DETERMINATION OF REALISTIC CUTOFF DATES FOR LATE-SEASON CONSTRUCTION WITH LIME-FLY ASH AND LIME-CEMENT-FLY ASH MIXTURES

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The strength and durability of lime-fly ash and lime-cement-fly ash materials are known to be related to both temperature and time of curing. Combining these two variables into a single parameter, degree-days, provides a means for correlating time and temperature to strength development of lime-fly ash and lime-cement-fly ash mixtures. Through the use of a theoretical heat-flow model and first-order weather station data, the curing temperatures of the materials in place were determined, and the degree-days expected for these materials under field curing were calculated for the critical construction period. Cutoff dates were established as the last days that these materials could be placed and still have sufficient time for curing before the onset of freezing weather. A frequency analysis was made on the calculated cutoff dates obtained from 20 years of weather data to establish realistic cutoff dates for placing stabilized materials on a probabilistic basis. The addition of small quantities of portland cement to the standard lime-fly ash mixture as an expedient for late-season construction appears beneficial. The frequency analysis of results from mixtures with the cement additive indicated that the construction season can be extended approximately 3 weeks in the Chicago area by the addition of small quantities of cement.

•ONE OF the problems associated with the use of lime-fly ash-aggregate mixtures is that of establishing realistic cutoff dates for terminating fall construction. If the time required for adequate curing of such mixtures under variable temperature conditions could be predicted, terminal dates for placement would ensure adequate strength development to withstand cyclic freezing and thawing without distress. Because the strength and durability of these mixtures are dependent on both time and temperature, no definitive answer can now be given for this problem.

This study was undertaken to determine more completely the effects of time and temperature on the strength properties of lime-fly ash-aggregate (LFA) mixtures. The data were then used to establish a procedure for combining the effects of time and temperature into a single parameter, designated as a "degree-day."

Prior studies indicated that for late-season construction an accelerated strength development of LFA mixtures could be achieved with the addition of small quantities of portland cement (1). Because the curing of lime-cement-fly ash-aggregate (LCFA) mixtures is also time- and temperature-dependent, these mixtures were included for time-temperature evaluation.

A theoretical heat-flow model was used to calculate the expected temperature at a point in the base layer of a LFA pavement using climatic data from a weather station in the Chicago area. The calculated temperature values were used to determine temperature profiles in the pavement from which the degree-days expected on any date

Publication of this paper sponsored by Committee on Lime and Lime-Fly Ash Stabilization.

were determined. Recurrence curves were established for cutoff dates that allow sufficient degree-days for adequate curing of the LFA mixtures to ensure adequate strength development prior to freezing and thawing.

Not all LFA mixtures will have the same relationship between strength and degree-days. Thus, it will be necessary to determine a relationship for any given mixture before the cutoff dates can be established. With a realistic strength-degree-day relationship for a given LFA mixture and data from a nearby first-order weather station, cutoff dates can be established for any location and material. Statistical analyses on the resulting data will lead to probabilistic cutoff dates and estimated recurrence intervals for certain cutoff dates.

MATERIALS

The fly ash used in this study was a conditioned fly ash obtained from a stockpile near the Commonwealth Edison electric generating plant in Will County, Illinois. The fly ash from the stockpile had been pulverized by primary crushing and scalped on a No. 4 sieve. Only the material smaller than No. 4 was used. A grain size distribution curve for the fly ash is shown in Figure 1.

The lime used in the study was a monohydrated dolomitic lime produced by Marblehead Lime Company, Chicago.

The aggregate was a locally available (Champaign) well-graded gravel. A grain size distribution curve of the gravel used in this study is also shown in Figure 1.

PROCEDURE

The laboratory investigations consisted of molding, curing, and testing specimens for a range of curing times at 6 preselected temperatures. A standard LFA mix with 2½ percent lime, 10 percent fly ash, and 87½ percent aggregate and an LCFA mix containing the same proportions as the LFA mix but an additional 1¼ percent portland cement and a concomitant reduction in the aggregate percentage were used throughout the study. The mixtures were compacted at optimum moisture content determined in accordance with ASTM procedure C-593. Curing conditions included a complete factorial of curing times (7, 14, 28, 42, 56 days) and curing temperatures (50, 60, 70, 85, 100, 120 F) to determine the effects of time and temperature on the properties of the mixtures.

