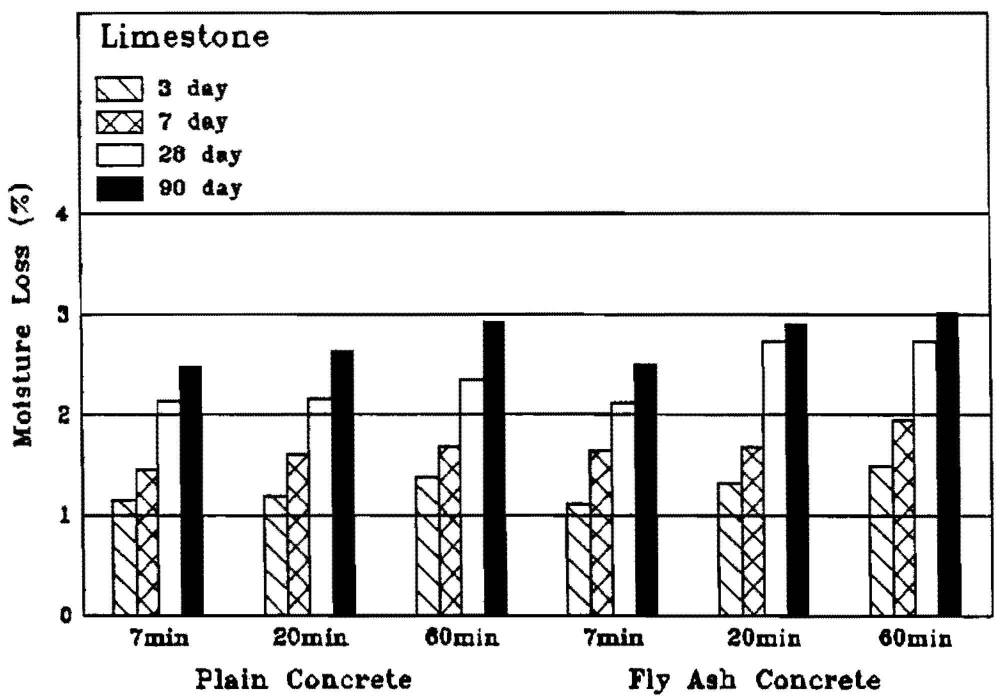


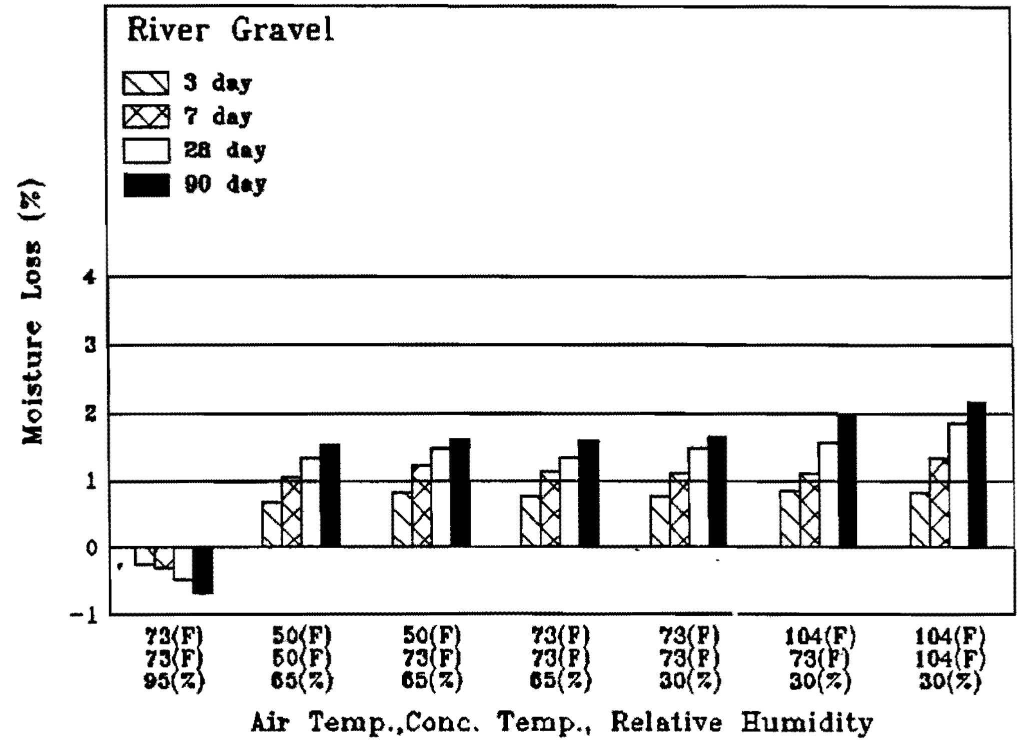
Figure 62. The effect of mixing time and fly ash on the moisture loss for 1.5 inch slump concrete; a) River gravel b) Limestone

contrary, the concrete was mixed in open air, thus allowing for some evaporation during mixing. Due to this difference in treatment of the concrete, evaporation from the concrete during mixing was more severe than from the specimens used in the time of setting tests. When the mixing time was extended to 60 minutes, hydration proceeded and significant amounts of the mixing water were lost. This resulted in a reduction in workability and required an addition of water, as previously mentioned. The same tendencies can be observed for limestone concrete. The only difference is that limestone concrete loses more water than river gravel concrete.

Figure 63 shows the effects of moist curing and of controlling the material temperatures on the moisture loss characteristics for 1.5 inch slump concrete. When the specimens were stored in moist condition, moisture gain rather than loss took place. The amount of moisture gain varies with the type of aggregate, increasing with an increase in aggregate porosity. The amount of moisture gain during the first 3 days was very significant for limestone concrete and was greater than the gain during the remainder of the curing period investigated. However, this observation for river gravel is not as significant as for limestone (see also Table D4a in Appendix D).

When warmer materials are used in the cold environment instead of materials with the same temperature as the environment, slightly greater moisture loss is observed at all ages. However, the increment of moisture loss remains almost constant as a function of age, which means that the temperature difference affects the test at an early age but not at a later age. The greater moisture loss was also caused by higher initial mixing water needed due to the temperature difference. Slightly lower moisture loss was observed when cooler material was used in the hot environment. The low moisture loss might be caused by the small amount of mixing water and by the relatively low temperature which produced less porous concrete.

Figures 64 and 65 show the effects of temperature and slump on the moisture loss characteristics for two different constant relative humidities of 65% and 30%, respectively. As the temperature increases, an increase of moisture loss is observed. At the early ages, the effect of temperature on the moisture loss is not significant but becomes greater with age. When the same tests were performed in a 65% relative humidity condition, almost the same results were obtained for the entire 90 days, the only difference being the smaller quantity of moisture loss at later ages. Again



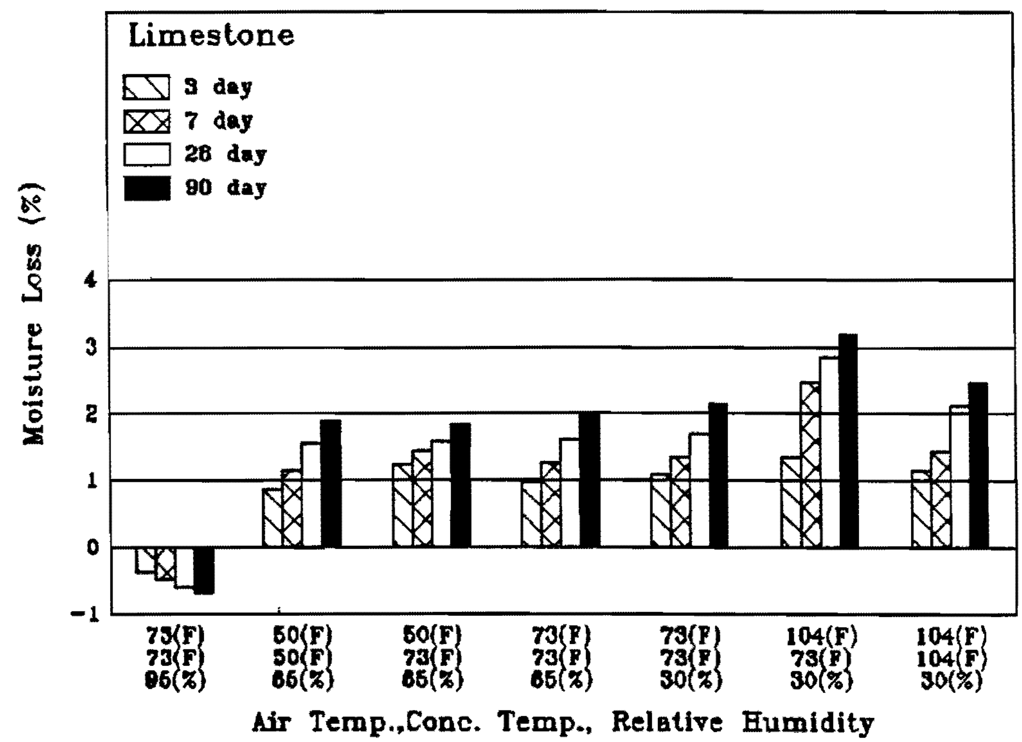


Figure 63. The effect of moist curing and controlling concrete temperature on moisture loss for 1.5 inch slump concrete; a) River gravel b) Limestone

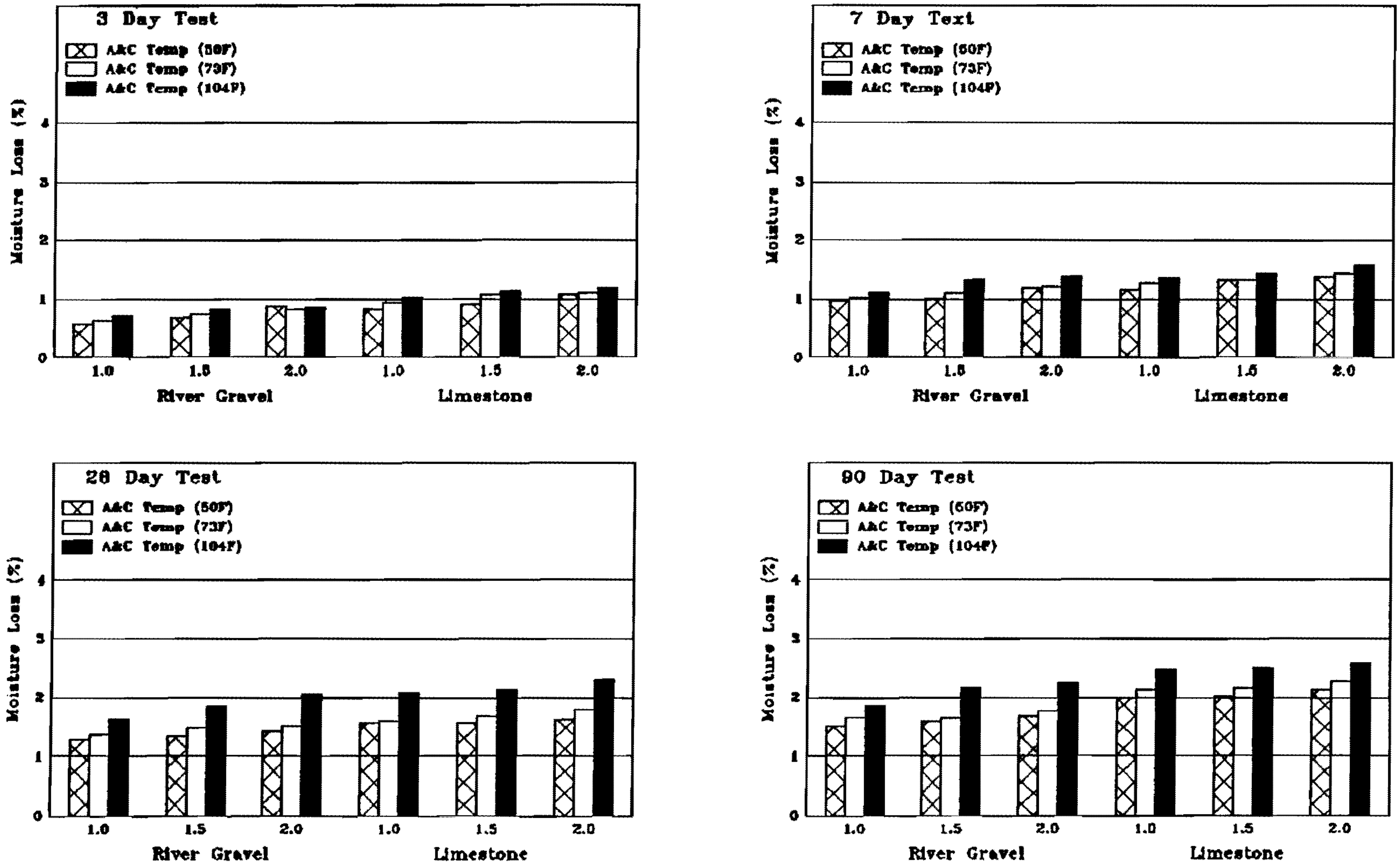


Figure 64. The effect of temperature and slump on the moisture loss at different ages, 65% RH and 9 mph wind

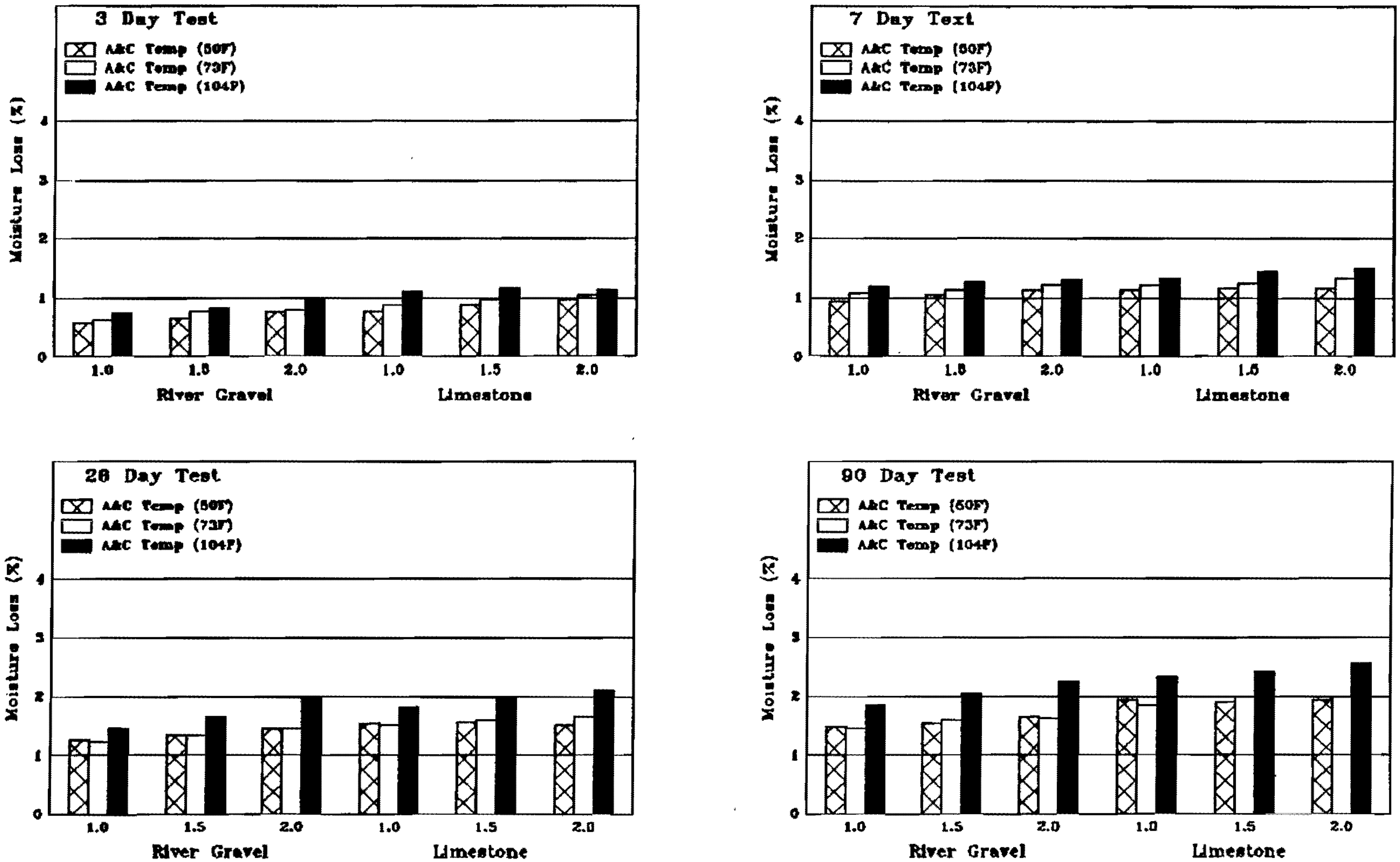


Figure 65. The effect of temperature and slump on the moisture loss at different ages, 30% RH and 6 mph wind

it can be seen that limestone concrete loses more water than river gravel concrete. The effect of slump on the change in moisture loss is more significant for river gravel than for limestone concrete.

Figure 66 shows the effect of consolidation method, fly ash and slump on the moisture loss characteristics. The effect of consolidation method does not appear to be significant. Quite contradictory results are seen in the figures. For the vibrated concrete, an increase of moisture loss as the slump increases can be observed; however, for the other two methods, the effect of slump was hard to identify. Fly ash concrete lost more water than plain concrete throughout the testing period, indicating the presence of a more porous structure. The lower rate of hydration in fly ash concrete, because of the lower chemical reactivity of fly ash compared to portland cement, is the reason it apparently remained more porous over a longer period of time than plain concrete. The extended porous period resulted in a high rate of moisture loss, which is shown in Figure 66 throughout the entire 90 days.

Regarding the effect of slump on the moisture loss of fly ash concrete, a greater loss is generally observed compared with the loss from the plain concrete, regardless of the slump. Like plain concrete, the effect of slump on the change in moisture loss is more significant for river gravel than limestone concrete. A greater moisture loss is observed with an increase in slump. This can be attributed to the increase in capillary porosity that occurs when the slump increases.

Moist Cured Condition   The effect of mixing time on moisture content is shown in Figure 67 a). As the mixing time increases, the moisture content increases. The differences are caused by the changes in the initial mixing water. These differences remained unchanged throughout the test period. The greater moisture content is generally associated with an increase in porosity.

Figure 67 b) shows the effect of mixing time on moisture loss. In this figure, moisture gain is shown instead of moisture loss. As the mixing time increases, the moisture gain increases, and the differences increase with time. The increased initial moisture gain and the increase of the differences with an increase in mixing time may be due to a greater porosity of the concrete. Because of the high initial moisture content, the concrete remained more porous due to the space occupied by the mixing water.

Figure 68 shows the effect of consolidation method on moisture content for

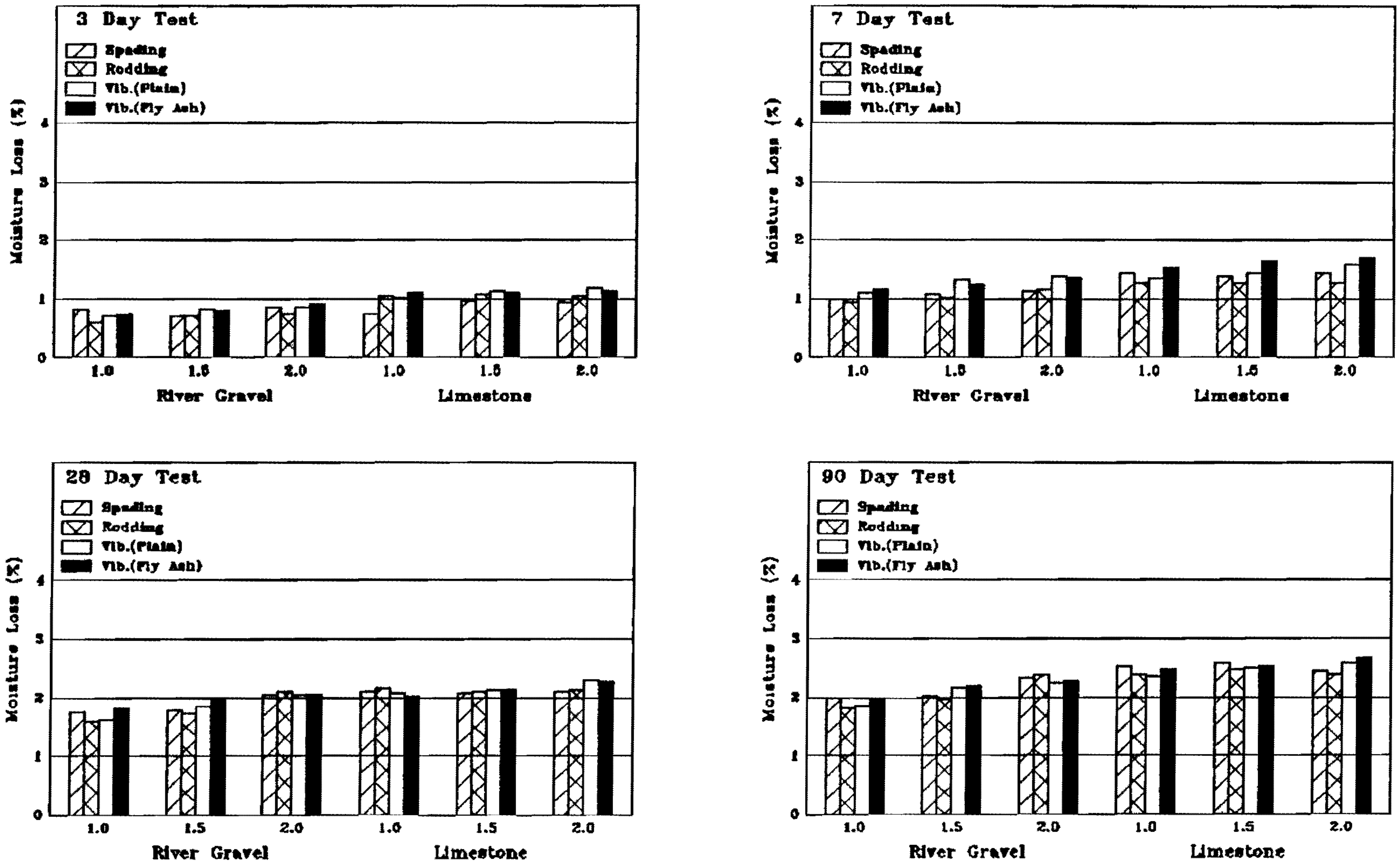
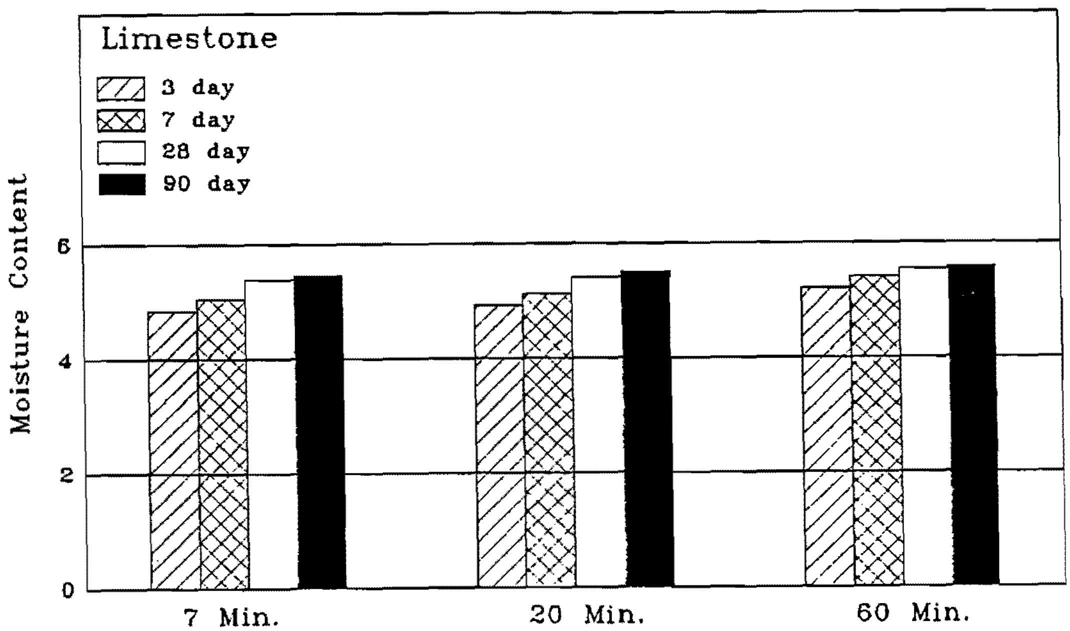


Figure 66. The effect of consolidation method, fly ash, and slump on the moisture loss at different ages



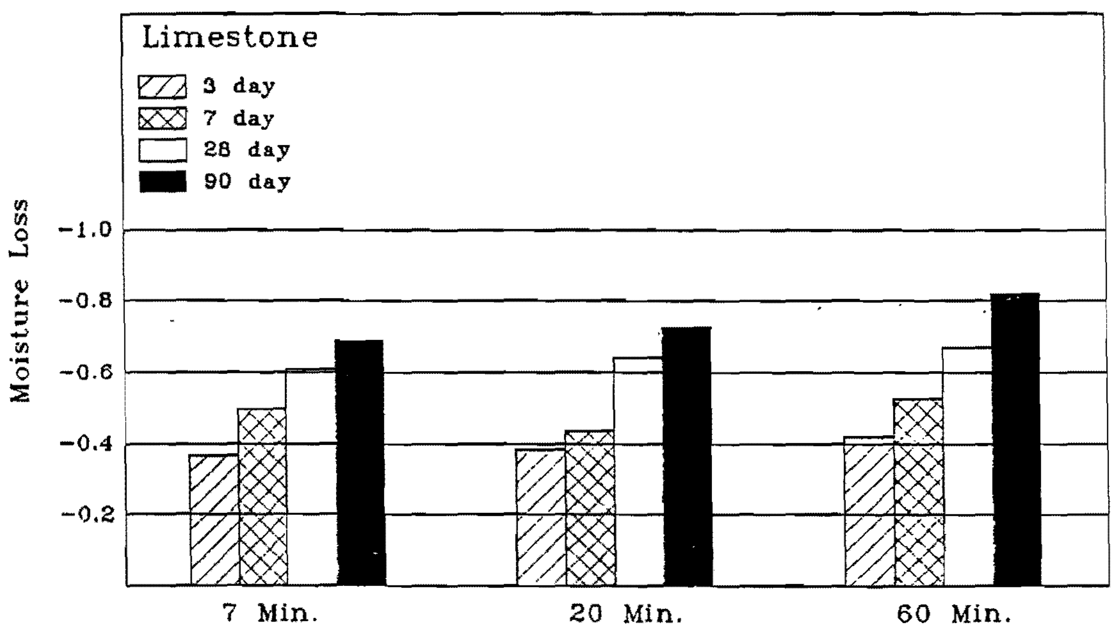


Figure 67 The effect of mixing time on moisture change in moist cured condition for 1.5 inch slump concrete; a) moisture content b) moisture loss