Results from the time-temperature study were evaluated and combined into a single parameter known as a degree-day. This was accomplished by subtracting a preselected base temperature from the curing temperature and multiplying the difference by the time in days the specimen was cured at that temperature. Strength versus degree-day curves for the LFA and LCFA mixtures are presented later in this report.

To establish the most representative degree-day curve for a given material, several base temperatures were tried to determine which would best normalize the time-temperature data. Base temperatures of 40, 45, 50, 55, 60, and 65 F were evaluated. Because of the nonlinear nature of the time-temperature and strength relationship of LFA materials, it was necessary to eliminate results from curing temperatures greater than 70 F when calculating degree-days from base temperatures less than 55 F and to eliminate results from curing temperatures below 70 F when determining degree-days from base temperatures greater than 55 F. Separating the results from specimens cured above and below 70 F resulted in degree-day curves with a high level of confidence. Results of these determinations are presented later in this report.

A laboratory investigation on the effects of cyclic curing temperatures on the strength of LFA mixtures was also made. For this phase of the study, curing temperatures were varied between 10 and 30 C (50 and 86 F) every 12 hours. Results from tests on specimens subjected to the cyclic temperature variations were compared to those obtained from specimens cured at a constant temperature of 20 C (68 F) for the same time period. A similar study was made on both LFA and LCFA mixtures at lower curing temperature ranges, in which specimens were cured under cyclic temperature conditions of from 45 to 55 F and a constant temperature of 50 F. The cyclic curing temperature was varied every 12 hours throughout the study, and specimens were tested from both curing conditions at the end of specified time periods.

PRESENTATION OF RESULTS

Results from the complete factorial of curing times and temperatures are shown in Figures 2 and 3. These data indicate that curing temperatures have a significant effect on the early strength development of both LFA and LCFA materials. LFA specimens cured at 120 F showed evidence of dehydration at the time of testing, which apparently influenced resulting strength development with the longer curing times (this is indicated by the broken line in Fig. 2). These data indicate the importance of maintaining sufficient moisture during curing, especially at high temperatures. Although some scatter exists in the data, definitive relationships were obtained for each time and temperature combination.

Figure 4 shows the beneficial strength gains that were achieved using the cement additive for short curing times at low temperatures.

Using the basic data shown in Figures 2 and 3, curves were developed that combine the time and temperature data into a single variable called a degree-day. The strengths of the LFA and LCFA materials were then correlated to the degree-days for the time and temperature conditions under which they were cured. The degree-days for a given time-temperature curing condition were obtained by subtracting a selected base temperature from the curing temperature and multiplying this difference by the number of days of curing at this temperature. A typical degree-day calculation for a curve of strength versus degree-day follows:

Curing temperature	= 100 F
Curing time	= 7 days
Compressive strength	= 690 psi
Base temperature	= 65 F
Number of degree-days	= $(100 - 65) \times (7) = 245$

Several base temperatures were tried in an attempt to develop the base temperature that produced the most consistent trends for calculating degree-days. A plot of the findings using a 40 F base is shown in Figure 5. The results in Figure 5 indicate that one base temperature cannot be used with all curing temperatures. Because of the nonlinear relationship between strength gain and temperature, a specific base temperature is valid for only a specific temperature range. Because there is a significant difference in the pavement temperature between early and late fall, different base temperatures were used to determine the degree-days for different temperature ranges. Data from curing temperatures of less than 70 F with a base temperature of 40 F produced the curves shown in Figures 6 and 7. Curing temperatures of less than 70 F would be typical for late fall in northern Illinois. Data from curing at temperatures of greater than 70 F and a base temperature of 65 F produced the curve shown in Figure 8.

Results from a British study on LFA mixtures (2) indicate there is a significant increase in the compressive strength of LFA materials due to cycling of the curing temperature over a narrow range. Data from the British study (Table 1) indicate that cycling the curing temperatures between 10 and 30 C (50 and 86 F) produced compressive strengths nearly double those obtained with the same materials cured at a constant temperature of 20 C (68 F). Since the actual temperature in the pavement system does not remain constant, it is reasonable to assume that temperature variations in this range in the field will have a similar effect. As will be shown later, the expected temperature variations calculated for the critical months of October, November, and December are not as large, and the base temperature is not as high, as those reported in the British study (2). To determine the effects of cyclic curing temperatures with a narrow range and low temperatures, the mixtures were cured at a constant temperature of 50 F and also under cyclic temperatures ranging between 45 and 55 F for a 14-day period. Results from this study are given in Table 2. These findings indicate that neither LFA nor LCFA mixtures had significantly different strength gains with cyclic curing temperatures compared with strengths obtained with constant-temperature curing. Apparently the increased strength gains obtained with the 50-85 F curing cycle reported

Figure 1. Grain size distribution curve for the fly ash and aggregate used in the study.

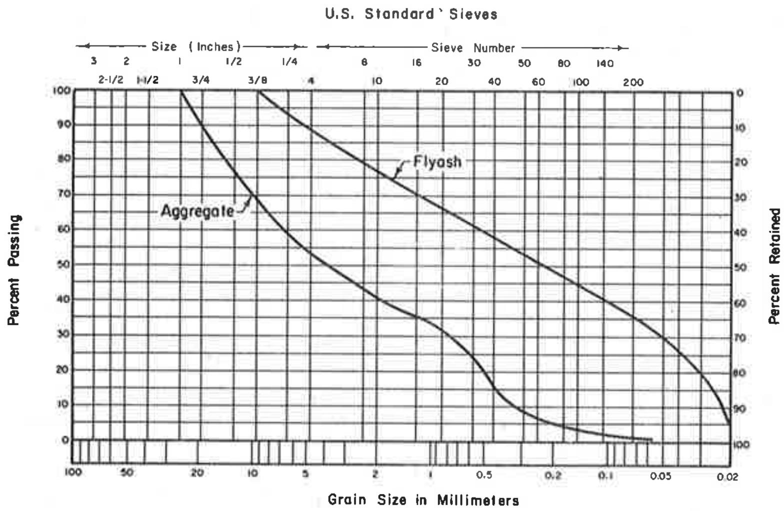


Figure 2. The effects of curing time on the strength of the LFA mixtures at various curing temperatures.

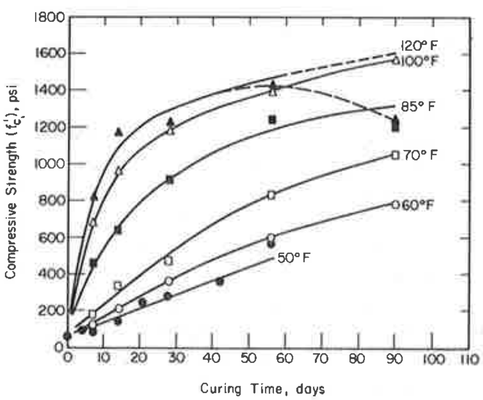


Figure 3. The effects of curing time on the strength of the LCFA mixtures at various curing temperatures.

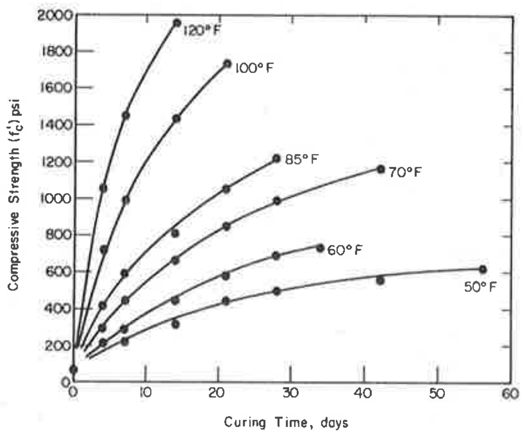


Figure 4. The effect of the cement additive on the strength of LFA mixtures cured at low temperatures (50 F).