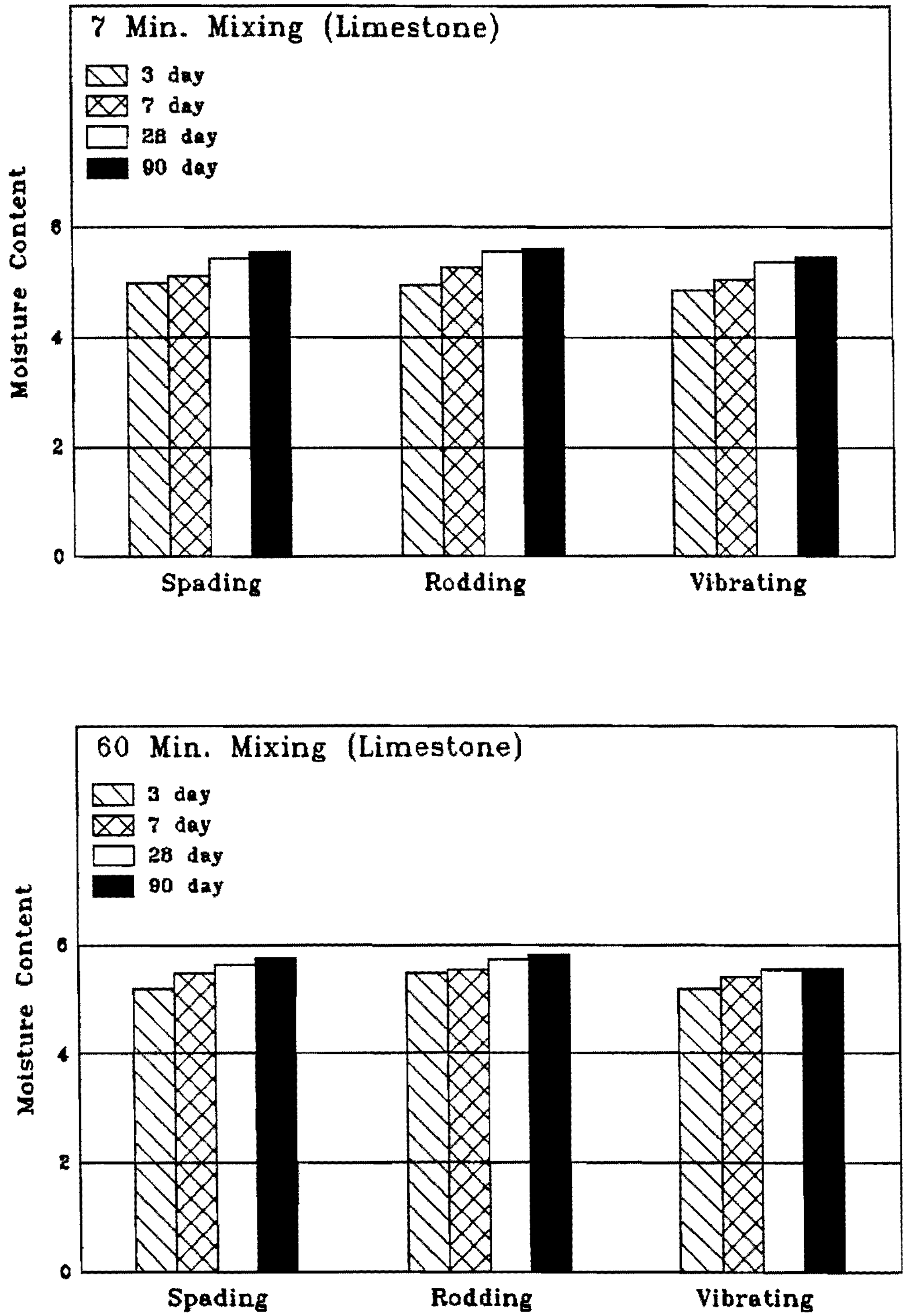


Figure 68. The effect of consolidation method on moisture content in moist cured condition for 1.5 inch slump concrete; a) 7 min. mixing b) 60 min. mixing

7 and 60 minute mixing times. The vibrating method shows the lowest moisture content. The rodding method shows slightly higher moisture content than the spading method. The observations were true for both mixing times. Lower moisture content means the concrete has less porosity. However, the effect of consolidation method in this environment was not as distinct as the effect in the hot and dry environment.

Figure 69 shows the effect of consolidation method on moisture loss for 7 and 60 minute mixing times. The smallest and greatest moisture gain occurred in the vibrated and rodded concrete specimens. For the 60 minute mixing, the increase in moisture gain was more distinct for the rodding method.

4.4.3 Conclusion

The following conclusions are based on the results of the laboratory tests for the shrinkage and weight loss of concrete. The conclusions are divided into two sections that refer to the results of the shrinkage and associated weight loss experiments, and the moisture content and moisture loss tests.

Shrinkage and Weight Loss :

1. The 90 day shrinkage values were found to be affected by the environmental conditions, increasing in order of increased evaporation rate.
2. Limestone concrete showed significantly higher shrinkage than river gravel concrete, because limestone concrete requires a greater initial water content to produce the same slump. The higher water requirement may be due to differences in surface texture and shape of the aggregate.
3. Next to aggregate type, water loss is the most important single factor affecting shrinkage.
4. Extended mixing time affects early shrinkage slightly and has no affect on long-term shrinkage.
5. For the particular source of fly ash used, there is no significant change in shrinkage when fly ash replaces 20% by weight of the cement on a 1:1 basis.
6. The variations of shrinkage for limestone concrete are greater than that for river gravel concrete.
7. Controlling material temperature did not change shrinkage significantly.

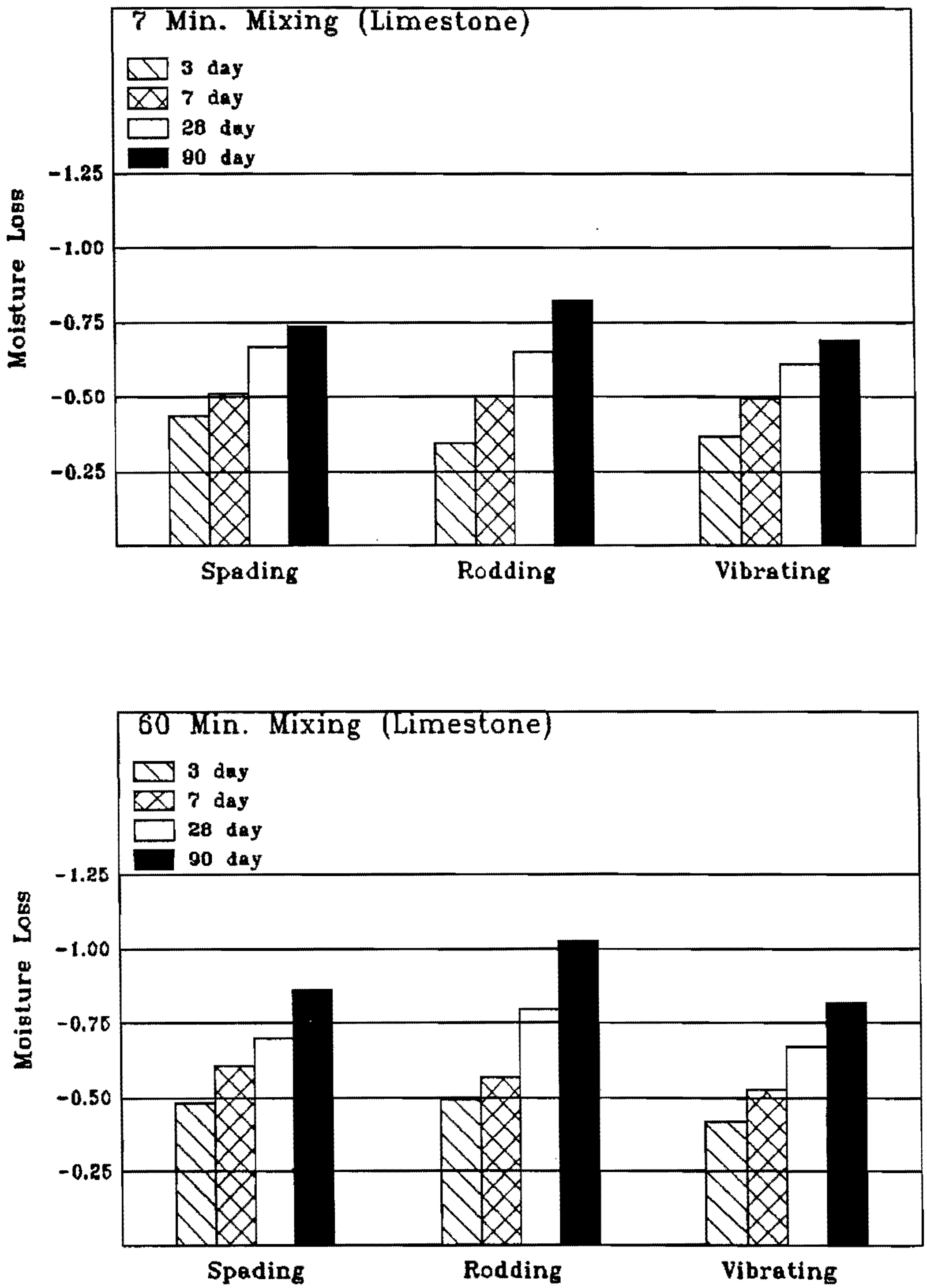


Figure 69. The effect of consolidation method on moisture loss in moist cured condition for 1.5 inch slump concrete; a) 7 min. mixing b) 60 min. mixing

8. The different consolidation methods did not cause any significant change in shrinkage.
9. The correlations between shrinkage and weight loss are almost linear and are affected by the type of aggregate. The replacement of fly ash affects the correlations slightly. However, the correlations are not affected by the curing conditions.

Moisture Content and Moisture Loss:

1. The moisture content at early ages depends primarily on the initial amount of mixing water which was increased slightly as the evaporation rate increased. However, the moisture content at ages later than 28 days decreases significantly as the evaporation rate increases because of the accumulative effect of drying.
2. The moisture content and the rate of moisture loss decrease with age, and approach an equilibrium condition. This condition depends on the pore structures generated during the specific curing condition.
3. The extended mixing time increases both the moisture content and moisture loss and is proportional to the required increase of initial mixing water to maintain slump.
4. Fly ash concrete seems to have almost the same pore structure as plain concrete. Therefore, the rate of moisture loss for fly ash concrete up to the age of 28 days remains almost equal to that for plain concrete.
5. Fly ash concrete appears to lose most of the evaporable water within 28 days, causing the subsequent moisture changes to be insignificant.
6. The limestone concrete specimens have initially almost the same moisture content as river gravel concrete. At later ages, however, the moisture content of limestone concrete is lower than in river gravel concrete. Therefore, limestone concrete appears to be more porous than river gravel concrete.
7. The effect of controlling material temperature on moisture content was not observed to be significant. When material temperature is controlled in a cold environment, moisture content is increased significantly, but moisture loss characteristics are not changed. In a hot environment, moisture content and moisture loss are not affected by the change in material temperature.
8. The effect of the consolidation methods on both the moisture content and moisture loss characteristics is not significant enough to be clearly observed in the tests conducted.

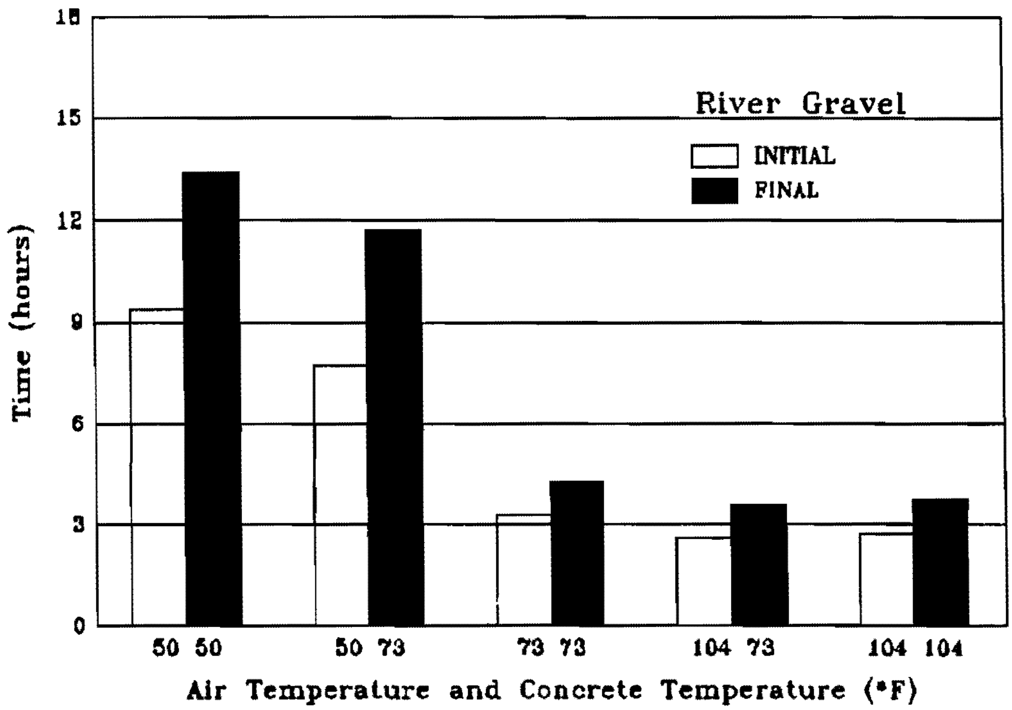
4.5 Time of Setting and Abrasion

4.5.1 Time of Setting

Time of setting is controlled by the rate of hydration, which is affected by the temperature. The specimens for time of setting tests were covered to minimize the effect of evaporation except during measurements, and therefore had almost no chance of moisture loss due to evaporation. Under field conditions, however, concrete might lose part of the mixing water through evaporation and cause an acceleration of the setting time.

Figures 70 through 72 show the effect of temperature on time of setting for different slumps and both aggregate types. Overall the setting times at 50°F ranged from 9 to 11 hours for initial time of setting, and from 13 to 15 hours for final setting, with the lowest values occurring for the lowest slump mixtures. At 73°F, initial setting occured at 3 to 4 hours and final setting at 4 to 6 hours. At 104°F, both setting times are shorter than for the lower temperature conditions. Initial and final setting times were about $2\frac{1}{2}$ and $3\frac{1}{2}$ hours, respectively. The changes of setting time from 50°F to 73°F are greater than the changes from 73°F to 104°F. The difference between the two setting times decreased as the temperature increased and the setting times decreased. The elapsed time between initial and final setting time at 50°F was about 4 to 5 hours, whereas the elapsed time at a greater temperature was 1 to 1.5 hours.

In the same figures, the effect of material temperature on setting time can be seen. Warmer materials in a cold environment reduce both the initial and final setting times. The shorter setting time is caused by a faster hydration due to the increase in mix temperature. Correspondingly, cooler materials in a hot environment decrease both setting times. However, the increase of setting time in a hot environment is not as significant as the decrease of setting time in a cold environment. In other words, controlling the material temperature in a cold environment is more effective than in a hot environment in changing the setting characteristics. Controlling material temperature significantly affects the setting time. The concrete temperature eventually matches that of the environment. The effect of controlling material temperature can last only a few hours or, at best, a day. Time of setting is an early age property of concrete, and occurred within



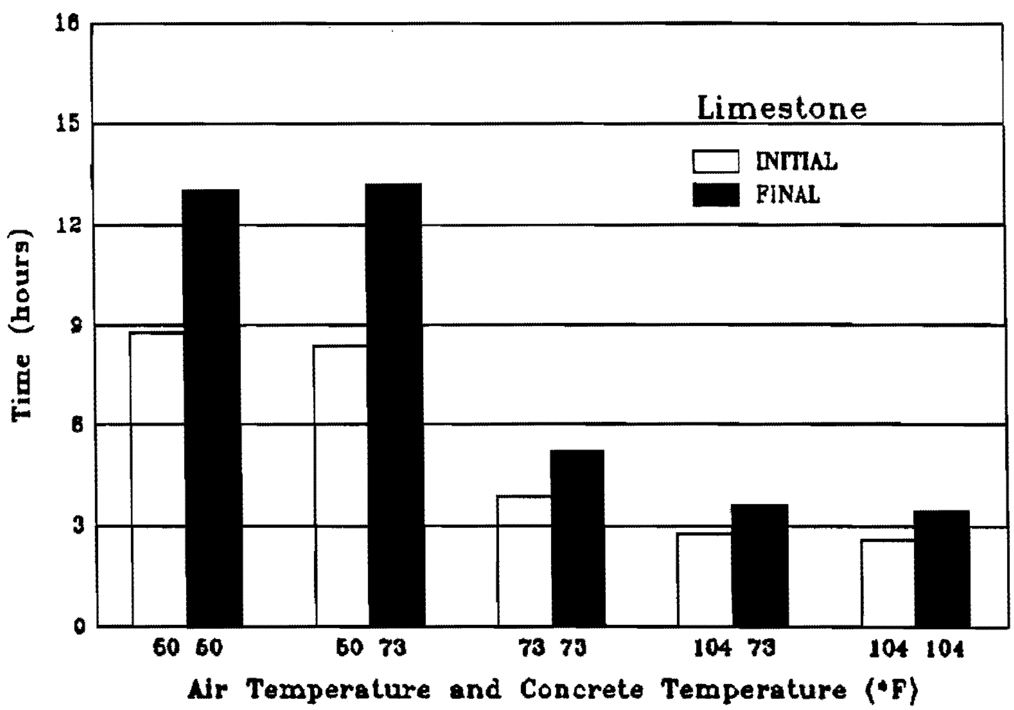


Figure 70. The effect of temperature on setting time, for 1.0 inch slump sealed concrete

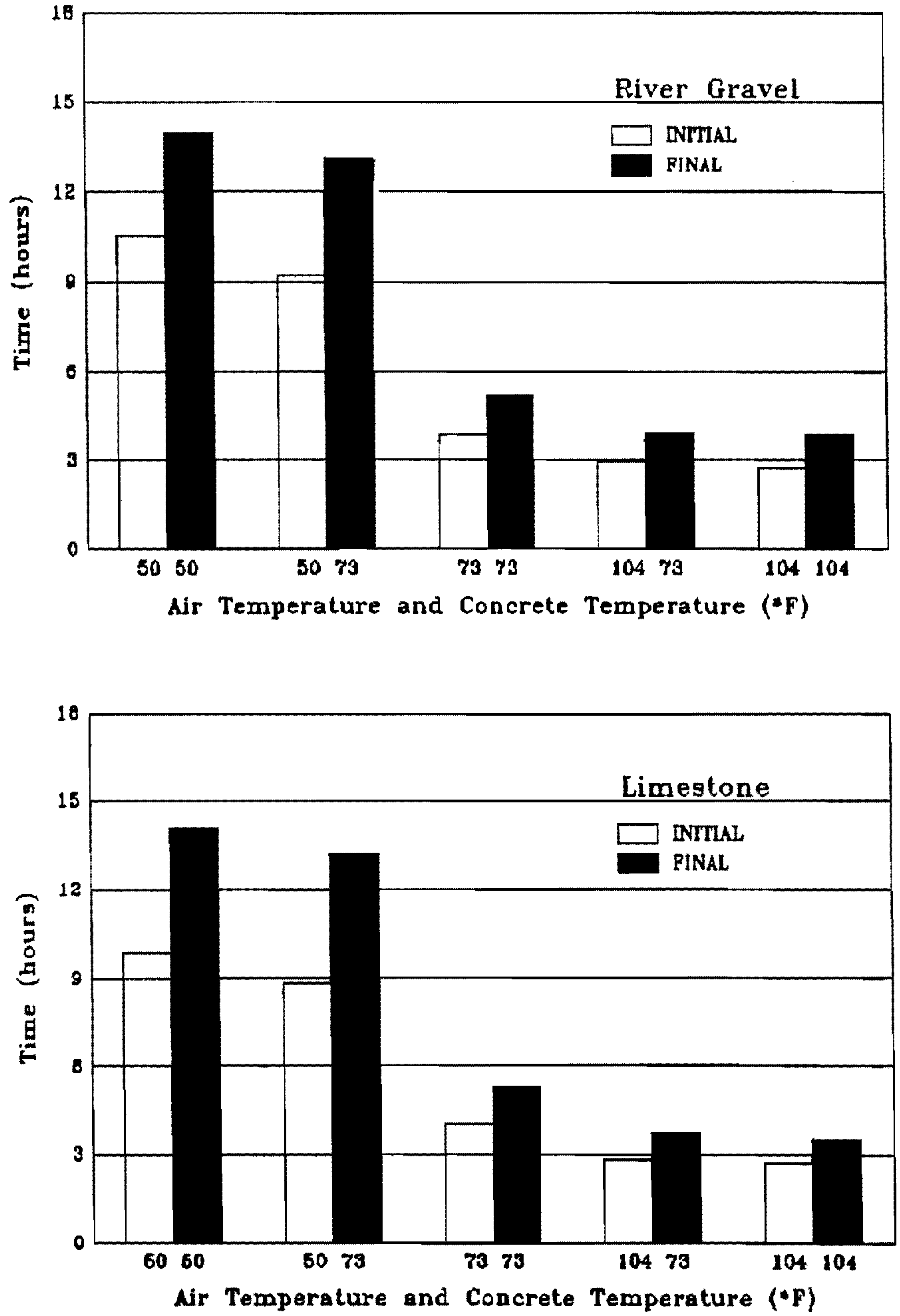
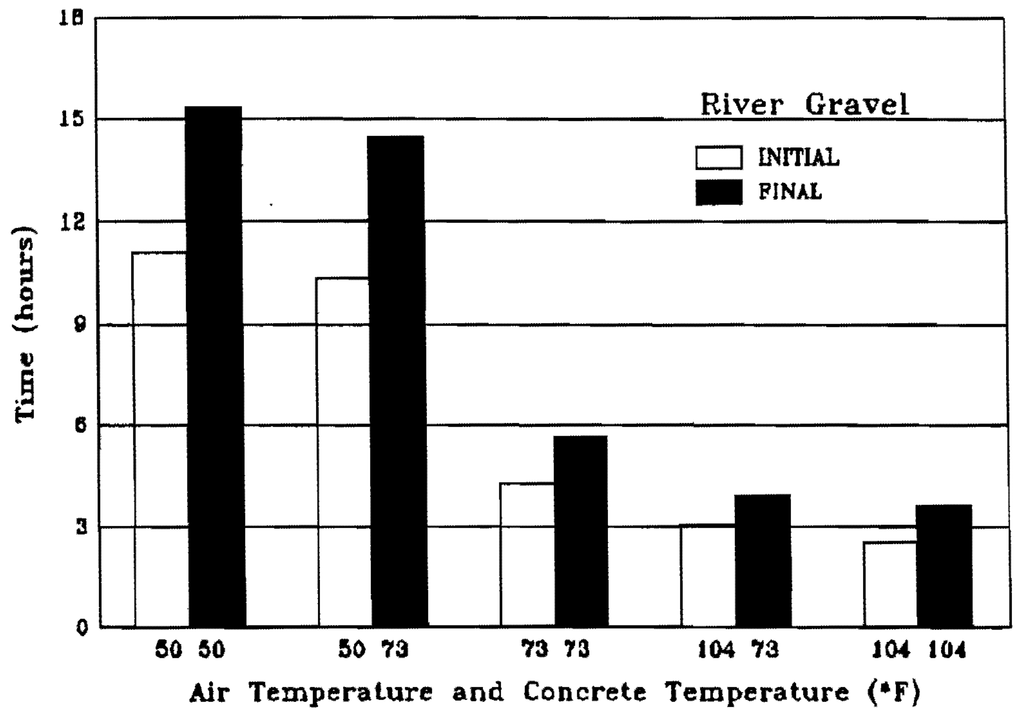


Figure 71. The effect of temperature on setting time, for 1.5 inch slump sealed concrete



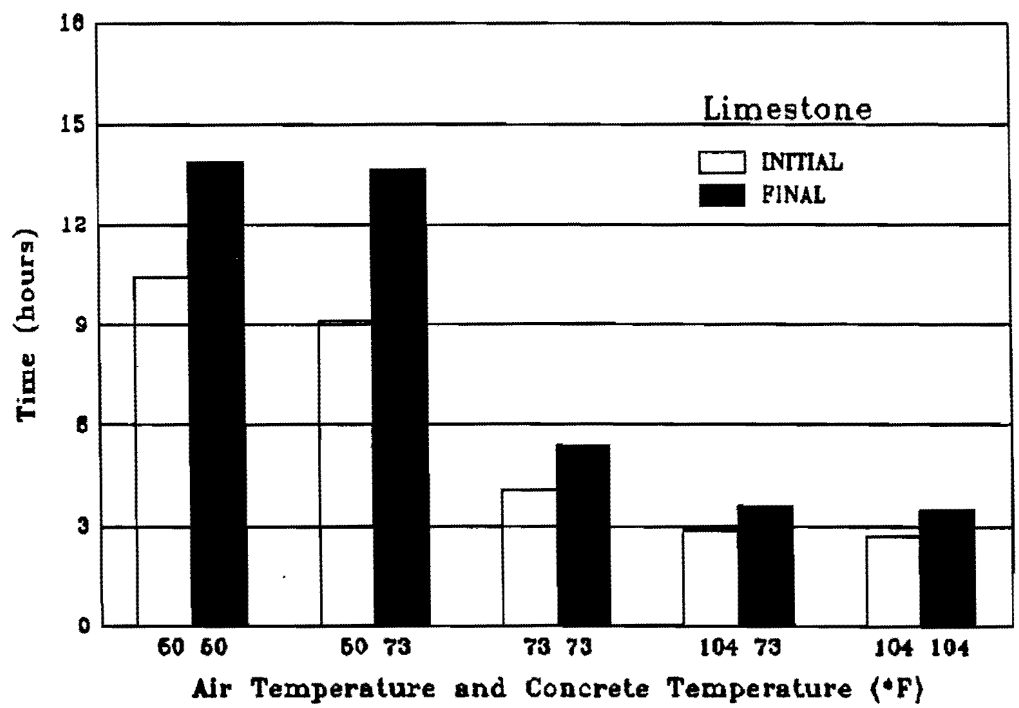


Figure 72. The effect of temperature on setting time, for 2.0 inch slump sealed concrete

a day in most cases. That is the reason setting times are affected significantly by temperature changes. Slight increases of setting time are also observed as the slump increases. This shows the effects of varying the amount of mixing water.