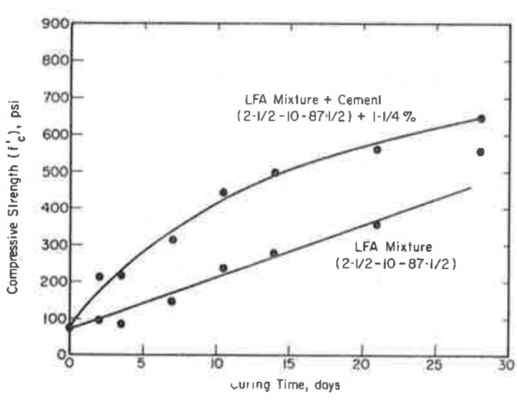
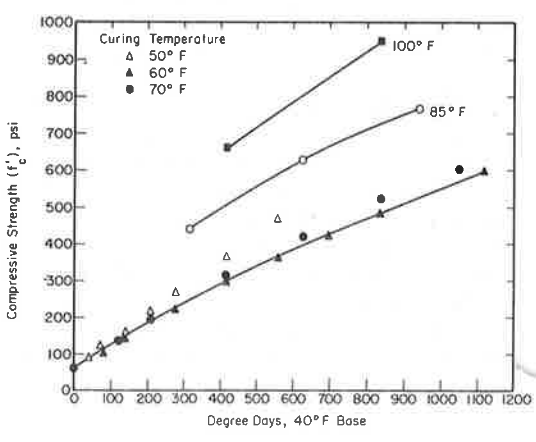


Figure 5. Degree-days versus compressive strength for the LFA mixtures showing accelerated strength gains at high curing temperatures.



in England (2) were the result of accelerated curing at the higher temperatures of the cycle. Similar strength gains due to accelerated curing can be predicted for cyclic variation in the curing temperature of from 50 to 85 F with data shown in Figure 2.

APPLICATION OF FINDINGS

Temperatures expected in typical pavement systems during late fall and early winter were calculated from weather bureau data using Dempsey's (3) heat flow model. Climatic data from the weather station located at Midway Airport in Chicago were used as input to determine temperatures at a reference point 2 in. into the base material (Fig. 9) at 4 a.m. and 1 p.m. on a daily basis (considered the appropriate times of maximum and minimum daily temperatures). Temperatures were calculated for each day from September 1 through December 31 (considered the critical construction period) over a 20-year period. The temperatures at the reference point in the base were then recorded and plotted versus the data for each of the 20 years and as a 20-year average.

Figure 10 shows a typical plot of the temperature at the reference point in the pavement on a twice-daily basis from November 1 through November 16 for a specific year. The degree-days for each date were calculated by computing the area under the curve above the base temperature (40 F), indicated by the cross-hatched areas in Figure 10. Figure 11 shows a typical plot of temperature versus time for the reference point later in the season. Note that the cyclic freezing and thawing did not start in the year represented until December 12.

Starting from the latest date at which the temperature at the reference point was high enough to cause degree-days, the degree-days were accumulated backwards, timewise, toward October and September. Figure 12 shows plots of typical cumulative degree-day curves for the 2 years of the analysis period. Note that the zero point for the cumulative degree-days was different by approximately 3 weeks for the 2 years represented.

Before determining cutoff data for the LFA and LCFA mixtures it is necessary to specify the criteria used for establishing minimum curing. Ideally, the minimum curing for materials in areas with heavy frost would be based on durability criteria. Freeze-thaw durability tests are time-consuming to perform, and reliable standards have not been established for various parts of the country. For purposes of illustration, a strength criterion is used in this paper to indicate minimum curing conditions. Compressive strengths of 350 and 450 psi are used for the basic illustrations that follow. This is not intended to imply that materials with compressive strengths greater than 450 psi will meet minimum durability standards or that materials with compressive strengths of less than 350 psi are not durable. These strength values were arbitrarily chosen for purposes of illustration of the technique, and no further significance should be placed on them. Later in this paper, the effect of choosing other strength criteria on the cutoff dates will be illustrated.