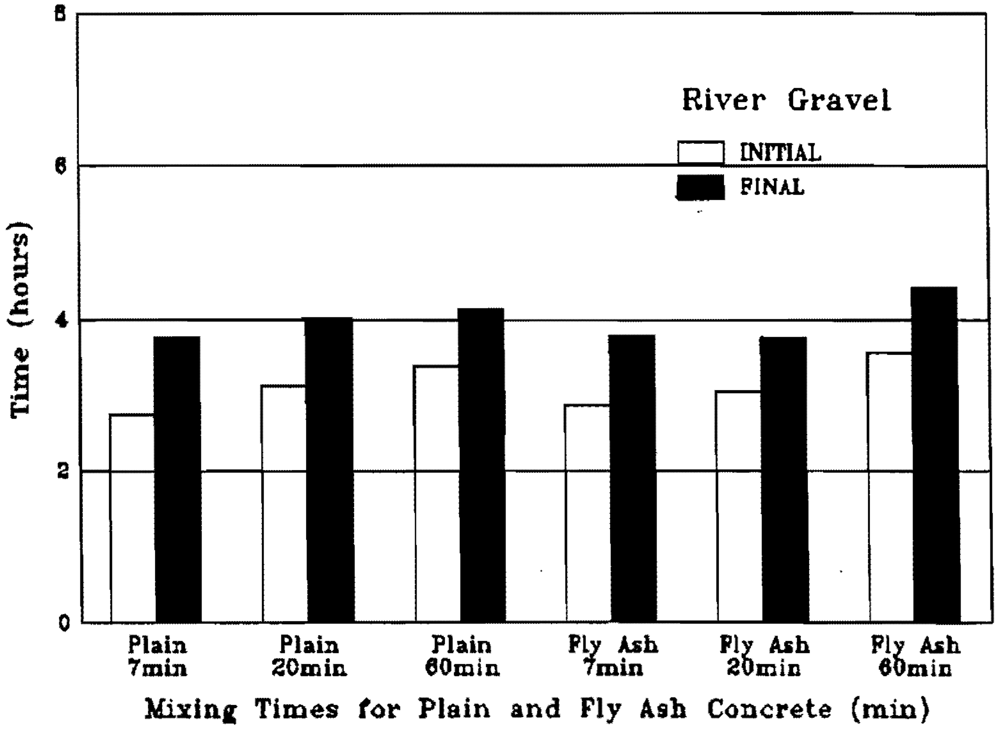
Figures 73, 74 and 75 show the effect of mixing time and fly ash on the setting times. Mixing time affects the setting time slightly. As the mixing time increases, the time of setting increases. Both the agitation, which disturbs the mixture, and the additional water, which was added to get the required workability, are believed to be the factors responsible for the delay in both setting times. The increase in setting times was almost proportional to the increase in mixing time.

Fly ash concrete showed almost the same, but slightly slower, setting times than plain concrete. The slightly slow setting times might be caused by the lower chemical reactivity of fly ash compared to that of portland cement. However, the effect of fly ash on time of setting is not as distinct as other tests reviewed in the previous section. The type of aggregate used in the mix affected the test results slightly. Because dry limestone can absorb more moisture than river gravel, the mortar specimens prepared with limestone aggregates might have less moisture than the specimens with river gravel. The smaller amount of initial mixing water might cause slightly shorter setting times in spite of the greater amount of water introduced.

Figure 76 shows the effect of slump on setting times for different air temperatures. As the slump increased, setting times were increased slightly. For the 50°F and 73°F temperatures, the slump changes affected both initial and final setting times distinctly. However, in the hot air temperatures, the setting times were almost identical and not affected by slump. The difference between the initial and final set remained almost constant with the change in slump.

4.5.2 Abrasion

Sandblasting tests were performed to evaluate the abrasion resistance of concrete pavement surfaces. Abrasion tests were performed on the initial bottom face of the beam specimens which was the smoothest face. After removal of the forms, the beams were turned upside down to expose the smooth surface to the environmental condition for the remainder of the test period. Figure 77 shows the effect of the environmental conditions on the abrasions expressed as depth in 10^{-2}cm



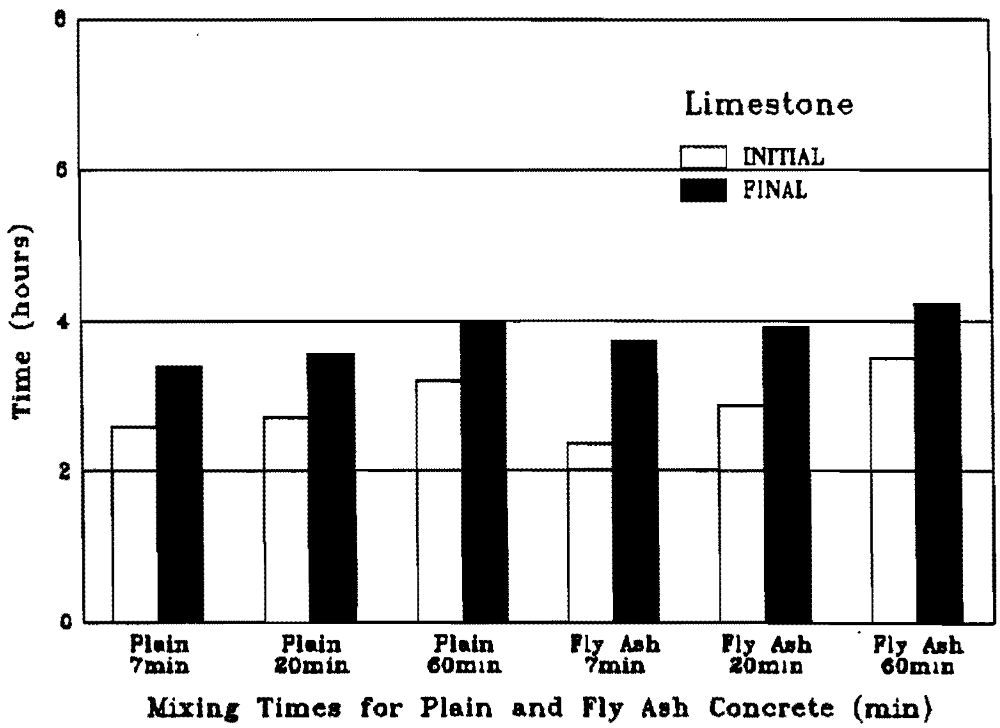
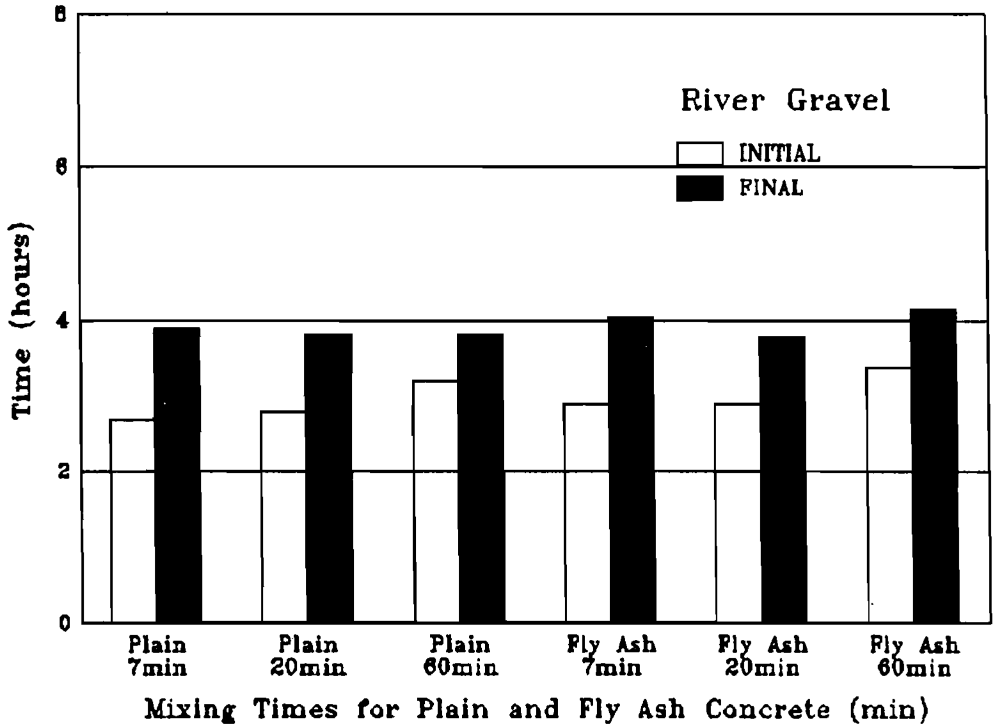


Figure 73. The effect of mixing time and fly ash on the setting time, for 1.0 inch slump



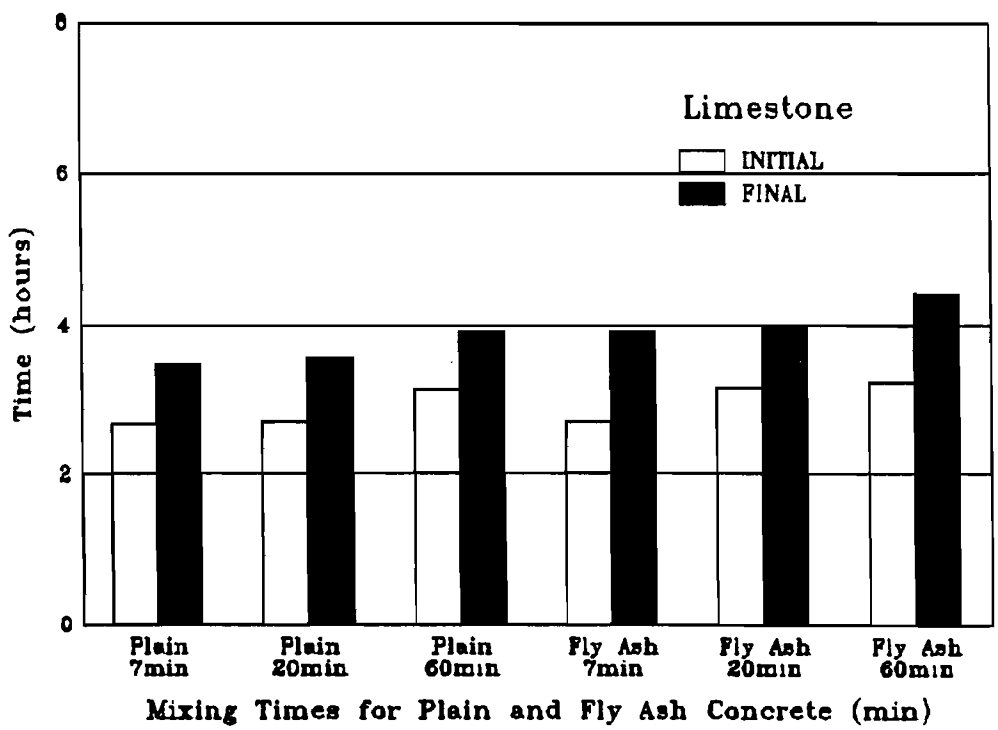


Figure 74. The effect of mixing time and fly ash on the setting time, for 1.5 inch slump

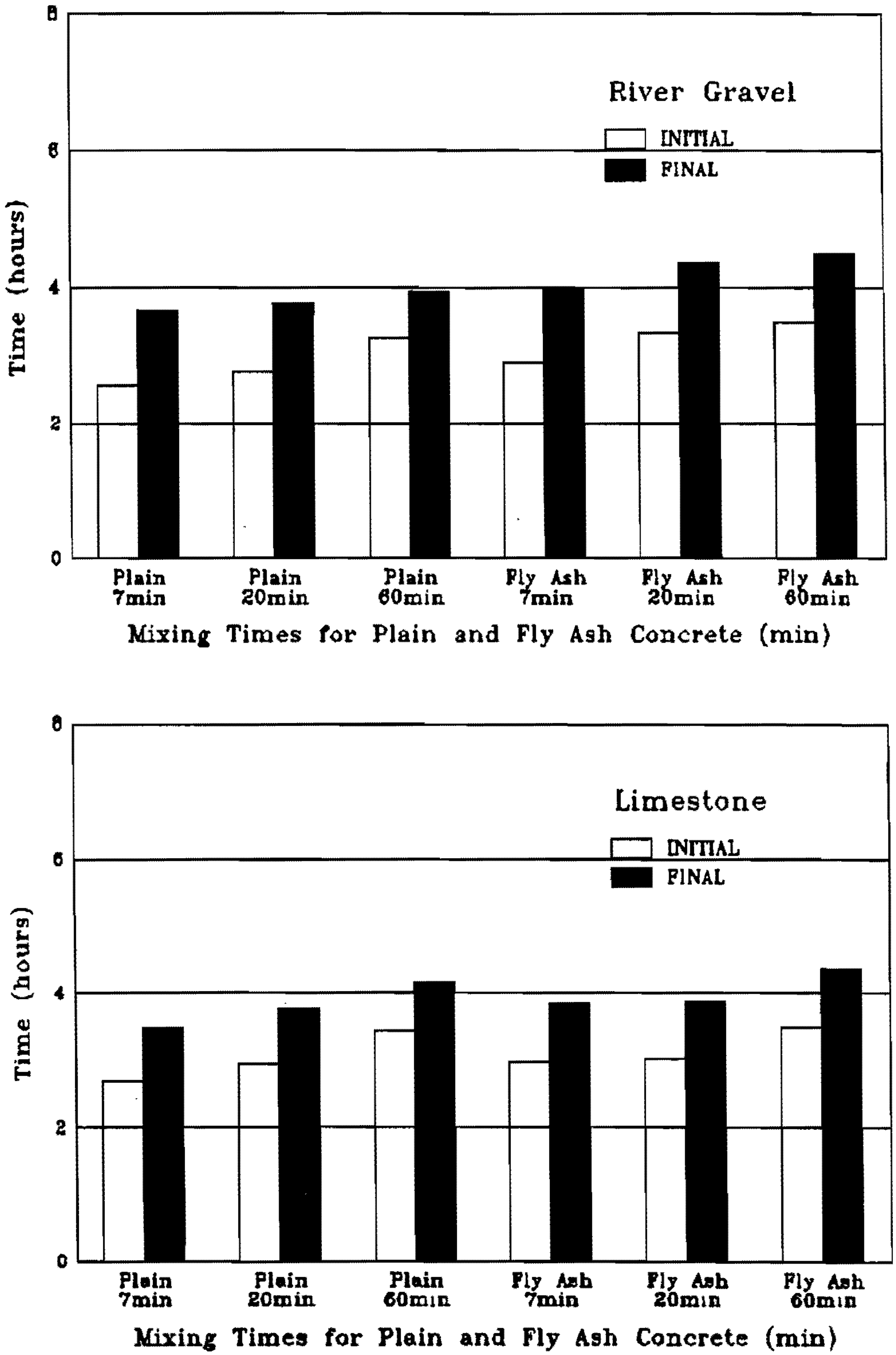


Figure 75. The effect of mixing time and fly ash on the setting time, for 2.0 inch slump

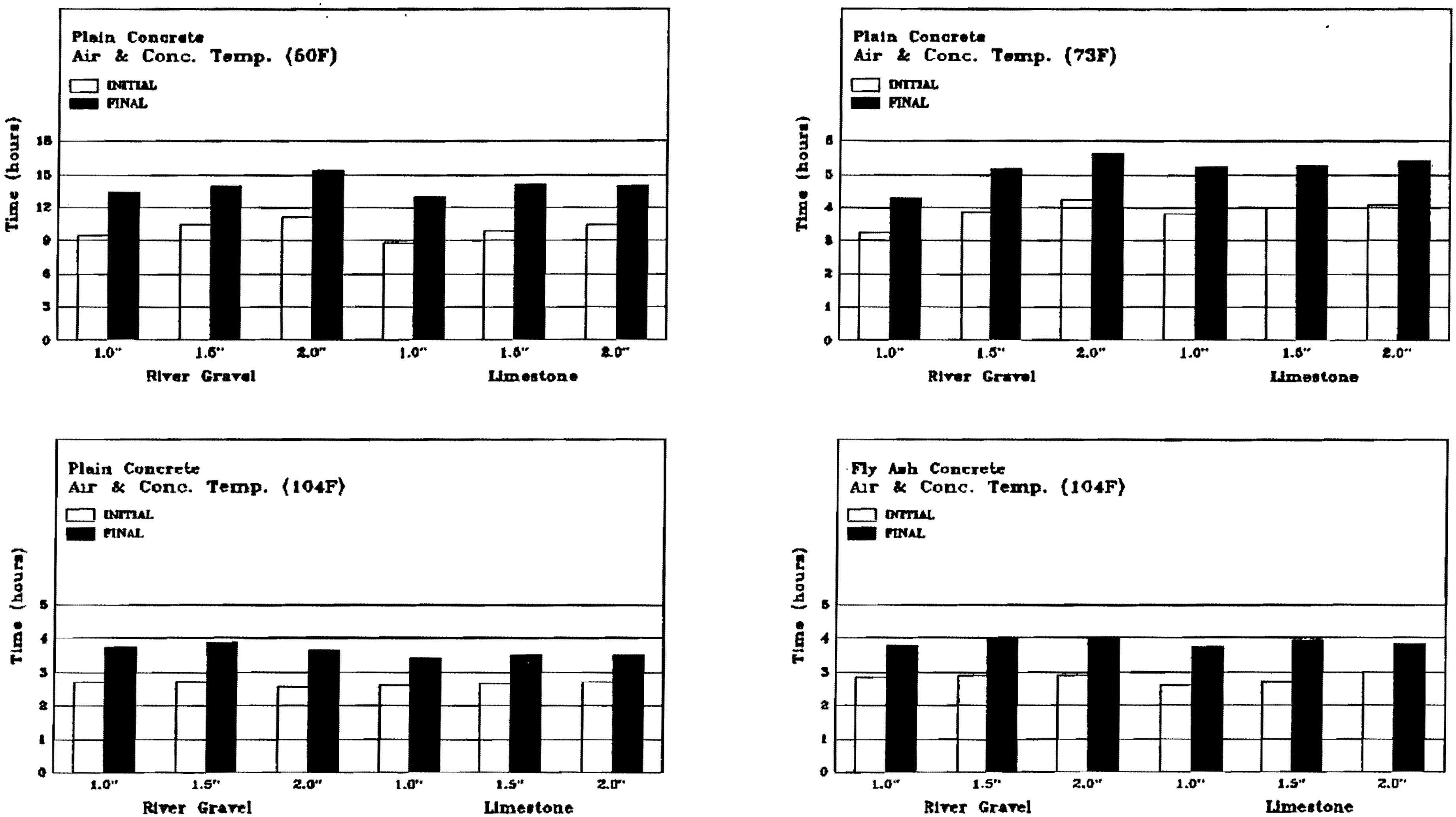


Figure 76. The effect of slump and aggregate type on the setting time for different temperatures

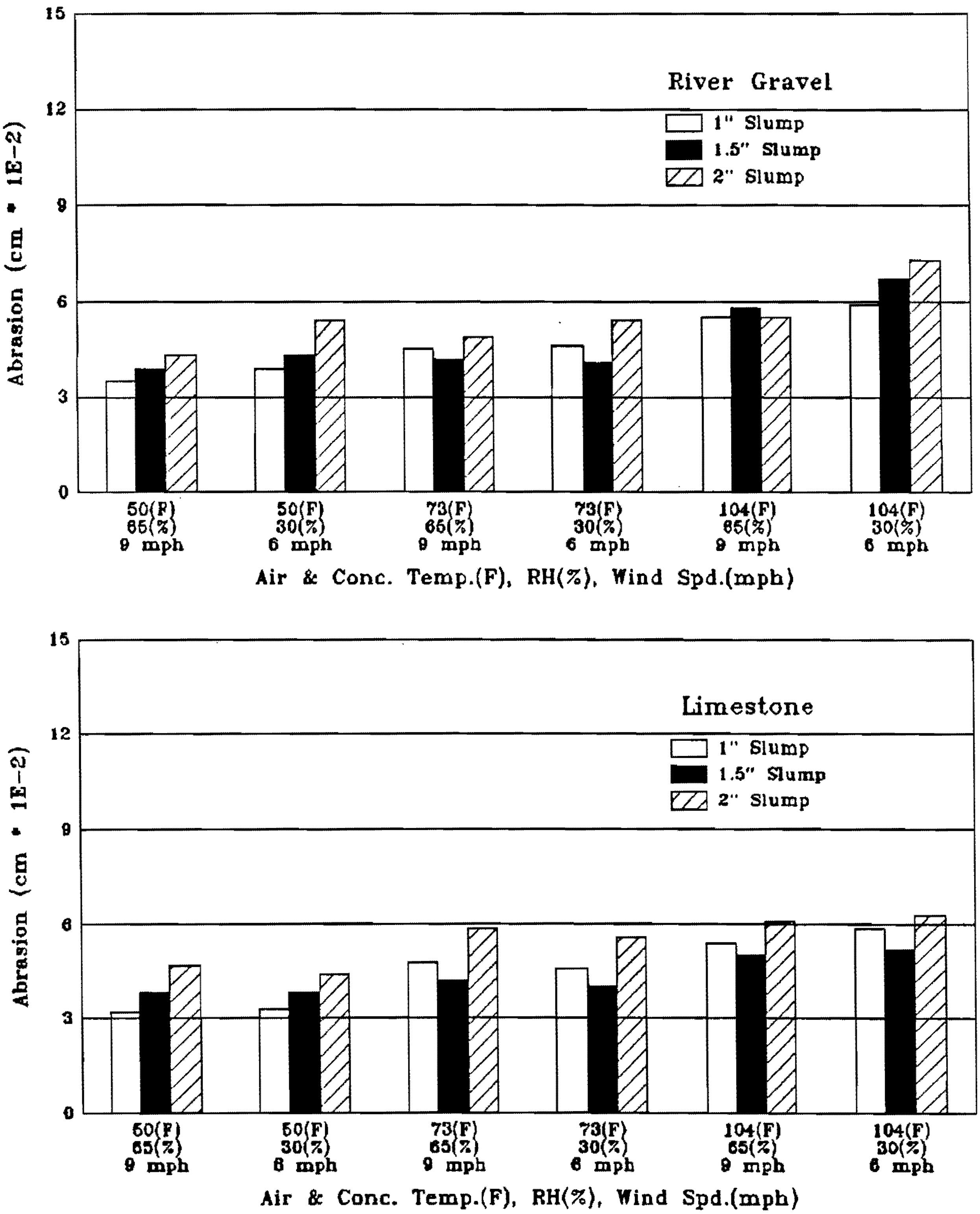


Figure 77. The environmental effects on 90 day abrasion coefficients; a) River gravel b) Limestone

(0.39×10^{-2}inch). Most of the abrasion occurred within the mortar, and embedded aggregates were very resistant to abrasion. The test results varied significantly, and depended on whether the target areas included aggregates or not. The test results were not significantly different for 50°F and 73°F, but greater values were observed at 104°F. The results generally show the expected trend of higher abrasion resistance with a lower slump.

Figure 78 shows the effect of mixing time for plain and fly ash concrete on the abrasion coefficient. The increase of abrasion resistance with an increase in slump was observed for the plain concrete. The effect of slump on abrasion was greater than the effect of mixing time. Fly ash concrete made with river gravel shows significant improvement in abrasion resistance over plain concrete. However, little changes can be observed for specimens made with limestone aggregates. Significantly lower abrasion for limestone concrete was observed than for river gravel concrete. Limestone is weaker than river gravel in strength, but the previously discussed possibility of moisture being supplied from the aggregate pores for longer periods apparently causes the mortar strength of limestone concrete to be greater than the mortar strength for river gravel concrete. This is further evidence that abrasion is not affected by the strength of the aggregate used in the specimen but by the mortar strength. Slight increases of abrasion with increased mixing time were observed for both the plain and fly ash concrete mixtures.

Figure 79 shows the effects of consolidation methods on abrasion. The rodding method gives the highest abrasion for all cases considered in this study. For the vibrating method, the effect of slump on abrasion can be clearly seen for the river gravel mixtures. The increase in abrasion with the increase in slump can be observed. For the rodded specimens, some large honeycombs formed during the batching procedure were observed. The honeycombs affected the test results and increased the abrasion significantly. For the limestone mixtures, the fly ash concrete showed slightly higher abrasion than plain concrete. The reverse was observed for the river gravel mixtures with slumps of 1.5 and 2.0 inches.

Figure 80 shows the test results of using continuous moist curing and different initial material temperature. Continuously moist cured concrete showed significantly lower abrasion than all of the other test conditions. Moist cured concrete specimens were tested in saturated surface dried condition, whereas all the other

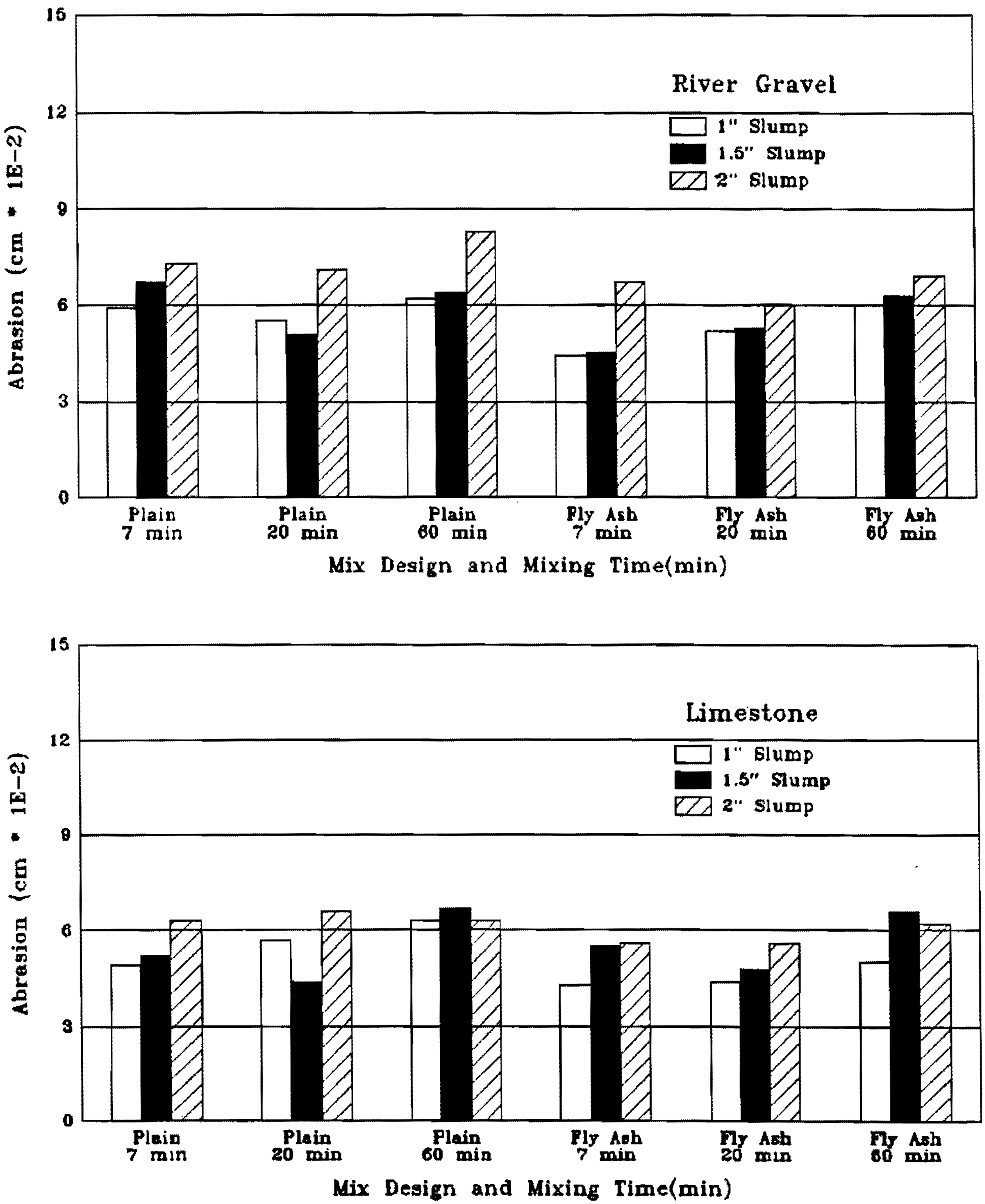


Figure 78. The effects of mixing time and fly ash on 90 day abrasion coefficients; a) River gravel b) Limestone

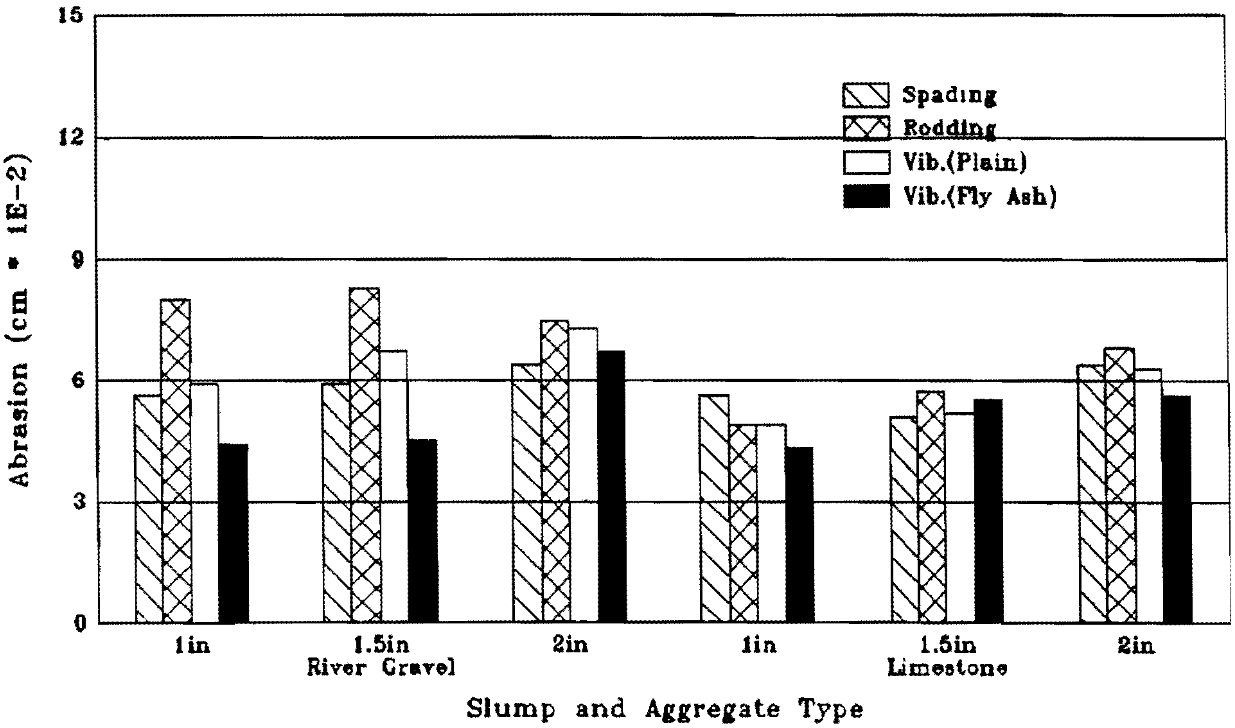


Figure 79. The effects of consolidation methods on 90 day abrasion coefficients; a) River gravel b) Limestone

specimens were tested in air dried condition. As seen from Figure 80, moist cured concrete showed significantly higher abrasion resistance. The moist cured specimens continued hydration which increased strength continuously and improved abrasion resistance significantly. For moist cured concrete, river gravel concrete showed higher abrasion resistance than limestone concrete, which might be caused by the differences in hardness between the two aggregates used. The observation seems to contradict the findings shown in Figure 78, in which limestone concrete shows greater abrasion resistance than river gravel concrete. A possible explanation for this is that when the specimens were moist cured, the porosity of the aggregate did not affect the test results. Instead, the strength of the aggregate affected the test results.

The effect on abrasion of using warmer materials in a cold environment was not significant. However, using cooler materials in a hot environment showed significant improvement of abrasion resistance for both aggregate types. The significant improvement in hot temperature is because of the delay in the fast initial hydration which generally results in a coarse and porous structure of the concrete. On the other hand, no significant improvement was observed for raising material temperatures in cold environments. The benefit of raising initial temperature, which increases the early hydration, was not long lasting and was not detected at later ages. From these test results, it can be concluded that using cool materials in hot environments is a very effective method to improve surface resistance of concrete pavement, but it is not as effective as using warm materials in cold temperature.

Figure 81 shows the correlations between the 28 day and 90 day abrasion coefficients. The figure shows that a fairly good correlation exists between the two test results, depending on the curing temperature and type of aggregates. For the types of environmental conditions investigated, the abrasion resistance for river gravel concrete ranged from 0.5 to 1.2 mm and from 0.35 to 0.75 mm at 28 and 90 days, respectively. For the limestone concrete, the same ranges were from 0.5 to 1.0 mm and from 0.32 to 0.63 mm at 28 and 90 days, respectively. From these results it can be observed that the variability of abrasion resistance decreases between 28 and 90 days and appears to approach a constant value with age, which might depend on the mix design.

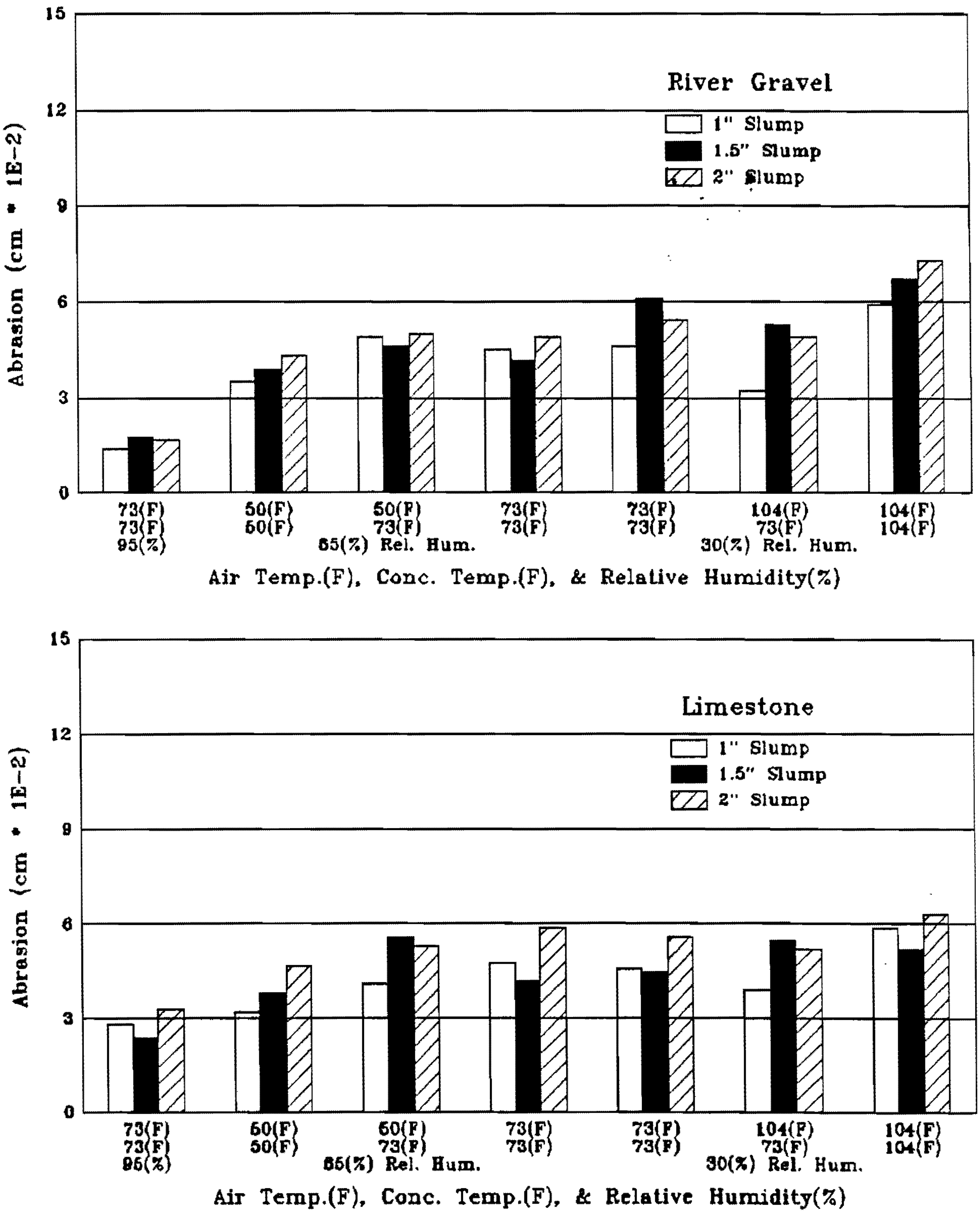


Figure 80. The effects of moist curing and controlling concrete temperature on 90 day abrasion coefficients. For 30%, 65%, and 95% RH, wind speed 9, 6, and 0 mph respectively; a) River gravel b) Limestone

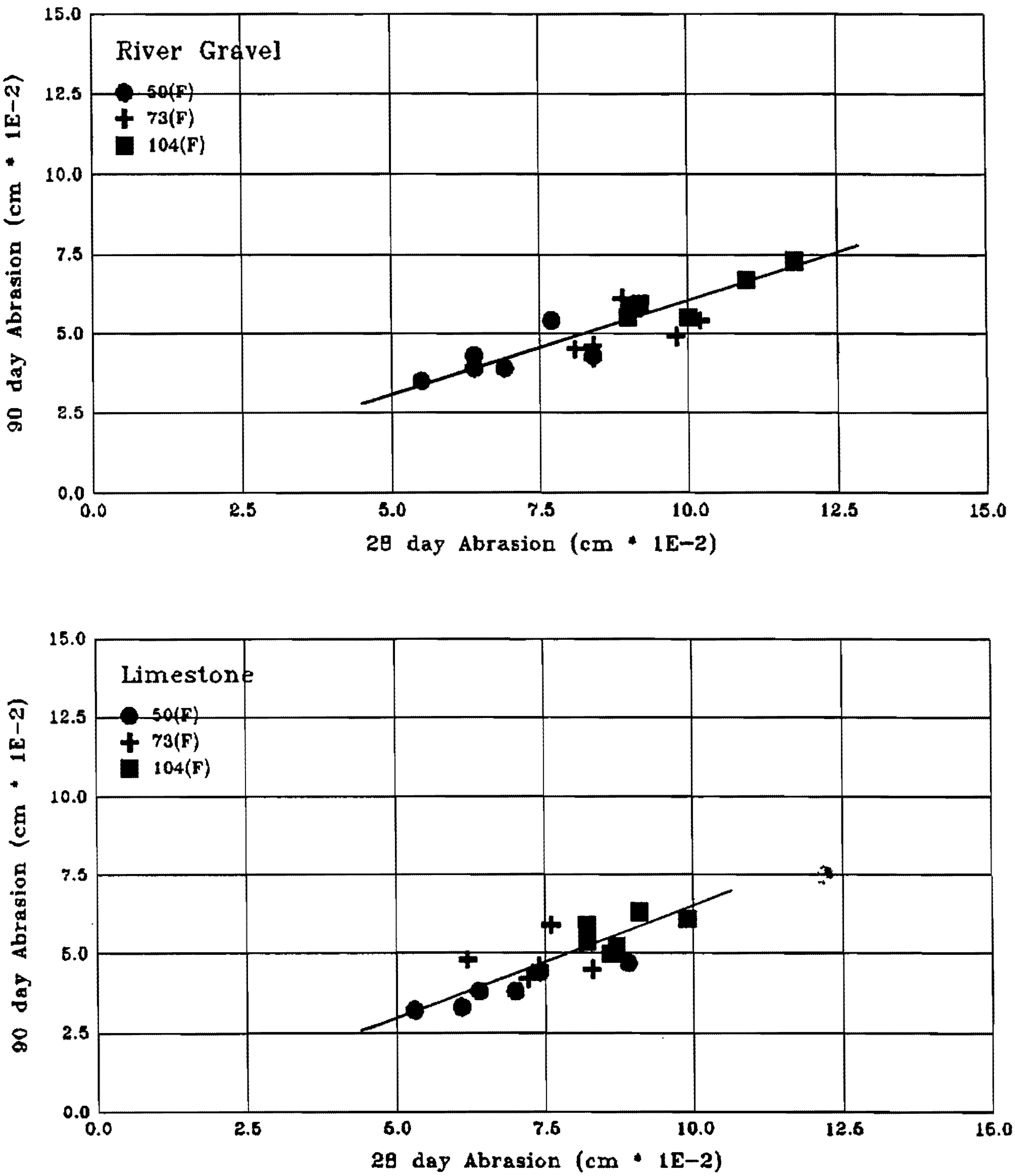


Figure 81. The correlations between the 28 day and 90 day abrasion coefficients; a) River gravel b) Limestone

Moist Cured Condition The effects of mixing time and consolidation method on the abrasion after 90 days are shown in Figure 82. The vibrating method shows the lowest abrasion and the spading method showed the greatest abrasion. As the mixing time increases, a significant increase of abrasion is observed for all three consolidation methods. The abrupt increase for the spaded concrete after 60 minutes mixing might be due to the honeycombs observed in the concrete.

Figure 83 shows the correlations between the 28 and 90 day abrasion. Significantly higher abrasion was observed for early ages. Vibrating and rodding method showed quite good correlations. For the two methods, the 90 day abrasion might be predicted from the 28 day abrasion. The spading method did not show as good a correlation as the other methods. A similar, odd observation was found with the results for the flexural strength (Figure 32). The abnormality most likely is caused by the honeycombing developed during the consolidation. The correlations of vibrating method and rodding method were distinctly different. This fact indicates that the abrasion test is dependent on the consolidation method employed.

4.5.3 Conclusion

The following conclusions are based on the results of the laboratory tests for setting time and abrasion. The conclusions are divided into two sections with reference to the results for setting time and abrasion respectively.

Time of Setting :

1. Temperature is the main parameter influencing the time of setting test. In a low temperature range, time of setting is quite slow, but increases at medium to high temperature.
2. The coarse aggregate type was not found to affect the setting time.
3. The effect of slump on setting time is minor.
4. Controlling the material temperature and slump affect the setting time slightly.
5. A slight increase of setting time is observed as the mixing time is extended.
6. Fly ash replacement does not affect the setting time.

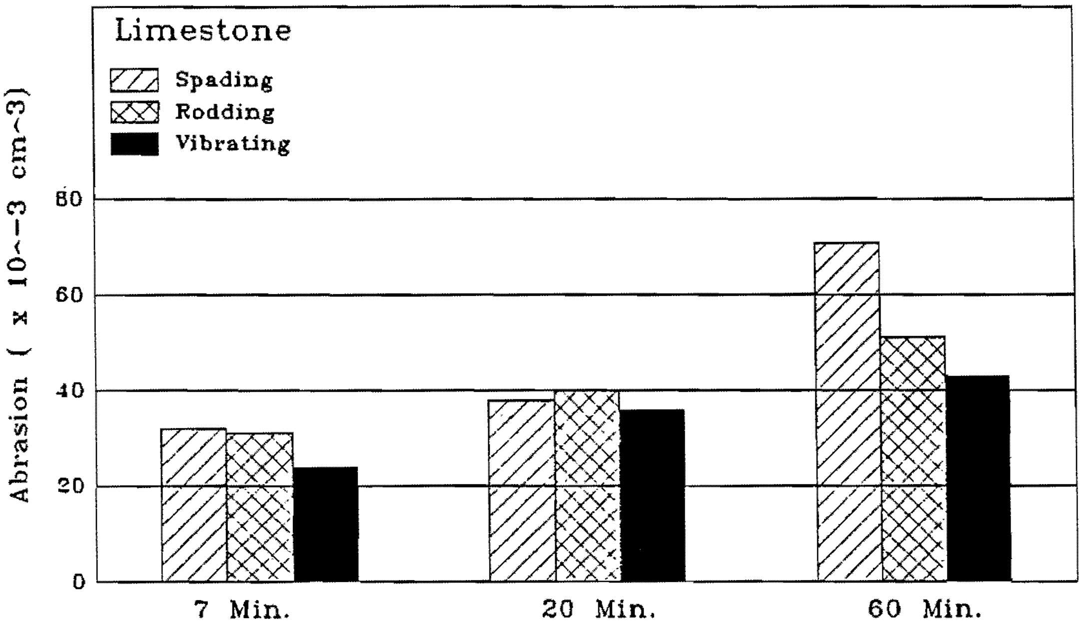


Figure 82. The effect of mixing time and consolidation method on 90 day abrasion coefficients in moist cured condition for 1.5 inch slump concrete

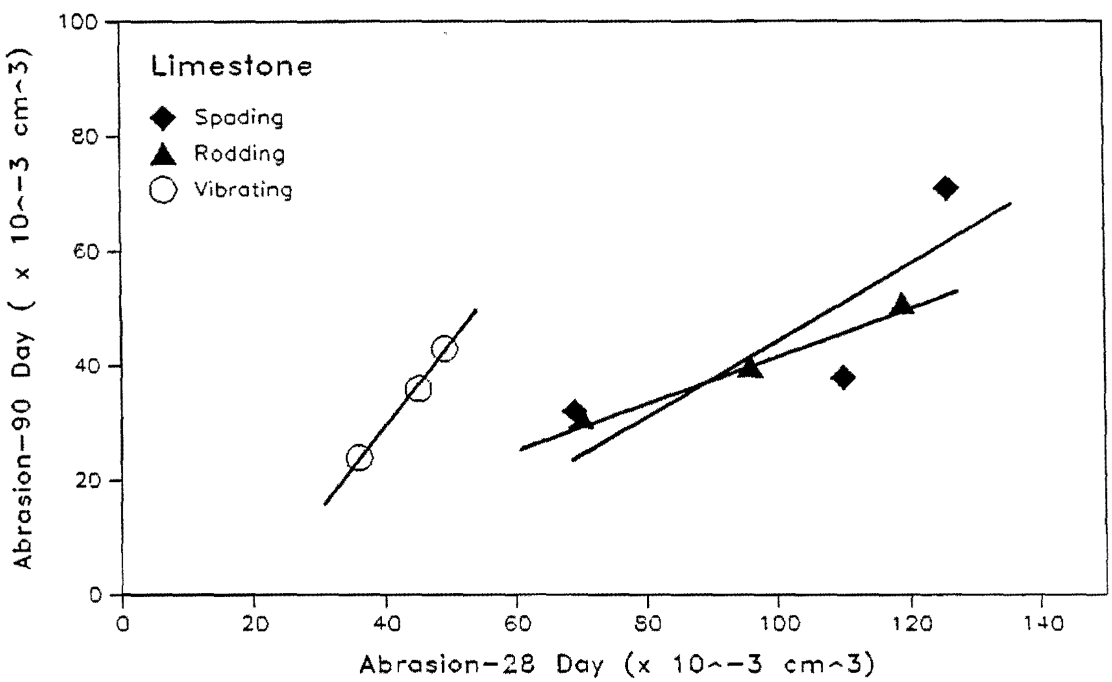


Figure 83. The correlations between the 28 day and 90 day abrasion coefficients for moist cured concrete

Abrasion :

1. Most of the abrasion occurred within the mortar, and almost no abrasion occurred on the surface of aggregate. As a result, quite large variations in abrasion resistance were observed during the study.
2. The abrasion resistance decreases as the evaporation rate increases. The effect of environmental conditions on the abrasion resistance is caused by the effect of moisture retention within the concrete and results in an improvement in the mortar quality.
3. Replacement of fly ash improves the surface properties slightly.
4. The abrasion resistance seems to decrease as the mixing time extends. However, the effect of mixing time on abrasion resistance is not as significant as the effect of slump or fly ash replacement.
5. Generally, the spading method of consolidation gives almost the same abrasion resistance as the vibrating method.
6. The rodding method of consolidation showed the lowest abrasion resistance due to the presence of honeycombs. Based on Item 5 above, the rodding is not expected to influence the abrasion resistance to a great extent.
7. Moist cured specimens have the best surface resistance. They had only half the abrasion of the other specimens cured in the dry condition.
8. Controlling the material temperature in a hot environmental condition has a greater effect on the abrasion resistance than controlling the temperature in a cold environment.
9. The variability of abrasion resistance decreases with age.

4.6 Summary

In Sections 4.1 through 4.5, the results of the laboratory portion of this study were presented and discussed. The data showed how the climatic parameters, air temperature, wind speed, and relative humidity, can be combined into a single variable that easily can be measured in the field during the construction phase of a CRCP project. The evaporation rate is measured with an Evaporometer that was developed in 1974 by the Materials and Tests Division of the Texas Department of Highways and Public Transportation. In this study, the evaporation rate was measured in the selected environmental conditions and a correlation established between the evaporation rate from the PCA Chart (see page 6) and the rate measured with the Evaporometer. A perfect linear relationship exists between these two parameters, indicating the usefulness of the Evaporometer in measuring the effect of the environment on the evaporation of water from concrete in the field during construction. To make the extensive results obtained in this study more useful to design and construction engineers, several figures and procedures have been developed. Figures 84 through 86 show the relationships between several important concrete properties and the evaporation rate as measured with the Evaporometer. The three figures show, respectively, the flexural strength, half-time shrinkage, and ultimate shrinkage plotted against the evaporation rate. The strength, half-time shrinkage, and ultimate shrinkage have been normalized with respect to the values obtained in a reference environment. For strength, the reference environment is the continuously moist cured environment. For shrinkage, the 73°F, 65% relative humidity, and 9 mph wind speed environment is the reference. The rate of evaporation in this environment is very close to that in the ASTM standard environment of 73°F, 50% relative humidity, and no wind. In Figures 87 and 88, normalized flexural strength and setting time are plotted as a function of the delay in placement (the mixing time) and the air temperature, respectively. Note that the results in Figures 87 and 88 apply to the most severe environmental condition with an Evaporometer reading of 0.34 lb/sq.ft./hr. In general, the effect of the rate of evaporation on the setting times decreases as the evaporation rate decreases.

To provide some typical data that can be used in the design phase of CRC pavements, Tables 9 and 10 give information on the reference values used to develop

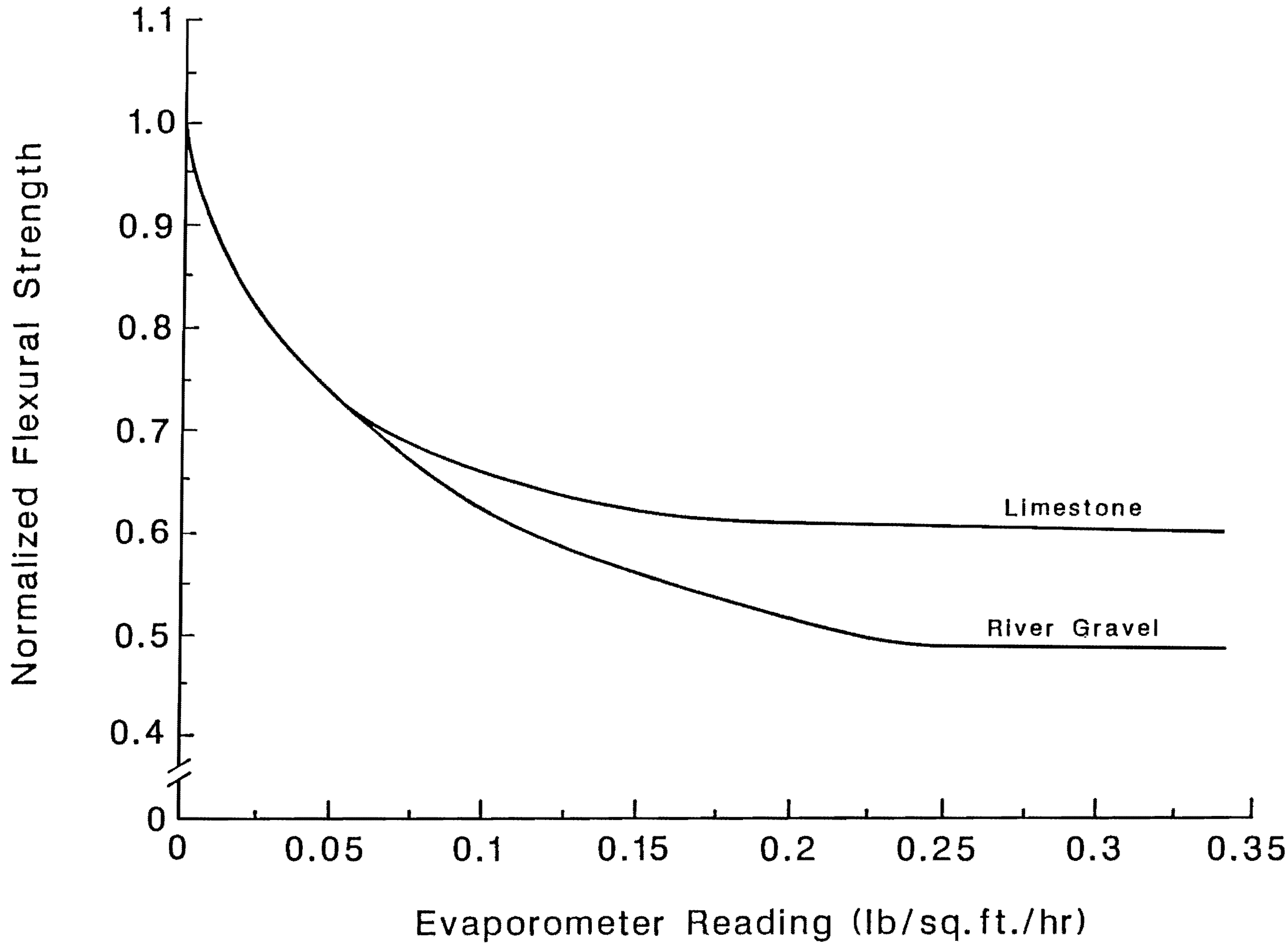


Figure 84. Normalized flexural strength versus Evaporometer reading for limestone and river gravel concrete. The reference environmental condition is 73°F, 95% RH, and no wind, and the results represent the average for 1 to 2 inch slump concrete.