The cumulative degree-days curve for a typical year is replotted in Figure 13. From the curve of degree-days versus strength in Figure 6, it is determined that a total of approximately 510 and 750 degree-days are required to develop the 350- and 450-psi compressive strengths respectively with the LFA mixture. Similarly, from Figure 7 it is determined that approximately 90 and 260 degree-days are required to develop the 350- and 450-psi strengths respectively for the LCFA mixture. The appropriate cutoff dates to accumulate the required degree-days of curing based on 350- and 450-psi criteria for LFA and LCFA mixtures are shown by the dashed lines in Figure 13.

Cutoff dates for LFA and LCFA mixtures were determined for each year for a typical 20-year period based on climatic data from Midway Airport, Chicago. A distribution of these cutoff dates based on the 450-psi criteria for the Midway area for the LFA and LCFA mixtures is shown in Figure 14. The earliest cutoff date for the LFA material to develop 450-psi compressive strengths was found to be September 26, and the earliest cutoff date for the LCFA material was October 18. Similarly, the latest cutoff dates were found to be October 16 and November 13 for the LFA and LCFA materials respectively.

A statistical analysis of frequency was made to determine the cutoff dates for different recurrence intervals for the LFA and LCFA materials. A procedure that is

Figure 6. Degree-days versus compressive strength for the LFA mixtures.

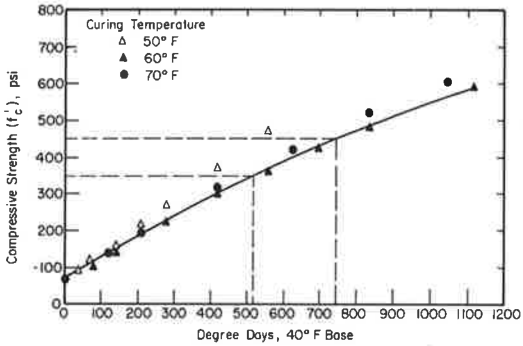


Figure 7. Degree-days versus compressive strength for the LCFA mixtures.

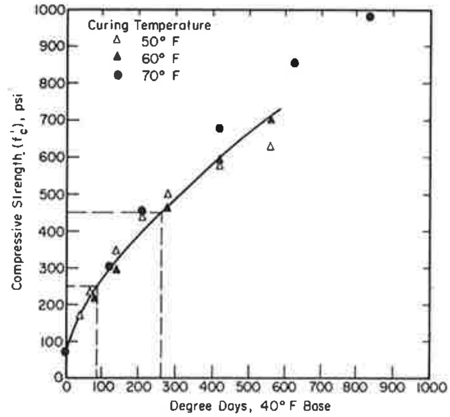


Figure 8. Degree-days versus compressive strength for the LFA mixtures at high curing temperatures.

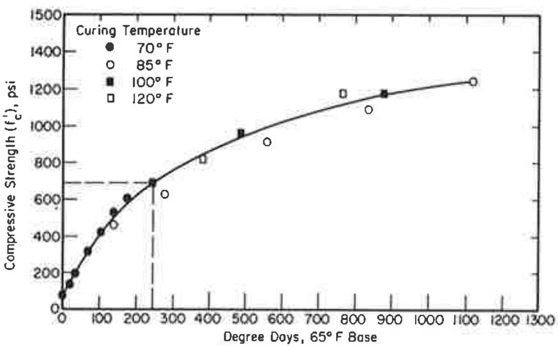


Figure 9. Typical pavement cross section showing location of reference point used for temperature profile determinations.

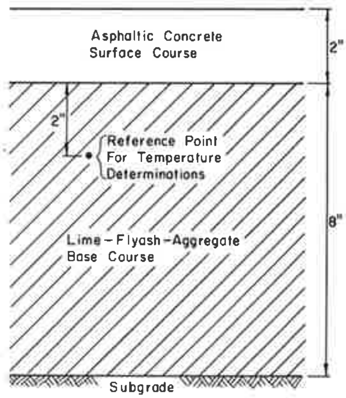


Table 1. Effect of curing in a high-range, high-temperature cycle on the strength of lime-fly ash-sand mixtures.