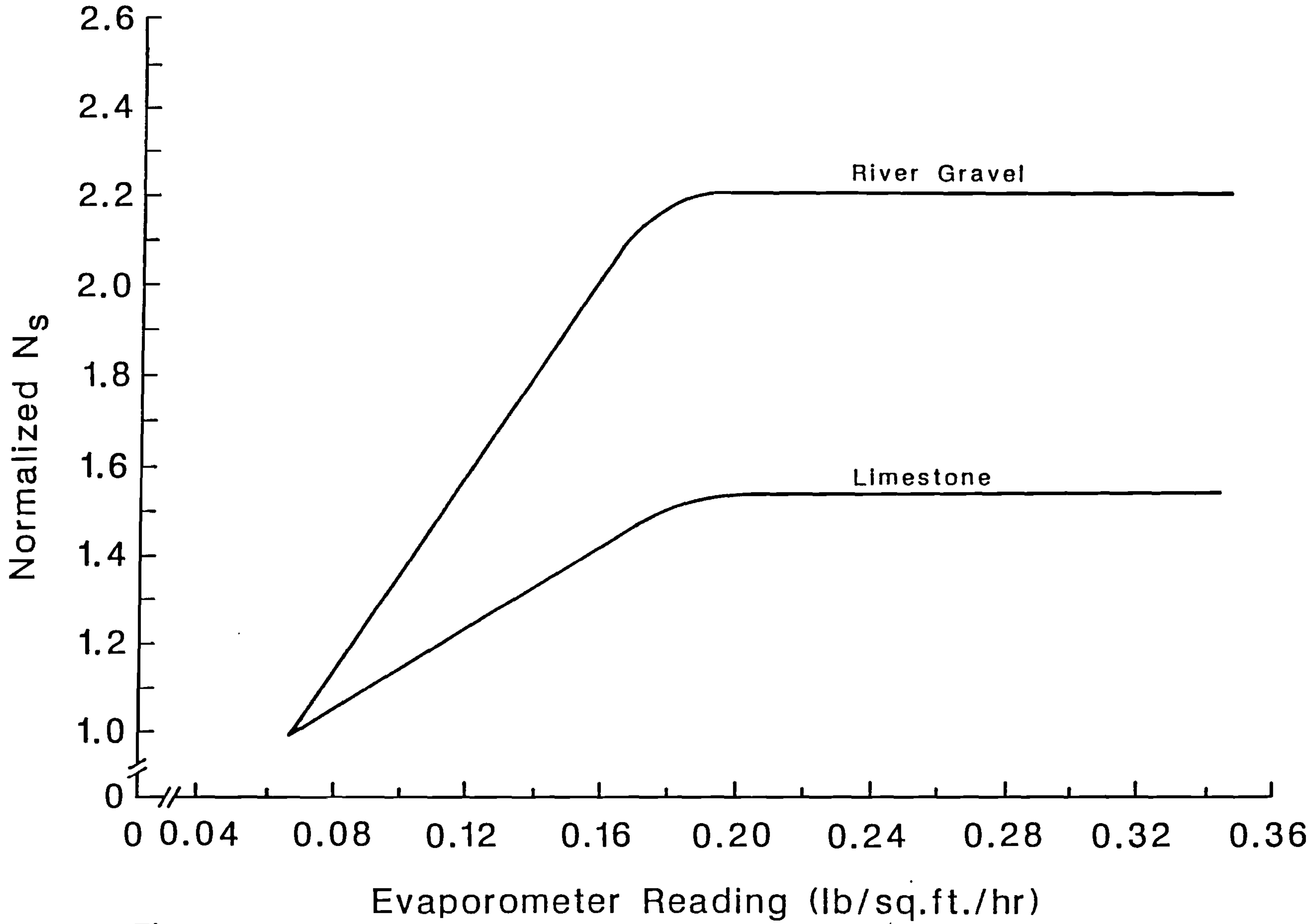


Figure 85. Normalized half time shrinkage, N_s, versus Evaporometer reading for limestone and river gravel concrete. The results represent the average for 1 to 2 inch slump concrete. The reference environmental condition is 50°F, 65% RH, and 9 mph wind which has the same evaporation rate as the ASTM Standard condition of 73°F, 50% RH, and no wind, according to the PCA Chart (2).

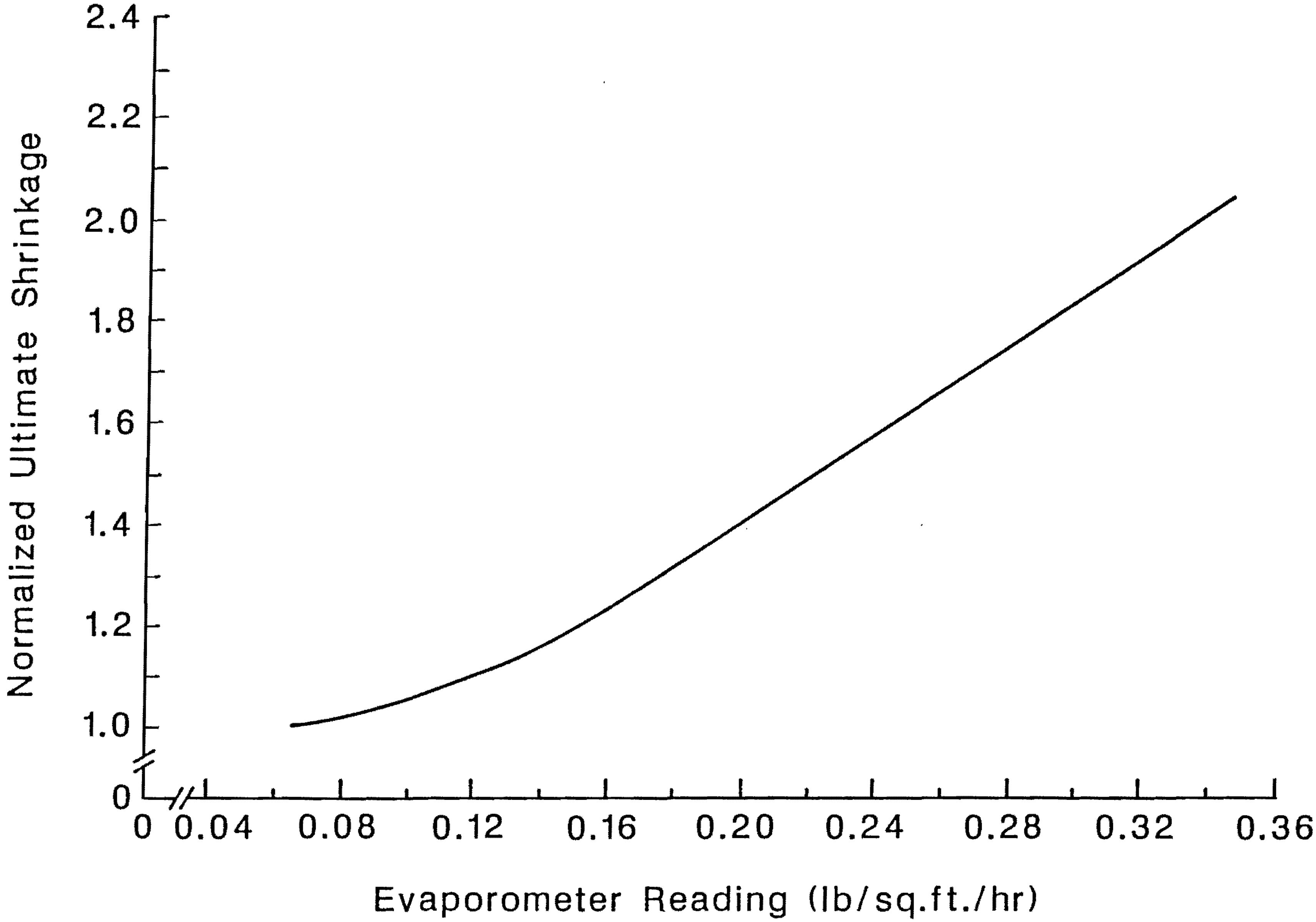


Figure 86. Normalized ultimate shrinkage, ϵ_s^∞, versus Evaporometer reading for limestone and river gravel concrete. The results represent the average for 1 to 2 inch slump concrete. The reference environmental condition is 50°F, 65% RH, and 9 mph wind which has the same evaporation rate as the ASTM Standard condition of 73°F, 50% RH, and no wind, according to the PCA Chart (2).

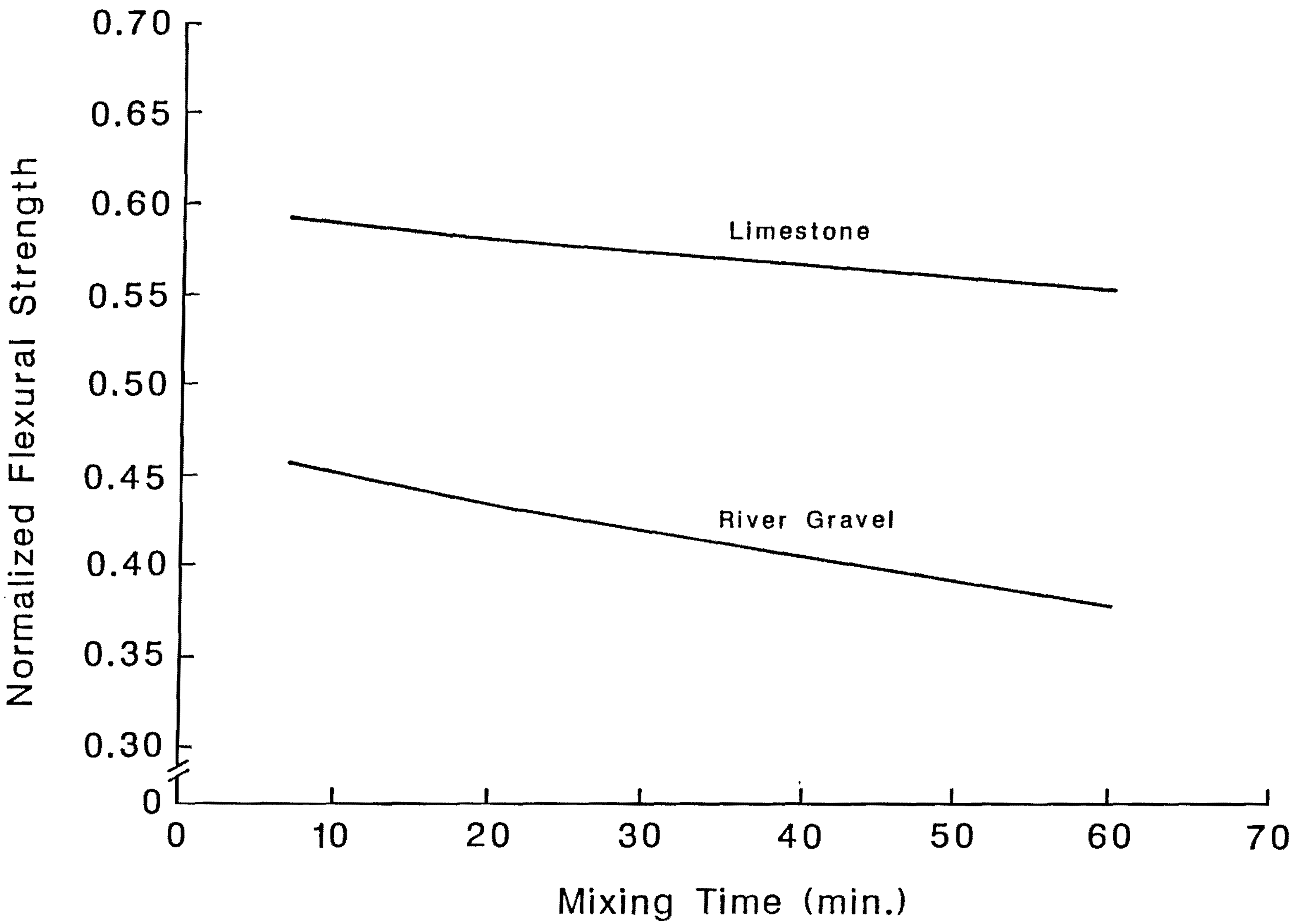


Figure 87. Normalized flexural strength versus mixing time for limestone and river gravel concrete exposed to 104°F, 30% RH, and 6 mph wind. The results represent the average for 1 to 2 inch slump concrete.

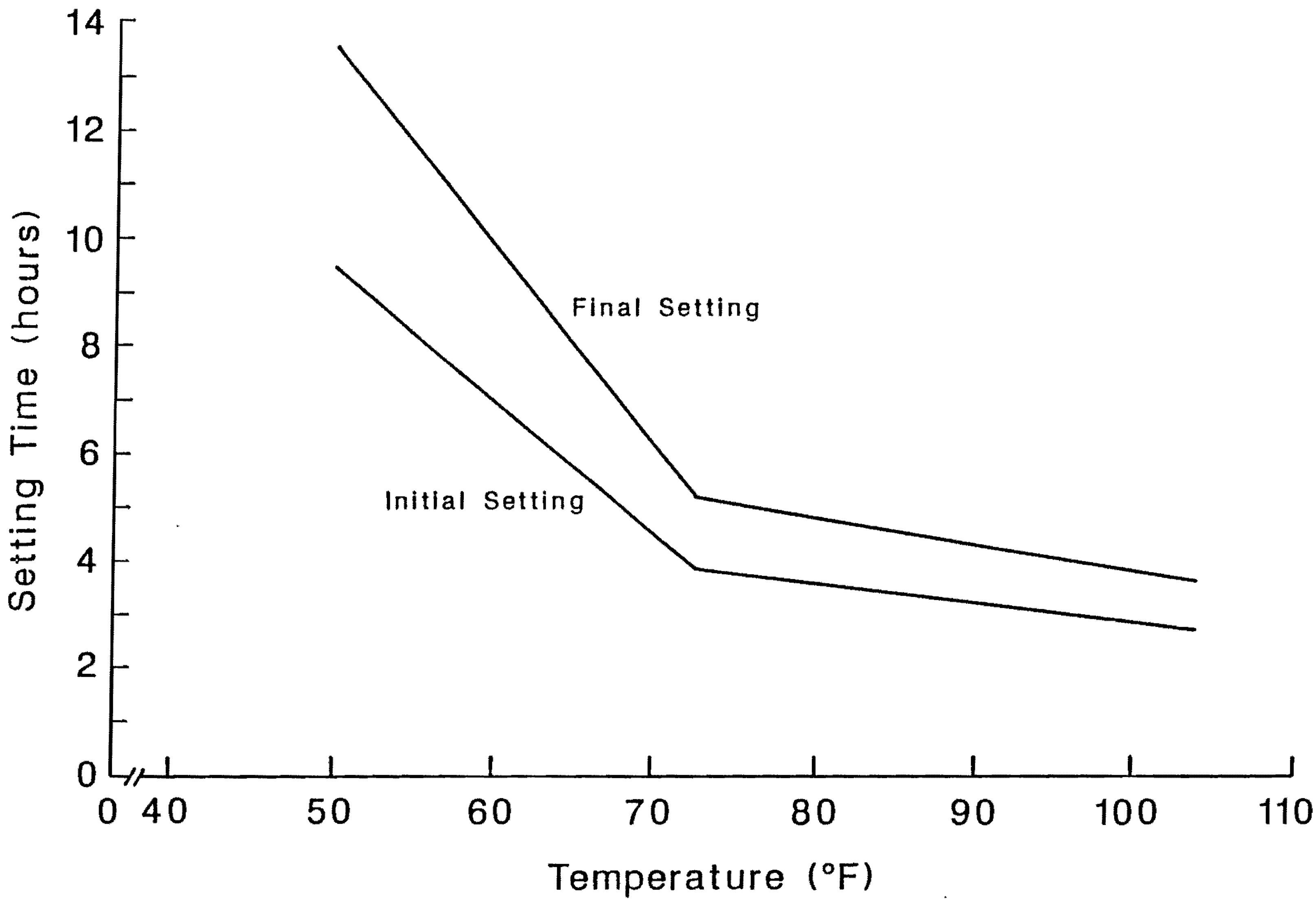


Figure 88. Initial and final setting time versus air temperature for sealed limestone and river gravel concrete. The results represent the average for limestone and river gravel concrete with 1 to 2 inch slump.

Table 9. Values of shrinkage half time, N_s, and ultimate shrinkage, ϵ_s^∞, for the reference condition of 50°F, 65% RH, and 9 mph wind*.

Shrinkage Constants	River Gravel			Limestone		
	1" Slump	1.5" Slump	2" Slump	1" Slump	1.5" Slump	2" Slump
N_s(days)	5.00	4.02	5.00	4.00	4.00	4.00
$\epsilon_s^\infty(x10^{-6}in/in)$	225	249	275	385	395	415

* The selected reference condition has the same evaporation rate as the ASTM standard condition of 73°F, 50% RH, and no wind, according to the PCA Chart (2)

Table 10. Values of 7 day flexural strength for the standard moist curing condition of 73°F and 95% RH.

Flexural Strength	River Gravel			Limestone		
	1" Slump	1.5" Slump	2" Slump	1" Slump	1.5" Slump	2" Slump
M_R(psi)	750	670	620	720	680	650

Figures 84 through 87. Table 9 includes the half-time shrinkage, N_s, and the ultimate shrinkage, ϵ_s^∞, and Table 10 shows the results for the 7 day flexural strength.

Procedure To evaluate the effect of a given environmental condition on the strength and shrinkage of a concrete, use Figures 84-86. The evaporation rate measured with the Evaporometer is entered on the horizontal axis and the normalized strength, half-time shrinkage, or ultimate shrinkage is read off the vertical axis. Using this value for the normalized strength and the aggregate type, the predicted strength, half-time shrinkage, or ultimate shrinkage is found by multiplying it by the appropriate values in Tables 9 and 10. Since the severe environmental condition only exists during daytime hours, the values from Tables 9 and 10 can be used to find a corrected value using the time proportions for each environment and adding the results together.

Example Assume that the evaporation rate measured by the Evaporometer is equal to 0.30 lb/sq.ft./hr and that the concrete contains limestone aggregates as the aggregate material and has a slump of 1.5 inch. Assume further that the period of analysis is 7 days and that the evaporation rate of 0.30 lb/sq.ft./hr represents the average environmental condition during the 7 days. Using Figures 84 through 86 and Tables 9 and 10, the following values are obtained:

$M_R = 0.62 \text{ x } 680 = 422$ psi

$N_s = 1.55 \text{ x } 4.00 = 6.20$

$\epsilon_s^\infty = 1.85 \text{ x } 395 = 731\text{x}10^{-6}$ inch/inch

Since the environmental condition is only existing 50% of the time, the corrected values become

$M_R = 422 \text{ x } 0.50 + 680 \text{ x } 0.50 = 550$ psi

$N_s = 6.20 \text{ x } 0.50 + 4.00 \text{ x } 0.50 = 5.10$

$\epsilon_s^\infty = 731 \text{ x } 0.50 + 395 \text{ x } 0.50 = 563\text{x}10^{-6}$ inch/inch

The values determined above can now be used as input to the design programs. To find the shrinkage value at any time, t, of the curing process, the following equation by Hansen and Mattock (31) is used:

$$\epsilon_s = \frac{\epsilon_s^{\infty} \times t}{N_s + t}$$

where ϵ_s = shrinkage strain

ϵ_s^{∞} = ultimate shrinkage strain

t = time in days since measurements began

N_s = the time in days to reach half of ϵ_s^{∞}.

V. CONCLUSIONS AND RECOMMENDATIONS

5.1 Conclusions

The following presents a summary of the major conclusions based on an analysis of the literature review and laboratory investigation conducted in this study.

1. A procedure has been developed that can quantify the effect of the environmental condition existing during construction of a CRC pavement, on the strength and shrinkage of the concrete.
2. The environmental parameters, air temperature, wind speed, and relative humidity, can be combined into a single parameter: the evaporation rate.
3. The evaporation rate can be easily measured during construction of a CRC pavement using the Evaporometer developed by the Materials and Tests Division of the Texas Department of Highways and Public Transportation.

5.2 Recommendations

Based on the results of this laboratory investigation and analysis, the following recommendations are made. These recommendations should help to assure that well performing CRC pavements are constructed.

1. The Evaporometer developed by the Materials and Tests Division of the Texas Department of Highways and Public Transportation should be used to measure the evaporation rate in the field during the construction of CRC pavements. This value for the evaporation rate can then be used to assess the influence of the particular environment on the physical properties of the concrete (see Items 2 and 3 below).
2. Whenever the concrete is exposed to a severe environmental condition with an evaporation rate of more than 0.29 lb/sq.ft./hr as measured by the Evaporometer, the concrete should be protected from excessive evaporation by covering it with wet burlap or other similar means. The necessary period of covering should be the smaller of 7 days and the duration of the severe climatic condition.
3. Whenever the use of wet curing is not practical, the design flexural strength, the half-time shrinkage, N_s, and the ultimate shrinkage, ϵ_s^∞, should be adjusted

according to the environmental conditions in order to consider the difference between continuously moist cured concrete and concrete cured using a curing compound. The design curves presented in Chapter 4, Section 4.6, provide the means for such an adjustment.

4. Whenever the concrete is exposed to a severe environmental condition with an evaporation rate of more than 0.29 lb/sq.ft./hr as measured by the Evaporometer, the effect of delays in placement on the flexural strength can be assessed by using Figure 87 and Table 10 in Chapter 4, Section 4.6.
5. The effect of the air temperature on initial and final setting time can be determined from Figure 88 in Chapter 4, Section 4.6.

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APPENDIX A

AGGREGATE TEST RESULTS

Table A1. Coarse aggregate information.

Item	River Gravel	Limestone
Rodded OD Unit Weight	101.1 pcf	96.3 pcf
Rodded SSD Unit Weight	101.7 pcf	98.8 pcf
Bulk Specific Gravity	2.59	2.53
Bulk Specific Gravity(SSD)	2.59	2.60
Apparant Specific Gravity	2.61	2.71
Absorption Capacity	0.61 %	2.70 %

Table A2. Sieve analysis of coarse aggregate.

Sieve Number	River Gravel				Limestone			
	Before Sieving		After Sieving		Before Sieving		After Sieving	
	Retain (%)	Cum Ret (%)	Retain (%)	Cum Ret (%)	Retain (%)	Cum Ret (%)	Retain (%)	Cum Ret (%)
1.5 in	2	2	-	-	0	0	-	-
1 in	-	-	0	0	-	-	0	0
3/4 in	40	42	-	-	39	39	-	-
1/2 in	-	-	66	66	-	-	66	66
3/8 in	40	82	-	-	47	86	-	-
#4	14	96	28	94	11	97	30	96
#8	-	-	1	95	-	-	0	96
Pan	4	100	5	100	3	100	4	100
Sum	100	222*	100	259*	100	222*	100	262*
Fineness Modulus	FM =	7.22	FM =	7.26	FM =	7.22	FM =	7.26

* Pan is not included

Table A3. Fine aggregate information.

Item	Value
Rodded OD Unit Weight	114.3 pcf
Rodded SSD Unit Weight	115.2 pcf
Bulk Specific Gravity	2.61
Bulk Specific Gravity(SSD)	2.62
Apparant Specific Gravity	2.67
Absorption Capacity	0.78 %

Table A4. Sieve analysis of fine aggregate.

Sieve Size	Percent Retained	Cumulative Percent
#4	1	1
#8	15	15
#16	18	34
#30	17	51
#50	36	87
#100	12	99
Pan	1	100
Sum	100	288
Fineness Modulus	FM =	2.88

APPENDIX B

CHEMICAL AND PHYSICAL PROPERTIES OF CEMENT

Table B1. Chemical analysis of cement.

Chemical Component		Weight Percent
Calcium oxide	(CaO)	64.17
Silicone dioxide	(SiO_2)	20.47
Aluminum oxide	(Al_2O_3)	5.31
Ferric oxide	(Fe_2O_3)	3.02
Magnesium oxide	(MgO)	0.98
Sulfur trioxide	(SO_3)	2.82
Alkalies	Na_2O	0.29
	K_2O	0.61
Others		0.70
Loss		1.53
Total		96.50

Compounds		Weight Percent
Tricalcium Sillicate	C_3S	56.75
Dicalcium Silicate	C_2S	15.95
Tricalcium Aluminate	C_3A	9.82
Tetracalcium Alumino Ferrite	C_4AF	9.28
Gypsum	$CaSO_4$	4.70
Total		99.00

Table B2. Physical properties of cement.

Physical Test	Results
Surface Area: Blaine	324 m^2/kg
Surface Area: Wagner Turbidimeter	1941 cm^2/g
-325	92.4 %

Type I Cement
Finish mill # 1

APPENDIX C

Table C1. SSD water content and adjustment for trial batch (lb/cy).