Mix	Unconfined Compressive Strength After 7 Days, psi		Ratio of 50-86 F f_c' to 68 F f_c'
	68 F	50-86 F	
A	100	180	1.80
B	230	510	2.22
C	130	280	2.15
D	85	170	2.00
E	140	300	2.14
F	105	260	2.48
G	130	275	2.12
H	110	230	2.09
J	110	240	2.18
K	75	140	1.87
		Average =	2.10

Source: Sherwood and Ryley (2).

Table 2. Effect of curing in a low-range, low-temperature cycle on the strength of LFA and LCFA mixtures.

Mixture	Unconfined Compressive Strength After 14 Days, psi		Ratio of 45-55 F f_c' to 50 F f_c'
	50 F	45-55 F	
LFA	156	146	0.94
LCFA	327	331	1.01

Figure 10. Calculated temperature profile at the reference point in the base course for 16 days in November 1932.

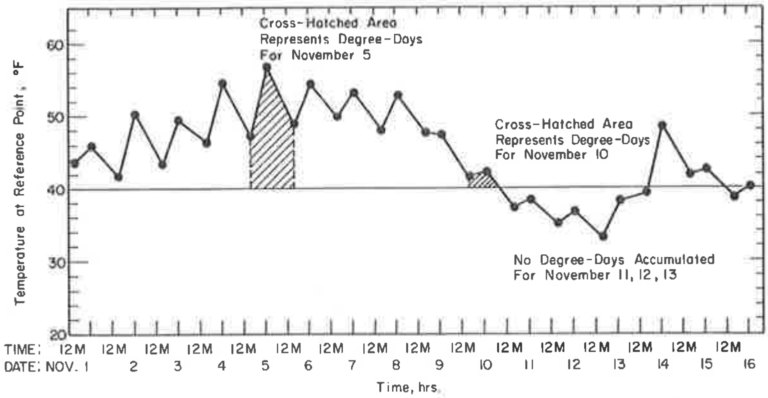


Figure 11. Calculated temperature at the reference point in the base course for 16 days in December 1944, indicating 5 freeze-thaw cycles.

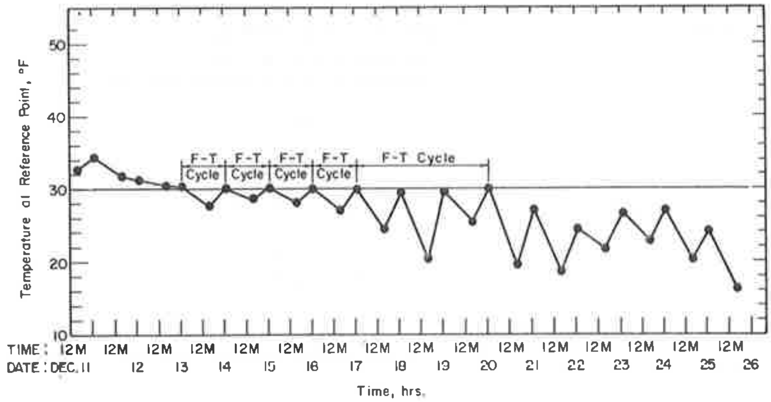
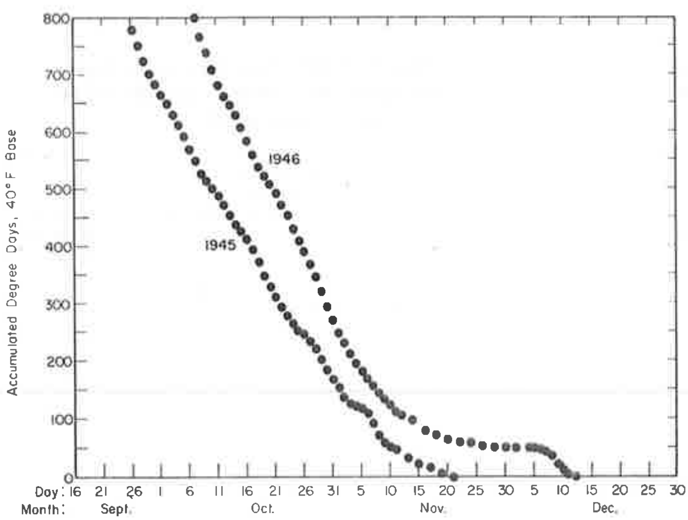