Temperature		River Gravel			Limestone		
Air	Concrete	1" Slump	1.5" Slump	2" Slump	1" Slump	1.5" Slump	2" Slump
50°F	50°F	-5.4	202	+5.4	-3.6	205	+3.6
	73°F	-6.0	210	+6.0	-4.2	217	+4.2
73°F	73°F	-6.1	214	+6.1	-4.7	218	+4.7
104°F	73°F	-6.9	221	+6.9	-5.8	234	+5.8
	104°F	-8.5	244	+8.5	-6.3	245	+6.3
Mix Design	Mixing Time						
Plain	7 min	-8.5	244	+8.5	-6.3	245	+6.3
	20 min	-11.9	251	+11.9	-10.1	247	+10.1
	60 min	-10.5	293	+10.5	-11.6	298	+11.6
Fly Ash	7 min	-10.6	228	+10.6	-12.6	232	+12.6
	20 min	-12.7	237	+12.7	-15.3	238	+15.3
	60 min	-14.4	289	+14.4	-16.5	297	+16.5

APPENDIX D

TEST RESULT SUMMARY

Table D1a. Compressive strength and pullout strength test results*

Given conditions: 7 min. mixing, plain concrete, vibrating

Air & Conc. Temp (°F)	RH(%) & Wind (mph)	Test Day (day)	River Gravel						Limestone					
			1" Slump		1.5" Slump		2" Slump		1" Slump		1.5" Slump		2" Slump	
			Comp. (psi)	Pullout (lb)	Comp. (psi)	Pullout (lb)	Comp. (psi)	Pullout (lb)	Comp. (psi)	Pullout (lb)	Comp. (psi)	Pullout (lb)	Comp. (psi)	Pullout (lb)
Air 50°F	65% 9 mph	3rd	2357	1450	2057	1280	1899	1120	2439	1390	2338	1260	1904	1080
		7th	3176	1950	3029	1580	2447	1370	3148	1660	2967	1470	2617	1300
		28th	4237	2140	3397	1930	3153	1760	4413	2110	4128	1880	3522	1760
		90th	4600	2430	3859	2240	3638	2050	4790	2360	4438	2070	4164	2140
Conc. 50°F	30% 6 mph	3rd	2493	1470	2332	1320	2149	1260	2643	1100	2515	1050	2107	850
		7th	3335	1660	3054	1490	2500	1400	3400	1590	3261	1370	2855	1280
		28th	4148	2030	3281	1810	2967	1700	4395	2110	4156	1840	3462	1680
		90th	4446	2330	3816	2300	3468	2000	4632	2350	4209	2240	3977	2050
Air 50°F Conc. 73°F	65% 9 mph	3rd	2427	1490	2320	1390	2244	1260	2432	1230	2313	1100	2233	1240
		7th	3240	1680	3154	1580	3068	1530	3584	1780	3412	1590	3241	1370
		28th	4443	2350	4167	1980	3812	1880	4977	2250	4739	2030	4595	2060
		90th	5137	2590	4459	2430	4387	2100	5328	2580	5226	2610	5142	2370
Air 73°F Conc. 73°F	95% 0 mph	3rd	3135	2130	2870	1570	2676	1760	3740	1740	3369	1890	2937	1560
		7th	3869	2130	3693	2280	3440	1980	4607	2330	3921	2140	3670	1970
		28th	4784	2790	4575	2510	4306	2030	5307	2690	4663	2410	4398	2140
		90th	5441	2870	5243	2610	5090	2360	5861	2960	5356	2710	4984	2360
	65% 9mph	3rd	2954	1580	2405	1360	2392	1390	3042	1530	2875	1360	2537	1250
		7th	3394	2060	3089	1830	2670	1530	3677	1930	3452	1750	2993	1570
		28th	3987	2170	3260	1870	3020	1610	4033	2090	3826	1830	3644	1760
		90th	4266	2720	3761	2080	3580	1900	4478	2240	4116	1950	3960	1900
	30% 6 mph	3rd	3046	1910	2551	1610	2495	1720	3163	1560	3241	1640	2831	1500
		7th	3515	2090	3152	1970	2800	1880	3662	1860	3401	1730	3271	1620
		28th	3981	2320	3304	2210	3138	2130	4038	1920	3900	1810	3823	1790
		90th	4218	2390	3757	2270	3554	2210	4380	2200	4103	1890	4012	1860

* Average of 3 tests except for 90 day pullout test which is an average of 2 tests (see Table 6, p. 38)

Table D1b. Compressive strength and pullout strength test results (continue)*

Given conditions: 7 min. mixing, plain concrete

Air & Conc. Temp (°F)	RH(%) & Wind (mph)	Test Day (day)	River Gravel						Limestone					
			1" Slump		1.5" Slump		2" Slump		1" Slump		1.5" Slump		2" Slump	
			Comp. (psi)	Pullout (lb)	Comp. (psi)	Pullout (lb)	Comp. (psi)	Pullout (lb)	Comp. (psi)	Pullout (lb)	Comp. (psi)	Pullout (lb)	Comp. (psi)	Pullout (lb)
Air	30%	3rd	2840	1690	2736	1510	2590	1400	3281	1360	3282	1349	3092	1190
104°F	6 mph	7th	3318	1890	3139	1760	3003	1710	4176	1910	3711	1810	3532	1510
Conc.	Vibra-	28th	3647	2210	3503	2030	3404	1890	4391	2110	4072	2050	4069	2080
73°F	ting	90th	3880	2360	3692	2240	3588	2140	4418	2160	4439	2260	4474	2240
	65%	3rd	2949	1600	2726	1360	2336	1290	3323	1370	3377	1220	3168	1150
	9 mph	7th	3314	1810	3167	1650	3021	1530	3620	1640	3708	1640	3598	1590
Air	Vibra-	28th	3587	2020	3440	1780	3112	1620	3883	1850	3911	1860	3813	1800
104°F	ting	90th	3847	2160	3636	1900	3526	1940	4246	2060	4097	1970	3906	1930
Conc.	30%	3rd	3001	1660	2878	1510	2543	1470	3361	1560	3376	1550	3316	1560
104°F	9 mph	7th	3137	1820	3054	1710	2971	1620	3786	1870	3749	1850	3636	1790
	Vibra-	28th	3505	2020	3455	2070	3342	2010	3919	2030	3960	1950	3780	1850
	ting	90th	3750	2260	3602	2130	3573	2240	4241	2160	4037	2090	3902	1980
	7	3rd	3001	1780	2726	1370	2444	1290	3051	1290	3058	1240	2857	1150
Air	min.	7th	3132	1890	2947	1500	2622	1420	3407	1630	3324	1550	3054	1380
104°F	mixing	28th	3315	2000	3268	1630	2896	1520	3753	1800	3637	1710	3352	1400
Conc.		90th	3466	2140	3644	1940	3083	1720	3934	2010	3814	1920	3562	1600
104°F	20	3rd	2918	1640	2531	1230	2322	1130	2990	1180	2888	1060	2765	910
RH	min.	7th	3074	1780	2733	1300	2707	1300	3245	1350	3123	1310	2963	1120
25%	mixing	28th	3218	1890	3021	1440	2847	1420	3643	1650	3572	1620	3242	1360
Wind		90th	3342	2020	3456	1730	2975	1500	3870	1920	3743	1810	3430	1530
6 mph	60	3rd	2798	1400	2361	930	2210	990	2839	1000	2735	940	2654	920
Spa-	min.	7th	2918	1530	2597	1090	2600	1170	3118	1190	2923	1100	2869	1070
ding	mixing	28th	3128	1660	3026	1260	2742	1290	3499	1660	3398	1480	3207	1450
		90th	3244	1640	3217	1610	2864	1440	3766	1850	3551	1580	3298	1560

* Average of 3 tests except for 90 day pullout test which is an average of 2 tests (see Table 6, p. 38)

Table D1c. compressive strength and pullout strength test results (continue)*

Given conditions: Air & concrete temperatures = 104°F, relative humidity = 30%, wind speed = 6 mph

Mix Design	Mixing Time (min.)	Test Day (day)	River Gravel 1" Slump Comp. (psi)	River Gravel 1" Slump Pullout (lb)	River Gravel 1.5" Slump Comp. (psi)	River Gravel 1.5" Slump Pullout (lb)	River Gravel 2" Slump Comp. (psi)	River Gravel 2" Slump Pullout (lb)	Limestone 1" Slump Comp. (psi)	Limestone 1" Slump Pullout (lb)	Limestone 1.5" Slump Comp. (psi)	Limestone 1.5" Slump Pullout (lb)	Limestone 2" Slump Comp. (psi)	Limestone 2" Slump Pullout (lb)
30% 6 mph	Rod-ding	3rd	2965	1430	2815	1360	2611	1320	3289	1400	3218	1360	3261	1380
		7th	3003	1430	3027	1540	2894	1480	3598	1540	3568	1680	3480	1540
		28th	3375	1690	3264	1780	3241	1630	3841	1970	3893	1950	3679	1750
		90th	3665	2140	3580	2000	3516	1910	4156	2140	4014	2020	3929	2060
Plain Con-crete	20 min. mixing	3rd	2761	1600	2665	1670	2325	1290	3203	1450	3040	1370	2691	1030
		7th	2827	1620	2997	1790	2570	1460	3509	1580	3156	1540	3020	1180
		28th	2959	1700	3154	2000	2973	1720	3845	1750	3691	1870	3391	1420
		90th	3182	1950	3508	2260	3424	2030	4208	1970	3890	1910	3558	1610
	60 min. mixing	3rd	2556	1460	2434	1400	2180	1150	3069	1320	2950	1220	2582	930
		7th	2652	1600	2838	1750	2370	1450	3391	1450	3025	1410	2856	1020
		28th	2731	1670	3065	1900	2807	1690	3846	1720	3485	1680	3187	1270
		90th	2984	1860	3356	1980	3154	1980	4084	1910	3643	1850	3365	1340
Con-crete with Fly Ash	7 min. mixing	3rd	2851	1700	2750	1580	2449	1320	3427	1680	3344	1580	3542	1630
		7th	3187	1850	2995	1710	2647	1640	3614	1810	3617	1750	3751	1820
		28th	3363	2020	3110	1780	3088	–	4156	1980	3882	1830	3980	1910
		90th	3502	2010	3440	2160	3260	2060	4435	2080	4124	1940	4120	2010
	20 min. mixing	3rd	2727	1560	2630	1470	2371	1510	3331	1540	3134	1480	3390	1630
		7th	2970	1680	2825	1690	2599	1550	3534	1650	3467	1660	3518	1790
		28th	3130	1950	3088	1790	2858	1670	3952	1890	3719	1830	3791	1930
		90th	3381	2080	3214	1980	3142	2020	4271	2080	3940	2000	4047	2030
	60 min. mixing	3rd	2693	1430	2544	1340	1974	1080	3225	1430	2910	1310	3122	1560
		7th	2811	1540	2700	1610	2168	1140	3378	1560	3236	1640	3388	1680
		28th	2978	1680	2885	1750	2720	1630	3705	1880	3552	1730	3573	1740
		90th	3162	1980	3086	1970	2990	1880	4311	2080	3712	1850	3788	1890

* Average of 3 tests except for 90 day pullout test which is an average of 2 tests (see Table 6, p. 38)

Table D2. 7 day Flexural strength and modified compressive strength test results*

Curing Conditions			River Gravel						Limestone					
Air Temp. (°F)	Conc. Temp. (°F)	Humidity & Wind % & mph	1" Slump		1.5" Slump		2" Slump		1" Slump		1.5" Slump		2" Slump	
			Flex. Str.	Mod. Str.	Flex. Str.	Mod. Str.	Flex. Str.	Mod. Str.	Flex. Str.	Mod. Str.	Flex. Str.	Mod. Str.	Flex. Str.	Mod. Str.
50	50	65% & 9mph	464	4872	458	4390	409	3667	487	3971	463	3742	413	2793
		30% & 6mph	440	4635	431	4189	360	3224	478	3568	442	3279	395	2466
	73	65% & 9mph	528	5438	493	4792	440	4314	520	4998	483	4247	446	3666
73	73	95% & 0mph	748	5808	669	4661	620	4482	720	5477	678	4670	653	4311
		65% & 9mph	423	4413	377	3720	357	3822	487	4818	424	3627	418	3167
		30% & 6mph	400	3856	356	3614	329	3354	473	4703	419	3486	392	2903
104	73	30% & 6mph	397	5354	388	5408	300	3963	469	5377	417	4516	388	4472
	104	65% & 9mph	343	5017	307	4209	311	4238	438	4818	404	4439	370	4079
		30% & 6mph	324	4579	318	4664	288	3953	433	4718	414	4239	368	3679
Mix Design	Consol. Method	Mixing Time												
Plain Concrete	Spading	7 min.	324	4907	315	4238	287	3824	391	4271	379	4059	353	3390
		20 min.	317	4594	295	4030	275	3510	336	4366	336	3767	311	3729
		60 min.	269	4360	238	3873	244	3057	330	3965	275	3774	288	3467
Plain	Rodding	7 min.	311	4758	287	4257	263	3467	408	4886	418	3454	345	3263
Plain Concrete	Vibrating	7 min.	324	4579	318	4664	288	3953	433	4718	414	4239	368	3679
		20 min.	319	4193	313	3947	253	3710	425	4480	413	4105	354	3557
		60 min.	301	3962	257	3792	218	3601	397	4080	403	3665	340	3574
Fly Ash	Vibrating	7 min.	299	4728	281	4313	264	3944	411	5076	376	4648	357	4547
		20 min.	282	4476	269	4040	244	3394	389	4581	360	4404	346	4358
		60 min.	273	4120	246	3735	232	3704	377	4500	325	3649	299	3031

* Flexural strength is an average of 2 tests, and modified compressive strength is an average of 3 tests (see Table 6, p. 38)

Table D3a. Shrinkage and weight loss test results*

Test condition: Air temperature = 50°F
Other conditions: 7 min. mixing, plain concrete, vibrating

Conc. Temp. (°F)	RH(%) & Wind (mph)	Test Date (day)	River Gravel						Limestone					
			1" Slump		1.5" Slump		2" Slump		1" Slump		1.5" Slump		2" Slump	
			Shr. (10^{-6})	Wt_{Loss} (%)	Shr. (10^{-6})	Wt_{Loss} (%)	Shr. (10^{-6})	Wt_{Loss} (%)	Shr. (10^{-6})	Wt_{Loss} (%)	Shr. (10^{-6})	Wt_{Loss} (%)	Shr. (10^{-6})	Wt_{Loss} (%)
50	65% & 9 mph	2nd	42	0.472	55	0.489	62	0.617	83	0.371	106	0.492	125	0.568
		3rd	92	0.795	123	0.883	117	0.859	103	0.584	158	0.722	196	0.871
		7th	141	1.015	172	1.113	174	1.185	199	0.900	228	0.999	281	1.201
		14th	181	1.152	193	1.234	191	1.256	248	1.188	315	1.306	369	1.570
		28th	192	1.235	218	1.358	213	1.374	324	1.420	393	1.659	453	1.801
		60th	203	1.339	224	1.398	251	1.522	376	1.613	426	1.729	470	1.899
		90th	210	1.433	236	1.502	282	1.675	438	1.739	450	1.846	504	2.029
	30% & 6 mph	2nd	46	0.534	72	0.776	78	0.801	102	0.618	118	0.654	147	0.920
		3rd	96	0.815	112	0.949	121	1.026	196	0.828	191	0.844	238	1.156
		7th	124	0.952	146	1.066	164	1.284	269	1.092	254	1.055	315	1.376
		14th	174	1.161	176	1.166	218	1.390	305	1.277	306	1.291	378	1.578
		28th	183	1.215	203	1.359	254	1.521	358	1.478	353	1.413	414	1.768
		60th	202	1.293	224	1.458	275	1.594	406	1.669	415	1.653	456	1.884
		90th	221	1.446	256	1.490	296	1.744	434	1.766	437	1.850	516	2.086
73	65% & 9 mph	2nd	66	0.551	75	0.605	92	0.811	117	0.491	141	0.607	133	0.623
		3rd	105	0.786	130	0.924	145	1.004	203	0.872	205	0.906	228	1.050
		7th	146	0.955	165	1.191	226	1.350	242	1.044	245	1.035	252	1.133
		14th	172	1.196	197	1.330	235	1.454	289	1.173	284	1.250	301	1.310
		28th	183	1.233	207	1.477	254	1.556	325	1.331	314	1.357	339	1.537
		60th	202	1.314	222	1.498	269	1.595	354	1.484	364	1.514	384	1.623
		90th	228	1.379	236	1.532	287	1.672	382	1.557	412	1.753	421	1.826

* Average of 3 tests (see Table 6, p. 38)

Table D3b. Shrinkage and weight loss test results (continue)* Test condition: Air temperature = 73 °F

Other conditions: 7 min. mixing, plain concrete, vibrating

Conc. Temp. (°F)	RH(%) & Wind (mph)	Test Date (day)	River Gravel 1" Slump Shr. (10^{-6})	River Gravel 1" Slump Wt_{Loss} (%)	River Gravel 1.5" Slump Shr. (10^{-6})	River Gravel 1.5" Slump Wt_{Loss} (%)	River Gravel 2" Slump Shr. (10^{-6})	River Gravel 2" Slump Wt_{Loss} (%)	Limestone 1" Slump Shr. (10^{-6})	Limestone 1" Slump Wt_{Loss} (%)	Limestone 1.5" Slump Shr. (10^{-6})	Limestone 1.5" Slump Wt_{Loss} (%)	Limestone 2" Slump Shr. (10^{-6})	Limestone 2" Slump Wt_{Loss} (%)
73	95% & 0 mph	2nd	-14	-0.145	-30	-0.207	-35	-0.306	-24	-0.187	-30	-0.230	-51	-0.282
		3rd	-18	-0.193	-39	-0.245	-45	-0.367	-33	-0.260	-51	-0.371	-69	-0.483
		7th	-30	-0.298	-49	-0.363	-54	-0.477	-51	-0.372	-60	-0.482	-78	-0.582
		14th	-37	-0.369	-58	-0.447	-64	-0.618	-66	-0.542	-81	-0.682	-102	-0.772
		28th	-47	-0.527	-65	-0.627	-73	-0.734	-81	-0.669	-92	-0.794	-108	-0.855
		60th	-58	-0.620	-74	-0.668	-82	-0.799	-90	-0.763	-104	-0.893	-120	-0.970
		90th	-73	-0.653	-84	-0.731	-94	-0.866	-99	-0.857	-112	-0.948	-123	-1.093
	65% & 9 mph	2nd	47	0.459	45	0.482	58	0.550	121	0.623	134	0.627	153	0.831
		3rd	93	0.768	83	0.741	95	0.786	203	1.026	215	1.131	224	1.138
		7th	148	0.990	132	0.979	146	1.092	280	1.142	294	1.293	368	1.557
		14th	162	1.104	171	1.142	177	1.169	311	1.368	339	1.377	423	1.783
		28th	192	1.263	198	1.324	242	1.565	349	1.510	397	1.661	440	1.883
		60th	204	1.314	220	1.427	269	1.694	382	1.642	424	1.773	468	1.922
		90th	229	1.435	272	1.570	281	1.711	416	1.769	485	1.936	524	2.165
	30% & 6 mph	2nd	64	0.471	65	0.521	73	0.633	94	0.499	152	0.769	169	0.861
		3rd	82	0.618	92	0.716	109	0.811	172	0.790	216	1.018	234	1.084
		7th	116	0.902	133	1.009	164	1.123	231	1.082	282	1.237	297	1.390
		14th	142	1.067	186	1.182	203	1.291	298	1.259	364	1.517	372	1.649
		28th	191	1.309	218	1.386	251	1.582	352	1.514	427	1.814	467	1.943
		60th	243	1.566	274	1.684	297	1.809	412	1.725	472	1.995	516	2.153
		90th	255	1.604	306	1.760	311	1.904	435	1.881	503	2.101	596	2.385

* Average of 3 tests (see Table 6, p. 38)

Table D3c. Shrinkage and weight loss test results (continue)* Test condition: Air temperature = 104°F

Other conditions: 7 min. mixing, plain concrete, vibrating**

Conc. Temp. (°F)	RH(%) & Wind (mph)	Test Date (day)	River Gravel						Limestone					
			1" Slump		1.5" Slump		2" Slump		1" Slump		1.5" Slump		2" Slump	
			Shr. (10^{-6})	Wt_{Loss} (%)	Shr. (10^{-6})	Wt_{Loss} (%)	Shr. (10^{-6})	Wt_{Loss} (%)	Shr. (10^{-6})	Wt_{Loss} (%)	Shr. (10^{-6})	Wt_{Loss} (%)	Shr. (10^{-6})	Wt_{Loss} (%)
73°F	30% & 6 mph	2nd	62	0.634	91	0.748	109	0.802	172	0.789	159	0.673	201	0.927
		3rd	138	1.007	168	1.182	196	1.331	297	1.319	331	1.423	359	1.518
		7th	204	1.337	236	1.503	290	1.621	374	1.609	382	1.663	456	1.943
		14th	271	1.581	308	1.826	321	1.954	481	2.001	534	2.200	592	2.488
		28th	336	1.947	355	2.167	397	2.309	548	2.322	582	2.464	654	2.729
		60th	384	2.256	467	2.687	506	2.867	665	2.765	679	2.710	748	3.004
		90th	420	2.482	491	2.757	527	2.915	711	2.971	746	3.086	801	3.225
104°F	65% & 9 mph	2nd	54	0.541	67	0.636	111	0.844	120	0.574	138	0.665	152	0.757
		3rd	123	0.928	154	1.012	147	1.036	204	0.968	229	1.024	174	1.135
		7th	185	1.262	199	1.325	208	1.363	354	1.518	379	1.654	413	1.771
		14th	234	1.517	242	1.547	236	1.540	433	1.824	469	1.910	501	2.103
		28th	306	1.821	329	2.001	331	1.992	509	2.179	544	2.285	583	2.452
		60th	326	1.950	365	2.164	376	2.231	572	2.324	589	2.448	611	2.593
		90th	356	2.025	394	2.347	419	2.416	625	2.497	644	2.622	677	2.815
	7 min mixing & Rod-ding	2nd	114	0.846	103	0.805	157	1.073	165	0.769	184	0.843	192	0.872
		3rd	151	1.008	192	1.238	213	1.375	284	1.289	277	1.248	315	1.344
		7th	209	1.385	243	1.586	265	1.662	352	1.492	403	1.752	458	1.899
		14th	267	1.633	302	1.841	319	1.964	482	2.013	508	2.123	585	2.437
		28th	303	1.911	344	2.080	402	2.381	552	2.319	597	2.409	652	2.770
		60th	385	2.228	417	2.384	442	2.556	649	2.615	691	2.881	736	3.019
		90th	453	2.517	477	2.639	508	2.926	710	2.856	738	3.087	773	3.219

* Average of 3 tests (see Table 6, p. 38)

** Except for 104°F where indicated

Table D3d. Shrinkage and weight loss test results (continue)* Test condition: Air temperature = 104°F

Other conditions: Plain concrete, spading

Conc. Temp. (°F)	Mixing Time (min)	Test Date (day)	River Gravel						Limestone					
			1" Slump		1.5" Slump		2" Slump		1" Slump		1.5" Slump		2" Slump	
			Shr. (10^{-6})	Wt_{Loss} (%)	Shr. (10^{-6})	Wt_{Loss} (%)	Shr. (10^{-6})	Wt_{Loss} (%)	Shr. (10^{-6})	Wt_{Loss} (%)	Shr. (10^{-6})	Wt_{Loss} (%)	Shr. (10^{-6})	Wt_{Loss} (%)
104°F	7 min	2nd	102	0.768	119	0.811	134	0.956	128	0.646	152	0.715	166	0.690
		3rd	175	1.183	184	1.234	173	1.204	209	0.957	173	1.219	187	1.239
		7th	224	1.458	272	1.686	258	1.493	323	1.452	432	1.813	453	1.901
		14th	279	1.766	296	1.816	305	1.807	482	2.040	553	2.290	568	2.377
		28th	337	2.058	369	2.135	374	2.142	587	2.429	614	2.500	695	2.852
		60th	402	2.358	429	2.428	435	2.594	632	2.639	724	2.997	761	3.166
		90th	426	2.523	440	2.637	474	2.787	678	2.870	773	3.174	804	3.355
	20 min	2nd	121	0.894	142	1.071	139	1.032	162	0.754	183	0.844	227	0.983
		3rd	172	1.118	183	1.246	195	1.477	284	1.258	306	1.318	319	1.285
		7th	249	1.533	273	1.701	279	1.605	392	1.742	474	2.084	477	1.925
		14th	312	1.899	327	1.917	322	1.891	543	2.283	562	2.308	571	2.395
		28th	364	2.151	379	2.252	367	2.173	665	2.743	682	2.821	711	2.908
		60th	431	2.488	471	2.658	476	2.365	707	2.901	722	3.017	783	3.158
		90th	491	2.669	501	2.840	545	2.984	766	3.081	776	3.198	830	3.395
	60 min	2nd	134	1.012	128	1.071	162	1.102	168	0.752	204	0.905	250	1.090
		3rd	175	1.179	219	1.355	228	1.469	247	1.135	339	1.456	315	1.377
		7th	274	1.696	282	1.739	295	1.782	438	1.821	493	2.067	492	2.095
		14th	331	1.975	367	2.157	379	2.168	611	2.534	628	2.649	648	2.682
		28th	407	2.270	414	2.322	456	2.563	764	3.244	752	3.007	769	3.115
		60th	456	2.572	482	2.736	511	2.876	818	3.331	788	3.246	837	3.410
		90th	480	2.743	538	3.056	545	3.095	830	3.424	835	3.355	871	3.598

* Average of 3 tests (see Table 6, p. 38)

Table D3e. Shrinkage and weight loss test results (continue)* Test condition: Air temperature = 104°F