Figure 12. Degree-days accumulated during the critical construction period for 1945 and 1946 for Chicago and vicinity.



used to evaluate hydrologic data was used to fit a theoretical frequency curve to the distribution of cutoff dates (Fig. 14) by the method of least squares. Cutoff dates versus recurrence interval curves were developed for compressive strengths of 300, 400, 450, and 500 psi for both the LFA and LCFA materials and are shown in Figure 15. Interpolation from curves makes it possible to select cutoff dates with a given probability of occurrence for any strength within the range of 300 to 500 psi. For a recurrence interval of 2 years and a compressive strength of 450 psi, the cutoff dates for the LFA and LCFA material are October 4 and October 29 respectively. Cutoff dates for other recurrence intervals can be determined in the same manner. The findings shown in Figure 15 indicate the probability of achieving the desired strength increases rapidly with the earlier cutoff dates. For example, the probability of achieving the 450-psi strength with the LFA mixture increases from 50 percent with an October 4 cutoff date to approximately 80 percent with a September 28 cutoff date (approximately one week earlier) to 95 percent with a September 20 cutoff date. The relationship between cutoff dates and the probability of obtaining the desired curing for LCFA materials is similar to that of the LFA materials except that the cutoff date for the LCFA occurs approximately 25 days later in the season. These results indicate that the addition of a small amount of portland cement ($1\frac{1}{4}$ percent) to the LFA mixture, thus making a LCFA mixture, will extend the probable cutoff date in the Chicago area approximately 3 weeks with no additional risk. The addition of greater quantities of portland cement also incurs a risk, however, because greater quantities of cement may result in a reduction of the compacted density and thus decrease the durability of the material in place.

Table 3 gives a record of the actual cutoff dates necessary to develop 350- and 450-psi compressive strengths at Chicago's Midway Airport based on recorded temperatures for the period 1960-1972. These cutoff dates are in excellent agreement with the dates predicted from 20-year temperature records of earlier years. Specifically, for 4 of the 12 years the cutoff date was earlier than the predicted mean, and for 3 of the 12 the cutoff date was on the mean cutoff date. Thus, the predicted cutoff dates for a given probability of success were valid for the 12-year period evaluated.

CONCLUSIONS

The following comments and conclusions are based on reasonable inferences from the data and analysis presented here:

1. The data and information necessary to establish reasonable cutoff dates using this procedure are (a) a curve showing strength-durability versus degree-days developed from a time-temperature study for the range of curing temperatures expected in the field; (b) the theoretical heat-flow model (3), and (c) weather data from a first-order weather station in the vicinity covering a minimum of 20 years.
2. An average cutoff date for the Chicago area for the LFA materials of the first half of October appears consistent with field experience.
3. The procedure presented also has potential for other applications with LFA and LCFA materials. It can be used, for instance, to determine the number of curing days necessary to ensure adequate strength of stabilized base materials prior to loading for unusual loading and climatic conditions.
4. Results of the frequency analysis on the distribution of cutoff dates for the LFA and LCFA materials indicate that the addition of a small percentage of portland cement to the standard LFA mix can significantly extend the fall construction season. An increase in the length of the fall construction season in the Chicago area of approximately 3 weeks is indicated with the addition of approximately 1 to $1\frac{1}{4}$ percent cement. Excessive cement may be detrimental, however, if it causes a reduction in the compacted density of the material.
5. The procedure presented is based on past climatic data. The reliability of the procedure for any given year can be improved by superimposing long-range (30-day) forecasts for the area on the results from the statistical analyses. In 1972, for example, the long-range forecast for the Chicago area for October was for wetter and much colder than normal climatic conditions. Results given in Table 3 show that 1972 had the earliest cutoff date of the 12 years analyzed.