Other conditions: Plain concrete, vibrating

Conc. Temp. (°F)	Mixing Time (min.)	Test Date (day)	River Gravel						Limestone					
			1" Slump		1.5" Slump		2" Slump		1" Slump		1.5" Slump		2" Slump	
			Shr. (10^{-6})	Wt_{Loss} (%)	Shr. (10^{-6})	Wt_{Loss} (%)	Shr. (10^{-6})	Wt_{Loss} (%)	Shr. (10^{-6})	Wt_{Loss} (%)	Shr. (10^{-6})	Wt_{Loss} (%)	Shr. (10^{-6})	Wt_{Loss} (%)
104°F	7 min.	2nd	62	0.628	76	0.601	112	0.849	161	0.789	179	0.830	174	0.836
		3rd	137	1.001	122	0.985	153	1.048	318	1.374	335	1.462	352	1.499
		7th	209	1.300	213	1.456	244	1.542	465	1.944	472	1.981	488	2.144
		14th	265	1.669	291	1.751	328	1.977	519	2.143	571	2.327	603	2.494
		28th	341	2.045	379	2.117	395	2.290	587	2.488	624	2.613	688	2.839
		60th	405	2.331	465	2.669	496	2.817	669	2.881	689	3.019	772	3.224
		90th	453	2.498	492	2.840	545	2.938	727	2.954	761	3.083	803	3.343
	20 min.	2nd	87	0.767	132	0.974	162	1.071	207	0.980	237	1.063	242	1.057
		3rd	158	1.011	191	1.273	209	1.377	286	1.291	299	1.222	216	1.382
		7th	196	1.348	257	1.609	296	1.799	361	1.586	427	1.770	483	2.026
		14th	263	1.666	318	1.902	331	2.018	527	2.214	539	2.181	587	2.483
		28th	346	2.071	402	2.394	440	2.516	599	2.483	662	2.730	692	2.886
		60th	422	2.413	463	2.687	487	2.779	684	2.865	736	3.084	754	3.187
		90th	443	2.522	509	2.844	502	2.975	731	3.009	781	3.238	810	3.311
	60 min.	2nd	83	0.701	133	0.975	149	1.021	194	0.806	221	0.979	253	1.116
		3rd	148	1.040	173	1.122	193	1.296	299	1.295	337	1.426	405	1.701
		7th	202	1.360	248	1.547	289	1.790	417	1.729	466	1.947	509	2.122
		14th	297	1.813	329	1.965	382	2.242	552	2.293	567	2.328	683	2.856
		28th	377	2.206	441	2.561	478	2.701	605	2.573	648	2.757	773	3.201
		60th	421	2.564	484	2.722	521	2.952	749	3.001	769	3.141	836	3.614
		90th	454	2.733	508	2.838	543	3.078	776	3.153	807	3.323	895	3.881

* Average of 3 tests (see Table 6, p. 38)

Table D3f. Shrinkage and weight loss test results (continue)* Test condition: Air temperature = 104°F

Other conditions: Concrete with fly ash, vibrating

Conc. Temp. (°F)	Mixing Time (min.)	Test Date (day)	River Gravel						Limestone					
			1" Slump		1.5" Slump		2" Slump		1" Slump		1.5" Slump		2" Slump	
			Shr. (10^{-6})	Wt_{Loss} (%)	Shr. (10^{-6})	Wt_{Loss} (%)	Shr. (10^{-6})	Wt_{Loss} (%)	Shr. (10^{-6})	Wt_{Loss} (%)	Shr. (10^{-6})	Wt_{Loss} (%)	Shr. (10^{-6})	Wt_{Loss} (%)
104°F	7 min.	2nd	118	1.030	126	1.106	123	1.013	243	1.168	236	1.004	261	1.193
		3rd	165	1.261	178	1.326	182	1.364	338	1.551	399	1.843	408	1.833
		7th	223	1.592	237	1.673	285	1.880	406	1.841	504	2.279	523	2.338
		14th	259	1.742	276	1.825	314	2.040	481	2.141	592	2.663	619	2.761
		28th	332	2.194	351	2.308	402	2.559	573	2.542	691	3.096	697	3.087
		60th	416	2.554	429	2.668	463	2.808	672	2.959	730	3.221	764	3.386
		90th	435	2.640	512	2.870	511	3.023	695	3.038	768	3.350	782	3.441
	20 min.	2nd	108	0.926	121	0.950	138	1.053	227	1.033	246	1.120	251	1.192
		3rd	152	1.222	183	1.346	231	1.606	363	1.661	402	1.817	403	1.842
		7th	226	1.574	258	1.823	297	1.982	431	1.948	497	2.229	534	2.368
		14th	269	1.766	301	2.070	384	2.465	503	2.232	557	2.870	682	3.018
		28th	363	2.320	374	2.382	427	2.820	574	2.560	689	3.116	778	3.483
		60th	406	2.561	438	2.708	512	3.071	656	2.879	768	3.388	827	3.700
		90th	436	2.741	485	2.964	539	3.235	713	3.149	838	3.681	895	3.970
	60 min.	2nd	138	1.117	142	1.127	168	1.292	241	1.146	260	1.214	289	1.362
		3rd	176	1.303	193	1.427	243	1.659	388	1.737	433	1.925	509	2.240
		7th	236	1.694	294	1.932	311	2.064	458	2.048	572	2.548	613	2.679
		14th	284	1.877	367	2.377	409	2.588	524	2.329	680	3.021	717	3.150
		28th	391	2.470	409	2.533	480	2.926	592	2.642	773	3.410	819	3.615
		60th	437	2.751	468	2.842	537	3.260	663	2.914	806	3.526	833	3.703
		90th	482	2.921	513	3.193	575	3.455	731	3.252	834	3.674	884	3.898

* Average of 3 tests (see Table 6, p. 38)

Table D4a. Moisture content and moisture loss test results*

Given conditions: 7 min. mixing, plain concrete, vibrating

Air & Conc. Temp. (°F)	RH(%) & Wind Speed (mph)	Test Day (day)	River Gravel						Limestone					
			1" Slump		1.5" Slump		2" Slump		1" Slump		1.5" Slump		2" Slump	
			Moist. Cont. (%)	Moist. Loss (%)	Moist. Cont. (%)	Moist. Loss (%)	Moist. Cont. (%)	Moist. Loss (%)	Moist. Cont. (%)	Moist. Loss (%)	Moist. Cont. (%)	Moist. Loss (%)	Moist. Cont. (%)	Moist. Loss (%)
Air 50°F	65 % 9 mph	3rd	2.869	0.967	2.977	0.963	3.233	0.964	2.962	0.871	3.127	0.971	3.388	0.971
		7th	2.560	0.940	2.746	1.042	2.762	1.226	2.612	1.125	2.840	1.152	3.052	1.170
		28th	2.065	1.167	2.361	1.835	2.263	1.265	2.156	1.456	2.328	1.465	2.553	1.520
		90th	1.782	1.294	2.192	1.089	2.189	1.305	1.565	1.732	2.091	1.608	2.169	1.734
Conc. 50°F	30% 6 mph	3rd	2.936	0.783	3.261	0.882	3.414	0.972	3.182	0.920	3.224	0.911	3.313	1.174
		7th	2.650	0.912	2.762	1.031	2.942	1.186	2.741	1.166	2.748	1.331	2.878	1.378
		28th	2.127	1.284	2.245	1.339	2.320	1.420	2.298	1.463	2.335	1.559	2.456	1.534
		90th	1.571	1.319	1.704	1.392	2.058	1.492	1.371	1.880	1.639	2.016	1.946	1.940
Air 50°F Conc. 73°F	65% 9 mph	3rd	3.071	0.676	3.193	0.804	3.309	1.082	3.139	1.061	3.396	1.230	3.415	1.350
		7th	2.779	1.091	2.802	1.223	2.912	1.394	2.619	1.378	2.852	1.443	2.911	1.767
		28th	2.147	1.318	2.423	1.482	2.361	1.664	2.344	1.460	2.437	1.590	2.495	1.943
		90th	1.692	1.450	2.167	1.634	1.963	1.721	1.925	1.536	2.084	1.827	2.119	2.128
Air 73°F	95% 0 mph	3rd	4.048	-0.185	4.481	-0.254	4.598	-0.358	4.713	-0.358	4.860	-0.369	4.958	-0.453
		7th	4.134	-0.281	4.594	-0.314	4.641	-0.448	5.018	-0.451	5.049	-0.496	5.126	-0.511
		28th	4.356	-0.411	4.686	-0.481	4.744	-0.509	5.234	-0.590	5.381	-0.609	5.452	-0.625
		90th	4.487	-0.631	4.744	-0.675	4.937	-0.707	5.363	-0.579	5.463	-0.692	5.565	-0.721
Conc. 73°F	65% 9 mph	3rd	2.952	0.774	3.130	0.864	3.377	0.912	3.217	0.894	3.218	0.982	3.551	1.064
		7th	2.534	1.080	2.674	1.125	2.909	1.225	2.528	1.233	2.596	1.262	2.695	1.346
		28th	1.946	1.236	1.901	1.337	1.983	1.451	2.146	1.505	2.164	1.611	2.181	1.664
		90th	1.599	1.445	1.560	1.593	1.586	1.638	1.558	1.861	1.624	1.979	1.677	1.995
	30% 6 mph	3rd	3.155	0.735	3.143	0.851	3.467	0.931	3.221	0.952	3.224	1.084	3.390	1.112
		7th	2.614	1.028	2.726	1.115	3.043	1.128	2.480	1.282	2.587	1.341	2.762	1.452
		28th	1.678	1.367	1.733	1.479	1.939	1.526	1.821	1.611	2.003	1.693	2.177	1.789
		90th	1.261	1.645	1.340	1.650	1.424	1.757	1.150	2.082	1.127	2.099	1.273	2.111

* Average of 3 tests (see Table 6, P. 38)

Table D4b. Moisture content and moisture loss test results (continue)*

Given conditions: 7 min. mixing, plain concrete, vibrating

Air & Conc. Temp. (°F)	RH(%) & Wind Speed (mph)	Test Day (day)	River Gravel						Limestone					
			1" Slump		1.5" Slump		2" Slump		1" Slump		1.5" Slump		2" Slump	
			Moist. Cont. (%)	Moist. Loss (%)	Moist. Cont. (%)	Moist. Loss (%)	Moist. Cont. (%)	Moist. Loss (%)	Moist. Cont. (%)	Moist. Loss (%)	Moist. Cont. (%)	Moist. Loss (%)	Moist. Cont. (%)	Moist. Loss (%)
Air 104°F Conc. 73°F	30% 6 mph	3rd	3.197	0.775	3.164	0.834	3.438	1.430	3.029	1.092	3.228	1.350	3.267	1.365
		7th	2.752	1.027	2.631	1.103	3.058	1.343	2.786	1.275	2.930	2.483	2.948	2.532
		28th	1.560	1.737	1.696	1.576	1.889	2.048	1.463	1.924	1.901	2.857	2.115	2.988
		90th	0.946	2.138	1.287	2.007	1.155	2.363	0.749	2.794	1.271	3.193	0.837	3.465
Air 104°F	65% 9 mph	3rd	3.107	0.732	3.195	0.822	3.351	0.988	3.274	1.117	3.330	1.170	3.454	1.147
		7th	2.271	1.189	2.344	1.284	2.560	1.406	2.805	1.337	2.829	1.445	2.897	1.498
		28th	1.556	1.450	1.731	1.663	1.874	1.963	1.712	1.811	1.864	1.970	1.959	2.100
		90th	0.867	1.846	0.993	2.042	1.012	2.235	0.984	2.518	1.334	2.425	1.317	2.543
Conc. 104°F	30% 6 mph	3rd	2.988	0.716	3.120	0.827	3.366	0.853	3.348	1.012	3.499	1.150	3.610	1.185
		7th	2.494	1.117	2.562	1.334	2.633	1.395	2.941	1.373	3.011	1.446	3.109	1.586
		28th	1.495	1.629	1.550	1.862	1.860	2.051	1.538	2.069	1.635	2.133	1.750	2.296
		90th	0.857	1.851	0.952	2.161	1.054	2.246	0.679	2.561	0.955	2.582	0.940	2.675
Air 104°F Conc. 104°F RH 30% Wind 6 mph	7 min. mixing	3rd	3.022	0.830	3.019	0.723	3.117	0.854	2.772	0.735	2.844	0.971	2.963	0.936
		7th	2.247	1.001	2.374	1.085	2.436	1.131	1.879	1.448	2.183	1.402	2.453	1.432
		28th	1.283	1.764	1.464	1.786	1.495	2.041	1.265	2.096	1.310	2.074	1.575	2.101
		90th	0.922	1.991	0.911	2.015	0.861	2.330	0.752	2.524	0.886	2.587	1.091	2.433
	20 min. mixing	3rd	3.198	0.951	3.109	0.894	3.177	0.962	3.027	0.797	3.017	1.524	3.055	1.129
		7th	2.357	1.391	2.440	1.351	2.557	1.273	1.976	1.468	2.041	2.354	2.564	1.262
		28th	1.799	1.901	1.913	1.856	2.082	2.333	1.312	2.745	0.768	3.218	1.737	1.781
		90th	1.117	2.322	1.127	2.514	1.003	2.546	0.724	3.093	0.597	3.354	1.006	2.556
Spading	60 min. mixing	3rd	3.368	0.960	3.343	0.976	3.468	1.028	3.361	0.843	3.582	1.738	3.503	1.022
		7th	2.466	1.513	2.559	1.518	2.674	1.315	2.695	1.573	2.837	2.467	2.916	1.506
		28th	2.054	2.023	2.033	2.053	2.188	2.390	1.403	2.999	1.652	3.406	1.829	1.902
		90th	1.286	2.636	1.254	2.674	1.161	2.622	0.814	3.201	0.941	3.638	1.091	2.649

* Average of 3 tests (see Table 6, P. 38)

Table D4c. Moisture content and moisture loss test results (continue) *

Test conditions: Air & concrete temperature =104°F, relative humidity = 30%, wind speed = 6 mph

Mix Design	Mixing Time (min.)	Test Day (day)	River Gravel						Limestone					
			1" Slump		1.5" Slump		2" Slump		1" Slump		1.5" Slump		2" Slump	
			Moist. Cont. (%)	Moist. Loss (%)	Moist. Cont. (%)	Moist. Loss (%)	Moist. Cont. (%)	Moist. Loss (%)	Moist. Cont. (%)	Moist. Loss (%)	Moist. Cont. (%)	Moist. Loss (%)	Moist. Cont. (%)	Moist. Loss (%)
Rod-ding	7 min. mixing	3rd	3.082	0.617	3.149	0.709	3.151	0.757	3.141	1.058	3.141	1.085	3.288	1.065
		7th	2.334	0.935	2.347	1.026	2.408	1.169	2.257	1.268	2.398	1.266	2.523	1.285
		28th	1.372	1.611	1.551	1.747	1.684	2.117	1.323	2.151	1.364	2.106	1.553	2.144
		90th	0.861	1.816	0.932	1.976	1.014	2.379	0.845	2.376	0.880	2.479	0.923	2.391
Plain Con-crete	20 min. mixing	3rd	3.151	0.795	3.353	0.842	3.388	0.869	3.475	1.159	3.533	1.190	3.608	1.261
		7th	2.465	1.087	2.904	1.223	2.683	1.258	3.143	1.484	3.111	1.596	3.343	1.673
		28th	1.505	1.711	1.637	1.858	1.695	2.168	1.837	2.193	1.849	2.162	1.841	2.393
		90th	1.050	1.947	1.052	2.376	1.087	2.546	1.158	2.542	0.966	2.647	1.005	2.715
	60 min. mixing	3rd	3.245	0.854	3.655	0.921	3.440	0.967	3.664	1.312	3.772	1.382	3.842	1.386
		7th	2.650	1.131	3.128	1.393	2.779	1.419	3.291	1.655	3.422	1.684	3.672	1.762
		28th	1.743	1.844	1.830	2.078	1.809	2.337	2.077	2.273	1.933	2.354	2.003	2.503
		90th	1.119	2.116	1.111	2.697	1.257	2.739	1.768	2.859	1.080	2.928	1.141	2.790
Con-crete with Fly Ash	7 min. mixing	3rd	2.077	0.742	1.967	0.790	1.559	0.925	2.371	1.118	2.095	1.107	1.853	1.135
		7th	1.741	1.167	1.395	1.244	1.454	1.367	1.636	1.536	1.449	1.638	1.673	1.687
		28th	0.830	1.814	0.491	1.973	0.569	2.048	0.950	2.027	0.492	2.131	0.720	2.278
		90th	0.661	1.980	0.450	2.186	0.532	2.259	0.545	2.480	0.377	2.512	0.490	2.658
	20 min. mixing	3rd	2.135	0.850	2.258	0.852	1.828	1.039	2.461	1.209	2.256	1.309	2.181	1.355
		7th	1.888	1.257	1.644	1.313	1.474	1.404	1.872	1.610	1.535	1.679	1.763	1.717
		28th	0.926	1.857	0.646	2.112	0.637	2.094	1.016	2.274	0.629	2.742	0.863	2.429
		90th	0.726	2.146	0.519	2.170	0.679	2.236	0.642	2.870	0.448	2.910	0.552	2.716
	60 min. mixing	3rd	2.242	0.978	2.536	1.059	2.068	1.076	2.590	1.475	2.325	1.484	2.605	1.589
		7th	1.976	1.444	1.816	1.480	1.722	1.534	2.014	2.297	1.727	1.951	2.018	1.900
		28th	1.069	2.346	0.714	2.168	0.783	2.199	1.111	2.639	0.822	2.735	0.967	2.828
		90th	0.827	2.429	0.665	2.248	0.749	2.356	0.746	2.990	0.653	3.031	0.639	3.080

* Average of 3 tests (see Table 6, P. 38)

Table D5. Time of setting test results (hrs:min)*

Air Temp. (°F)	Conc. Temp. (°F)		River Gravel						Limestone					
			1" Slump		1.5" Slump		2" Slump		1" Slump		1.5" Slump		2" Slump	
			Initial Set	Final Set	Initial Set	Final Set	Initial Set	Final Set	Initial Set	Final Set	Initial Set	Final Set	Initial Set	Final Set
50°F	50°F	Avg.	9:24	13:23	10:30	13:59	11:06	15:22	8:47	13:02	9:52	14:03	10:27	13:55
		Range	:48	:25	:00	:63	–	–	:17	:07	:24	:25	:24	:00
	73°F	Avg.	7:44	11:43	9:12	13:07	10:20	14:28	8:24	13:11	8:51	13:11	9:08	13:39
		Range	:48	:38	:36	:58	:16	:20	:66	:08	:24	:25	:35	:60
73°F	73°F	Avg.	3:16	4:17	3:52	5:10	4:15	5:38	3:50	5:14	4:00	5:17	4:05	5:25
		Range	:15	:39	:36	:39	:18	:20	:40	:35	:40	:34	:26	:39
104°F	73°F	Avg.	2:35	3:36	2:57	3:54	3:02	3:57	2:45	3:35	2:50	3:44	2:52	3:37
		Range	:44	:38	:24	:31	:07	:05	:03	:09	:04	:14	:07	:19
	104°F	Avg.	2:44	3:45	2:42	3:53	2:34	3:39	2:36	3:25	2:41	3:30	2:42	3:30
		Range	:05	:08	:00	:14	:02	:08	:13	:10	:14	:15	:12	:18
Mix Design	Mixing Time													
Plain Con-crete	7 min. mixing	Avg.	2:44	3:45	2:42	3:53	2:34	3:39	2:36	3:25	2:41	3:30	2:42	3:30
		Range	:05	:08	:00	:14	:02	:08	:13	:10	:14	:15	:12	:18
	20 min. mixing	Avg.	3:08	4:01	2:48	3:48	2:46	3:45	2:44	3:34	2:42	3:34	2:57	3:47
		Range	:07	:06	:59	:30	:18	:18	:12	:16	:02	:11	:15	:19
	60 min. mixing	Avg.	3:23	4:09	3:12	3:48	3:15	3:56	3:12	3:59	3:08	3:56	3:26	4:09
		Range	:12	:17	:28	:35	–	–	:03	:31	:29	:28	:06	:09
Conc. with Fly Ash	7 min. mixing	Avg.	2:52	3:47	2:53	4:02	2:54	3:59	2:36	3:45	2:42	3:56	2:59	3:51
		Range	:27	:24	:07	:06	:11	:07	–	–	–	–	:12	:10
	20 min. mixing	Avg.	3:03	3:45	2:54	3:47	3:19	4:23	2:53	3:55	3:10	3:59	3:02	3:52
		Range	:12	:08	:22	:19	:21	:34	–	–	–	–	:22	:17
	60 min. mixing	Avg.	3:34	4:25	3:22	4:09	3:29	4:30	3:31	4:14	3:14	4:25	3:29	4:22
		Range	:09	:11	:10	:09	:12	:05	–	–	:09	:12	:12	:09

* Average of 2 tests (see Table 6, p. 38)

Table D6. Sandblasting test results*

Air Temp. (°F)	Conc. Temp. (°F)	Relative Humidity & Wind Speed (%) & (mph)	River Gravel						Limestone					
			1" Slump		1.5" Slump		2" Slump		1" Slump		1.5" Slump		2" Slump	
			28day (cm)	90day (cm)	28day (cm)	90day (cm)	28day (cm)	90day (cm)	28day (cm)	90day (cm)	28day (cm)	90day (cm)	28day (cm)	90day (cm)
	50	65% & 9mph	0.055	0.035	0.064	0.039	0.084	0.043	0.053	0.032	0.064	0.038	0.089	0.047
50		30% & 6mph	0.069	0.039	0.064	0.043	0.077	0.054	0.061	0.033	0.070	0.038	0.074	0.044
	73	65% & 9mph	0.045	0.049	0.071	0.046	0.071	0.050	0.117	0.041	0.121	0.056	0.137	0.053
		95% & 0mph	0.043	0.014	0.044	0.018	0.050	0.017	0.031	0.028	0.036	0.024	0.045	0.033
73	73	65% & 9mph	0.081	0.045	0.084	0.042	0.098	0.049	0.062	0.048	0.072	0.042	0.076	0.059
		30% & 6mph	0.084	0.046	0.089	0.061	0.102	0.054	0.074	0.046	0.083	0.045	0.082	0.056
	73	30% & 6mph	0.063	0.042	0.072	0.053	0.083	0.049	0.049	0.039	0.074	0.055	0.082	0.052
104	104	65% & 9mph	0.090	0.055	0.091	0.058	0.100	0.055	0.082	0.054	0.086	0.050	0.099	0.061
		30% & 6mph	0.092	0.059	0.110	0.067	0.118	0.073	0.082	0.059	0.087	0.052	0.091	0.063
Mix Design	Consol. Method	Mixing Time												
Plain		7 min.	0.091	0.056	0.108	0.059	0.101	0.064	0.076	0.056	0.099	0.051	0.106	0.064
Conc.	Spading	20 min.	0.107	0.062	0.112	0.068	0.118	0.069	0.093	0.041	0.109	0.055	0.114	0.061
		60 min.	0.117	0.068	0.112	0.073	0.119	0.074	0.114	0.049	0.112	0.064	0.135	0.083
Plain	Rodding	7 min.	0.090	0.080	0.100	0.083	0.110	0.075	0.061	0.049	0.071	0.057	0.083	0.068
Plain	Vibra-	7 min.	0.092	0.059	0.110	0.067	0.118	0.073	0.072	0.049	0.087	0.052	0.091	0.063
Conc.	ting	20 min.	0.102	0.055	0.105	0.051	0.114	0.071	0.075	0.057	0.092	0.044	0.095	0.066
		60 min.	0.104	0.062	0.114	0.064	0.131	0.083	0.094	0.063	0.102	0.067	0.104	0.063
Fly	Vibra-	7 min.	0.084	0.044	0.097	0.045	0.093	0.067	0.080	0.043	0.083	0.055	0.082	0.056
Ash	ting	20 min.	0.092	0.052	0.089	0.053	0.096	0.060	0.090	0.044	0.093	0.048	0.091	0.056
Conc.		60 min.	0.102	0.060	0.103	0.063	0.104	0.069	0.099	0.050	0.104	0.066	0.108	0.062

* Average of 8 tests (see Table 6, p. 38)

Table D7. Standard test summary

Given conditions: Air & concrete temperature = 73°F, RH = 95%, wind speed = 0 mph, 1.5 inch slump, limestone, plain concrete

Table D7a. Compressive and pullout strength*

Mixing Time (min.)	Test Date (day)	Spading		Rodding		Vibrating	
		Comp. (psi)	Pullout (lbs.)	Comp. (psi)	Pullout (lbs.)	Comp. (psi)	Pullout (lbs.)
7	3rd	3264	1830	3243	1720	3369	1890
	7th	4380	2210	4013	2160	3921	2140
	28th	5377	2630	4900	2720	4663	2410
	90th	5434	2710	4998	3240	5356	2710
20	3rd	3031	1590	3132	1660	3347	2330
	7th	4140	1760	3922	2020	4195	2730
	28th	4560	2320	4262	2690	4946	3040
	90th	4942	2520	4479	3070	5313	3150
60	3rd	2948	1370	2896	1590	3850	2310
	7th	4000	1590	3361	1970	3935	2350
	28th	4317	2080	4135	2480	4858	2750
	90th	4596	2390	4279	2960	5183	3040

* Average of 3 tests except for the 90 day pullout test which is an average of 2 tests (see Table 6, p. 38)

Table D7b. Flexural strength and modified compressive strength*

Test Date (day)	Mixing Time (min.)	Spading		Rodding		Vibrating	
		Flex. (psi)	Comp. (psi)	Flex. (psi)	Comp. (psi)	Flex. (psi)	Comp. (psi)
7th	7	693	4415	688	4619	678	4670
	20	669	3900	666	4307	666	4456
	60	634	3415	602	3973	649	4213

* Flexural strength is an average of 2 tests (see Table 6, p. 38)
Modified compressive strength is an average of 3 tests

Table D7c. Abrasion by sandblasting*

Mixing Time (min.)	Spading		Rodding		Vibrating	
	28 day	90 day	28 day	90 day	28 day	90 day
7	0.069	0.032	0.070	0.031	0.036	0.024
20	0.110	0.038	0.096	0.040	0.045	0.036
60	0.126	0.071	0.117	0.051	0.049	0.043

* Average of 8 tests (see Table 6, p. 38)

Table D7. Standard test summary (continue)

Table D7d. Shrinkage and weight loss*

Mixing Time (min.)	Test Date (day)	Spading		Rodding		Vibrating	
		Shrink. (10^{-6})	Wt Loss (%)	Shrink. (10^{-6})	Wt Loss (%)	Shrink. (10^{-6})	Wt Loss (%)
7	2nd	-36	-0.310	-42	-0.339	-30	-0.230
	3rd	-49	-0.415	-63	-0.400	-51	-0.371
	7th	-63	-0.518	-75	-0.581	-60	-0.482
	14th	-88	-0.721	-90	-0.706	-81	-0.682
	28th	-104	-0.919	-112	-0.918	-92	-0.794
	60	-117	-1.009	-129	-1.063	-104	-0.893
	90th	-129	-1.024	-148	-1.149	-112	-0.948
20	2nd	-43	-0.355	-53	-0.407	-26	-0.211
	3rd	-60	-0.425	-72	-0.556	-43	-0.311
	7th	-72	-0.600	-84	-0.720	-64	-0.523
	14th	-93	-0.732	-99	-0.825	-89	-0.705
	28th	-99	-0.928	-123	-0.957	-98	-0.819
	60th	-111	-0.985	-138	-1.089	-112	-0.923
	90th	-127	-1.089	-157	-1.206	-127	-1.006
60	2nd	-52	-0.466	-57	-0.543	-45	-0.271
	3rd	-65	-0.481	-78	-0.623	-51	-0.406
	7th	-84	-0.726	-90	-0.786	-81	-0.671
	14th	-96	-0.926	-108	-0.917	-96	-0.874
	28th	-116	-1.023	-129	-1.090	-117	-1.008
	60th	-127	-1.089	-142	-1.182	-120	-1.012
	90th	-140	-1.183	-166	-1.251	-132	-1.132

* Average of 3 tests (see Table 6, p. 38)

Table D7e. Moisture content and moisture loss*

Mixing Time (min.)	Test Date (day)	Spading		Rodding		Vibrating	
		M.C. (%)	M.L. (%)	M.C. (%)	M.L. (%)	M.C. (%)	M.L. (%)
7	3rd	4.975	-0.441	4.968	-0.348	4.846	-0.368
	7th	5.118	-0.511	5.290	-0.504	5.049	-0.496
	28th	5.450	-0.668	5.560	-0.649	5.381	-0.609
	90th	5.548	-0.737	5.632	-0.821	5.463	-0.692
20	3rd	5.179	-0.459	5.249	-0.439	4.928	-0.381
	7th	5.225	-0.536	5.487	-0.544	5.127	-0.437
	28th	5.546	-0.675	5.670	-0.748	5.425	-0.640
	90th	5.618	-0.751	5.746	-0.911	5.509	-0.726
60	3rd	5.212	-0.482	5.486	-0.495	5.200	-0.421
	7th	5.482	-0.609	5.559	-0.566	5.422	-0.525
	28th	5.645	-0.700	5.729	-0.799	5.540	-0.670
	90th	5.779	-0.863	5.845	-1.027	5.588	-0.821

* Average of 3 tests (see Table 6, p. 38)

APPENDIX E

AVERAGE STANDARD DEVIATIONS

Tests		Average Standard Deviations*	
		Average	Standard Deviations
Strength Tests	Compressive(psi)	72	35
	Pullout(lb)	58	36
	Flexural(psi)	16	14
	Modified Compressive(psi)	132	88
Durability Tests	Shrinkage($\times 10^{-6} in/in$)	41	21
	Wt. Loss(%)	0.043	0.019
	Moisture Content(%)	0.052	0.024
	Moisture Loss(%)	0.052	0.023

* Average standard deviations for strength tests, shrinkage tests, moisture content tests, and moisture loss tests. The average was determined by averaging the results for aggregate type, environmental conditions, and slump.

APPENDIX F

CONCRETE MIX DATA

Batch Code	Type	Batch Weight (lb/cy) Cement	Water	F.A.	C.A.	Air(%)	Slump (in.)	Unit Wt. (pcf)	w/c Actual
R1/1	SH	516.6	202.6	1072.0	2134.1	4.3	1	149.25	.39
	MC	516.6	210.3	1072.0	2134.1	4.4	1	146.76	.41
R1/2	SH	516.6	222.1	1062.8	2122.2	4.7	3/4	147.17	.43
	MC	516.6	199.8	1062.2	2120.8	3.8	1 1/4	148.59	.39
R1/3	SH	516.6	202.2	1064.1	2137.1	5.1	3/4	146.36	.39
	MC	516.6	192.2	1064.1	2137.1	4.6	1 1/4	148.43	.37
R2/4	SH	516.6	213.6	1072.0	2134.1	5.3	1 1/4	146.60	.41
	MC	516.6	221.3	1072.0	2134.1	4.8	1 1/2	146.72	.43
R2/5	SH	516.6	218.5	1062.2	2120.8	4.6	1 1/2	147.65	.42
	MC	516.6	198.7	1062.2	2120.8	5.0	1 1/2	145.58	.39
R2/6	SH	516.6	203.8	1064.1	2137.1	5.5	1 3/8	145.58	.39
	MC	516.6	197.5	1064.1	2137.1		1 5/8		.38
R3/7	SH	516.6	216.7	1072.0	2134.1	6.0	2	144.40	.42
	MC	516.6	210.3	1072.0	2134.1	5.6	2	142.57	.41
R3/8	SH	516.6	227.9	1062.2	2120.0	5.1	2	143.95	.44
	MC	516.6	205.8	1062.2	2120.0	5.6	2	144.32	.40
R3/9	SH	516.6	216.2	1064.1	2137.1	6.4	1 3/4	145.58	.42
	MC	516.6	207.6	1064.1	2137.1	7.0	2 1/4	145.06	.40
L4/10	SH	516.6	214.5	1065.4	2143.3	4.6	1	146.64	.42
	MC	516.6	230.1	1065.4	2143.3	4.6	3/4	146.28	.45
L4/11	SH	516.6	224.2	1063.1	2140.1	5.9	1 1/2	143.39	.43
	MC	516.6	217.6	1063.1	2140.1	4.8	1 1/4	144.32	.42
L4/12	SH	516.6	191.7	1073.0	2191.2	5.9	1 1/8	143.43	.37
	MC	516.6	216.0	1073.0	2191.2	4.5	3/4	148.31	.42
L5/13	SH	516.6	224.9	1065.4	2143.3	4.7	1 1/2	145.0	.44
	MC	516.6	228.9	1065.4	2143.3	4.7	1 1/2	145.0	.44
L5/14	SH	516.6	224.2	1063.1	2140.1	5.9	1 1/2	143.39	.43
	MC	516.6	219.2	1063.1	2140.1	5.1	1 1/2	144.25	.42
L5/15	SH	516.6	201.9	1073.0	2191.2	7.5	1 5/8	141.27	.39
	MC	516.6	210.5	1073.0	2191.2	6.7	1 1/2	144.49	.41
L6/16	SH	516.6	230.6	1065.4	2134.3	6.2	2 1/4	143.43	.45
	MC	516.6	225.0	1065.4	2151.6	4.4	2	147.58	.44
L6/17	SH	516.6	228.4	1063.1	2140.1	4.9	2	145.26	.44
	MC	516.6	221.7	1063.1	2140.1	5.7	2 1/4	147.43	.43
L6/18	SH	516.6	196.2	1073.0	2191.2	7.9	2 1/4	141.19	.38
	MC	516.6	217.7	1073.0	2191.2	6.8	2 1/8	143.31	.42

Concrete mix data (continue)

Batch Code	Type	Batch Weight (lb/cy) Cement	Water	F.A.	C.A.	Air(%)	Slump (in.)	Unit Wt. (pcf)	w/c Actual
R7/19	SH	516.6	206.0	1064.8	2124.1	5.0	1	146.64	.40
	MC	516.6	201.4	1064.8	2141.1	4.5	1	147.42	.40
R7/20	SH	516.6	206.9	1049.3	2132.0	4.9	3/4	148.03	.40
	MC	516.6	196.9	1049.3	2132.0	5.1	7/8	146.72	.39
R8/21	SH	516.6	214.1	1064.8	2124.1	6.0	1 1/2	143.92	.41
	MC	516.6	204.1	1064.8	2124.1	5.4	1 1/2	144.81	.40
R8/22	SH	516.6	212.6	1049.3	2132.0	6.6	1 3/4	142.49	.41
	MC	516.6	202.6	1049.3	2132.0	5.6	1 3/8	146.03	.40
R9/23	SH	516.6	222.3	1064.8	2124.1	6.6	2	144.08	.43
	MC	516.6	209.8	1064.8	2124.1	7.5	2	140.37	.41
R9/24	SH	516.6	214.1	1049.3	2132.0	8.9	2 1/8	140.01	.41
	MC	516.6	214.2	1049.3	2132.0	6.8	2	142.57	.41
L10/25	SH	516.6	230.5	1063.5	2134.3	4.9	1		.45
	MC	516.6	214.7	1063.5	2134.3	5.0	1	144.49	.41
L10/26	SH	516.6	199.9	1064.8	2185.3	4.7	1	146.48	.39
	MC	516.6	216.1	1064.8	2185.3	5.8	1 1/4	145.30	.41
L11/27	SH	516.6	218.6	1063.5	2134.3	5.3	1 1/2	144.24	.42
	MC	516.6	218.6	1063.5	2143.3	5.3	1 1/2	144.24	.42
L11/28	SH	516.6	210.1	1063.5	2143.3	6.8	2	141.35	.41
	MC	516.6	220.1	1063.5	2143.3	6.8	2	141.35	.42
L12/29	SH	516.6	227.6	1063.5	2143.3	6.8	2	141.35	.43
	MC	516.6	226.3	1088.2	2143.3	5.0	1 7/8	141.96	.43
L12/30	SH	516.6	210.4	1064.8	2185.3	6.5	1 7/8	141.96	.41
	MC	516.6	226.1	1064.8	2185.3	7.0	2 1/4	142.37	.43
R13/31	SH	516.6	212.4	1062.1	2132.6	4.2	1 1/4	146.89	.41
	MC	516.6	197.6	1062.1	2132.6	4.7	1 1/4	145.62	.40
R13/32	SH	516.6	212.8	1072.1	2130.4	4.6	1	147.58	.41
	MC	516.6	197.1	1072.1	2130.4	4.6	1	147.17	.40
R14/33	SH	516.6	209.5	1062.1	2132.6	5.4	1 3/4	144.97	.41
	MC	516.6	200.5	1062.1	2132.6	4.5	1 1/4	146.19 0	.40
R14/34	SH	516.6	221.1	1072.1	2130.4	4.2	1 1/2	146.19	.43
	MC	516.6	211.9	1072.1	2130.4	4.5	1 1/2	144.89	.42
R15/35	SH	516.6	217.6	1062.1	2132.3	5.5	2 1/4	143.75	.42
	MC	516.6	207.6	1062.1	2132.3	4.8	1 3/4	145.42	.40
R15/36	SH	516.6	228.4	1072.1	2130.4	4.3	2	145.67	.44
	MC	516.6	214.7	1072.7	2130.4	4.3	2	146.81	.42

Concrete mix data (continue)

Batch Code	Type	Batch Weight (lb/cy) Cement	Water	F.A.	C.A.	Air(%)	Slump (in.)	Unit Wt. (pcf)	w/c Actual
L16/37	SH	516.6	230.1	1050.4	2174.1	5.2	3/4	144.44	.45
	MC	516.6	230.1	1050.4	2174.1	5.3	1	144.97	.45
L16/38	SH	516.6	223.5	1063.1	2162.5	5.7	1	147.01	.43
	MC	516.6	219.1	1063.1	2162.5	4.4	1 1/8	145.91	.42
L17/39	SH	516.6	229.5	1050.4	2174.1	5.5	1 1/4	143.43	.45
	MC	516.6	232.7	1050.4	2174.1	5.2	1 3/4	142.73	.45
L17/40	SH	516.6	226.1	1063.1	2162.5	4.7	1 3/8	146.03	.44
	MC	516.6	226.7	1063.1	2162.5	5.3	1 1/4	145.67	.44
L18/41	SH	516.6	232.9	1050.4	2174.1	6.3	2	140.74	.46
	MC	516.6	232.9	1050.4	2174.1	6.4	2	139.89	.46
L18/42	SH	516.6	226.7	1063.5	2162.5	5.3	1 3/4	145.79	.44
	MC	516.6	234.1	1063.1	2162.5	5.7	1 3/4	145.18	.45
R1/43	SH	516.6	216.8	1064.7	2129.5	4.8	1	146.85	.42
	MC	516.6	219.7	1064.7	2129.5	4.6	3/4	146.44	.43
R2/44	SH	516.6	227.2	1064.7	2129.5	5.0	1 1/2	147.37	.41
	MC	516.6	214.9	1064.7	2129.5	5.6	1 1/2	143.22	.42
R3/45	SH	516.6	219.7	1064.7	2129.5	6.5	2 1/2	143.22	.43
	MC	516.6	225.3	1064.7	2129.5	4.9	2	145.34	.44
L4/46	SH	516.6	220.5	1065.6	2171.0	5.0	1		.43
	MC	516.6	200.3	1065.6	2171.0	4.5	1	146.28	.39
L5/47	SH	516.6	215.1	1065.6	2171.0	4.8	1 1/2	144.97	.42
	MC	516.6	215.7	1065.6	2171.0		1 1/2	144.04	.42
L6/48	SH	516.6	215.7	1065.5	2171.0	5.5	2	142.86	.42
	MC	516.6	226.9	1065.6	2171.0	5.5	2		.44
R1/49	SH	516.6	204.8	1066.2	2127.5	6.2	1 1/4	144.97	.40
	MC	516.6	212.3	1066.2	2127.5	4.2	1 1/4	147.09	.41
R2/50	SH	516.6	215.2	1066.2	2127.5	5.6	1 1/2	147.21	.42
	MC	516.6	230.6	1066.2	2127.5	4.3	1 1/2	146.68	.45
R3/51	SH	516.6	226.5	1066.5	2127.5	5.0	2	145.83	.44
	MC	516.6	220.3	1066.2	2127.5	6.2	2 1/4	145.87	.43
L4/52	SH	516.6	220.5	1066.1	2151.1	5.7	1 1/8	149.94	.43
	MC	516.6	230.0	1066.1	2151.1	5.6	7/8	146.11	.45
L5/53	SH	516.6	226.1	1066.1	2151.1	5.5	1 1/2	144.73	.44
	MC	516.6	227.9	1066.1	2151.1	5.5	1 1/4	146.24	.44
L6/54	SH	516.6	238.7	1066.1	2151.1	5.0	2		.46
	MC	516.6	227.9	1066.1	2151.1	5.8	2 1/4	144.00	.44

Concrete mix data (continue)

Batch Code	Type	Batch Weight (lb/cy) Cement	Water	F.A.	C.A.	Air(%)	Slump (in.)	Unit Wt. (pcf)	w/c Actual
R13/55	SH	516.6	222.5	1067.7	2133.0	7.4	1 1/8	143.26	.43
	MC	516.6	216.7	1067.7	2133.0	7.2	3/4	147.42	.42
R13/56	SH	516.6	231.5	1066.2	2135.7	4.1	3/4	147.62	.45
	MC	516.6	220.0	1066.2	2135.7	4.0	1 1/8	148.92	.43
R14/57	SH	516.6	220.5	1055.0	2121.6	7.6	1 1/2	145.17	.43
	MC	516.6	223.1	1055.0	2121.6	7.5	1 1/2	145.63	.43
R14/58	SH	516.6	217.8	1043.9	2134.4	6.0	1 3/4	144.44	.42
	MC	516.6	217.8	1043.9	2134.4	5.0	1 3/4	146.60	.42
R15/59	SH	516.6	212.5	1065.9	2135.6	6.0	1 7/8	144.85	.41
	MC	516.6	207.3	1065.9	2135.6	5.8	2	144.12	.40
R15/60	SH	516.6	231.4	1013.9	2129.6	6.2	1 3/4	145.58	.45
	MC	516.6	244.4	1013.9	2129.6	6.2	1 3/4	147.09	.47
L16/61	SH	516.6	205.9	1064.0	2191.1	4.8	1 1/8	145.26	.40
	MC	516.6	203.0	1064.0	2191.4	4.5	7/8	141.18	.39
L16/62	SH	516.6	216.4	1038.5	2156.0	4.9	1 1/4	147.09	.42
	MC	516.6	211.4	1038.5	2156.0	6.3	1 1/4	144.65	.41
L17/63	SH	516.6	208.9	1064.5	2210.2	6.8	1 1/4	144.85	.40
	MC	516.6	213.9	1064.5	2189.4	6.5	1 3/8	143.83	.41
L17/64	SH	516.6	226.3	1035.0	2190.2	6.2	1 1/4	144.93	.44
	MC	516.6	214.9	1035.0	2190.2	4.2	1 3/8	146.28	.42
L18/65	SH	516.6	219.2	1066.6	2191.2		2 1/4	143.47	.42
	MC	516.6	214.0	1066.6	2191.2	5.9	2 1/8	143.06	.41
L18/66	SH	516.6	244.8	1051.6	2182.5	7.9	2 1/4	142.37	.47
	MC	516.6	236.0	1052.9	2186.7	7.6	1 3/4	141.11	.45
R13/67	SH	516.6	224.8	1067.7	2133.0	7.4	1 1/4	143.35	.44
	MC	516.6	208.1	1067.7	2133.0	5.6	1 1/4	146.89	.40
R13/68	SH	516.6	227.6	1066.2	2135.7	4.6	7/8	147.01	.44
	MC	516.6	237.4	1065.9	2136.2	3.8	1 1/4	148.11	.47
R14/69	SH	516.6	225.7	1055.0	2121.6	5.7	1 1/2	145.71	.44
	MC	516.6	220.5	1055.0	2121.6	7.2	1 1/4	146.72	.43
R14/70	SH	516.6	240.9	1043.9	2134.2	5.2	1 5/8	144.65	.47
	MC	516.6	235.7	1043.9	2134.4	4.9	1 1/4	146.56	.46
R15/71	SH	516.6	207.3	1065.9	2135.6	7.2	2	142.86	.40
	MC	516.6	207.3	1065.9	2135.6	9.4	2	143.67	.40
R15/72	SH	516.6	240.9	1013.9	2129.6	5.5	2	143.14	.47
	MC	516.6	238.1	1013.9	2129.6	6.8	2	144.24	.47

Concrete mix data (continue)

Batch Code	Type	Batch Weight (lb/cy)					Slump (in.)	Unit Wt. (pcf)	w/c Actual
		Cement	Water	F.A.	C.A.	Air(%)			
L16/73	SH	516.6	208.9	1064.0	2191.4	4.7	7/8	146.52	.40
	MC	516.6	209.4	1064.0	2191.4	6.4	1 1/4	143.71	.41
L16/74	SH	516.6	241.2	1038.5	2156.0	4.8	1 1/4	146.52	.47
	MC	516.6	236.6	1038.5	2156.0	4.9	1 1/8	147.13	.46
L17/75	SH	516.6	217.6	1064.5	2189.4	5.8	1 1/2	145.12	.42
	MC	516.6	223.1	1064.5	2189.4	4.5	1 1/2	146.19	.43
L17/76	SH	516.6	225.6	1035.0	2190.2	4.5	1 1/2	143.59	.44
	MC	516.6	225.2	1035.0	2190.2	5.2	1 1/4	144.44	.44
L18/77	SH	516.6	230.5	1066.6	2191.2	6.9	1 7/8	142.89	.45
	MC	516.6	214.1	1066.6	2191.2	5.9	1 3/4	144.85	.41
L18/78	SH	516.6	243.5	1052.9	2186.7	5.5	1 3/4	142.80	.48
	MC	516.6	243.5	1052.9	2186.7	5.6	2 1/2	142.33	.48
R13/79	SH	516.6	222.2	1067.7	2133.0	5.1	3/4	144.58	.43
	MC	516.6	235.2	1067.7	2133.0	4.4	3/4	146.85	.46
R13/80	SH	516.6	256.0	1065.9	2136.2	4.4	1 1/8	146.97	.50
	MC	516.6	245.8	1066.2	2135.7	4.5	1 1/8	145.38	.48
R14/81	SH	516.6	256.9	1055.5	2121.6	5.7	1 3/8	146.03	.50
	MC	516.6	246.4	1055.5	2121.6	6.5	1 1/2	144.04	.48
R14/82	SH	516.6	251.3	1043.8	2134.4	5.0	1 1/2	144.49	.49
	MC	516.6	246.1	1043.9	2134.4	5.0	1 5/8	146.03	.48
R15/83	SH	516.6	235.6	1065.9	2135.6	6.8	1 3/4	143.14	.46
	MC	516.6	233.3	1065.9	2135.6	6.3	1 3/4	144.69	.45
R15/84	SH	516.6	240.5	1013.9	2129.6	5.4	2	146.68	.48
	MC	516.6	240.5	1013.9	2129.6	6.4	2	146.07	.48
L16/85	SH	516.6	226.9	1064.0	2191.4	7.1	1	142.69	.44
	MC	516.6	218.6	1064.0	2191.4	4.7	1	146.85	.42
L16/86	SH	516.6	239.2	1038.2	2155.6	4.9	3/4	147.66	.46
	MC	516.6	230.7	1038.2	2155.6	6.3	1 1/4	144.65	.45
L17/87	SH	516.6	234.6	1064.5	2189.4	8.5	1 1/2	141.96	.45
	MC	516.6	212.1	1064.5	2189.4	6.6	1	144.32	.41
L17/88	SH	516.6	230.7	1035.0	2190.2	5.0	1 1/4	145.71	.45
	MC	516.6	223.0	1035.0	2190.2	5.0	1 1/4	143.55	.43
L18/89	SH	516.6	229.8	1066.6	2191.2	6.3	1 3/4	143.83	.44
	MC	516.6	208.8	1066.6	2191.2	6.9	2 1/4	142.21	.40
L18/90	SH	516.6	248.2	1052.9	2186.7	5.9	1 3/4	145.58	.48
	MC	516.6	243.5	1052.9	2186.7	5.9	2 1/4	143.32	.47

Concrete mix data (continue)

Batch Code	Type	Batch Weight (lb/cy) Cement*	Water	F.A.	C.A.	Air(%)	Slump (in.)	Unit Wt. (pcf)	w/c Actual
R19/91	SH	516.6	216.5	1063.1	2128.3	5.0	1 1/4	146.15	.42
	MC	516.6	216.5	1063.1	2128.3	5.6	1 1/4	145.22	.42
R20/92	SH	516.6	218.1	1069.3	2131.8	4.7	1 1/2	146.40	.42
	MC	516.6	224.7	1069.3	2131.8	2.4	1 1/4	148.88	.43
R21/93	SH	516.6	215.3	1072.1	2134.4	5.5	2	145.10	.42
	MC	516.6	229.3	1072.1	2134.1	6.2	2	144.32	.44
L22/94	SH	516.6	212.0	1052.4	2188.6	4.5	1 1/4	145.50	.41
	MC	516.6	216.7	1052.4	2188.6	3.7	1	144.61	.42
L23/95	SH	516.6	224.9	1068.0	2171.0	4.8	1 1/4	146.85	.44
	MC	516.6	222.7	1067.7	2173.6	4.4	1 1/2	143.59	.43
L24/96	SH	516.6	213.8	1064.6	2168.7	4.6	2	146.68	.41
	MC	516.6	210.4	1064.6	2168.7	4.9	1 3/4	148.51	.41
R19/97	SH	516.6	226.9	1063.1	2128.3	5.2	1 1/4	146.64	.44
	MC	516.6	230.0	1063.1	2128.3	4.8	3/4	149.57	.45
R20/98	SH	516.6	212.9	1069.3	2131.8	4.8	1 3/4	144.77	.41
	MC	516.6	212.9	1069.3	2131.8	5.0	1 1/2	145.38	.41
R21/99	SH	516.6	217.9	1098.9	2134.4	6.2	2 1/2	144.12	.42
	MC	516.6	228.3	1098.9	2134.4	6.1	2 1/2	143.58	.44
L22/100	SH	516.6	212.1	1052.4	2188.6	3.8	7/8	146.56	.41
	MC	516.6	221.8	1052.4	2188.6	4.6	1 1/8	147.01	.43
L23/101	SH	516.6	197.7	1068.8	2173.6	4.6	1 1/2	143.87	.38
	MC	516.6	215.2	1068.0	2171.0	5.1	1 3/4	145.79	.42
L24/102	SH	516.6	214.4	1064.6	2168.7	4.5	1 3/4	145.79	.42
	MC	516.6	235.3	1064.6	2168.7	4.8	2	145.22	.46
R19/103	SH	516.6	231.0	1063.1	2128.3	5.8	3/4	148.47	.45
	MC	516.6	243.1	1063.1	2128.8	3.6	1 1/8	146.89	.47
R20/104	SH	516.6	231.9	1069.3	2131.8	5.1	1 1/2	145.58	.45
	MC	516.6	225.1	1069.3	2131.8	4.9	1 1/2	145.99	.44
R21/105	SH	516.6	228.3	1072.1	2134.4	5.7	1 3/4	145.01	.44
	MC	516.6	236.6	1072.1	2134.4	4.5	1 3/4	146.40	.46
L22/106	SH	516.6	221.1	1052.4	2188.6	3.6	1	148.03	.43
	MC	516.6	221.7	1052.4	2188.6	3.9	3/4	146.24	.43
L23/107	SH	516.6	223.7	1068.0	2171.0	5.5	1 3/4	144.44	.43
	MC	516.6	218.5	1068.0	2171.0	4.5		145.34	.42
L24/108	SH	516.6	232.1	1064.1	2168.7	4.0	1 3/4	145.52	.45
	MC	516.6	216.0	1064.6	2168.7	5.1	2 1/4	144.85	.42

* Mixtures with 20 % of cement weight replaced by fly ash with a 1:1 ratio.

Concrete mix data (continue)

Batch Code	Type	Batch Weight(lb/cy)					Slump	Unit Wt.	w/c
		Cement	Water	F.A.	C.A.	Air(%)	(in.)	(pcf)	Actual
L5/109	SH	516.6	215.7	1065.4	2149.3	4.8	1 1/2	146.85	.42
	MC	516.6	226.0	1065.4	2149.3	7.8	1 1/2	142.61	.44
L5/110	SH	516.6	190.6	1071.0	2158.4	6.8	1 1/2	144.00	.37
	MC	516.6	192.3	1071.0	2158.4	6.0	1 3/8	143.96	.37
L5/111	SH	516.6	222.9	1065.0	2149.3	6.6	1 1/2	143.63	.43
	MC	516.6	217.9	1065.0	2149.3	7.0	1 3/8	144.23	.42
L5/112	SH	516.6	202.4	1071.0	2158.4	5.5	1 1/2	144.69	.39
	MC	516.6	206.3	1071.0	2158.4	6.2	1 1/2	145.17	.40
L5/113	SH	516.6	197.3	1071.0	2158.4	4.9	1 1/4	145.83	.38
	MC	516.6	220.6	1071.0	2158.4	5.5	1 1/2	146.76	.43
L5/114	SH	516.6	227.3	1065.4	2149.3	4.9	1 1/2	145.26	.44
	MC	516.6	220.9	1065.4	2149.3	5.4	1 5/8	144.81	.43
L5/115	SH	516.6	217.5	1071.0	2158.4	6.2	1 1/2	143.75	.42
	MC	516.6	213.3	1071.0	2158.4	6.8	1 3/8	142.53	.41
L5/116	SH	516.6	228.6	1071.0	2158.4	5.6	1 1/2	143.96	.44
	MC	516.6	214.0	1071.0	2158.4	4.9	1 1/4	145.14	.41