Figure 13. Accumulated degree-days for 1946 in Chicago showing calculated cutoff dates for LFA and LCFA mixtures to develop 450-psi compressive strengths.

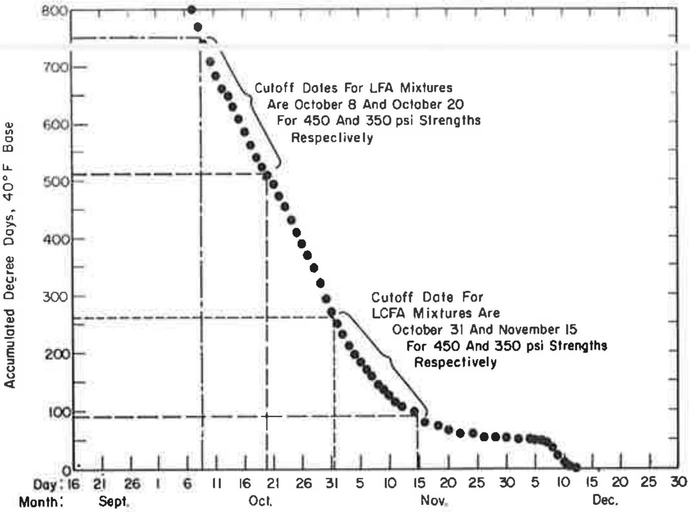


Figure 14. Distribution of cutoff dates for LFA and LCFA mixtures for the 20-year period from 1929 to 1948.

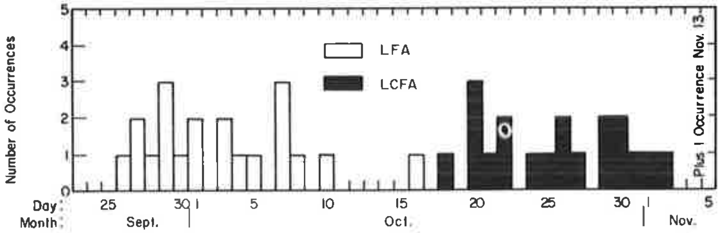


Figure 15. Projected cutoff dates for LFA and LCFA mixtures at various strengths for the Chicago area.

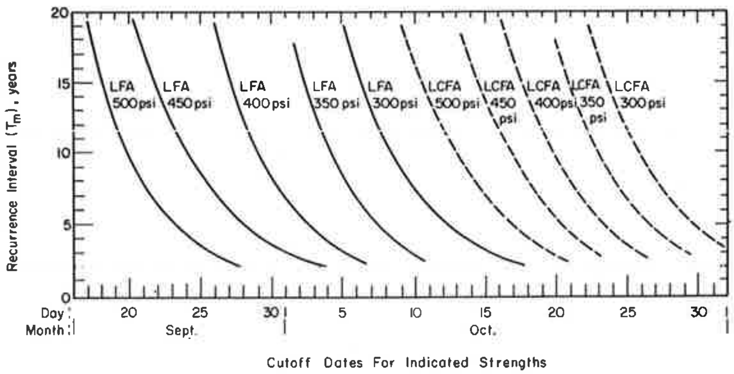


Table 3. Cutoff dates for LFA mixtures to develop adequate curing for 450-psi compressive strength based on actual temperatures recorded at Chicago's Midway Airport for the period 1960-1972.

	Variations From 30-Year Norms			Actual Cutoff Dates, 1960-1972	
Year	Temperature Deviation From Mean for Month of October	Cumulative Degree-Days per Month	Calendar Days	350-psi LFA	450-psi LFA
1960	+0.5	+15	+1	Oct. 14	Oct. 5
1961	+1.0	+30	+2	Oct. 16	Oct. 6
1962	+2.2	+66	+4	Oct. 17	Oct. 8
1963	+9.2	+276	+15	Oct. 28	Oct. 19
1964	-4.1	-123	-7	Oct. 6	Sept. 28
1965	-1.1	-33	-2	Oct. 11	Oct. 2
1966	-1.7	-51	-3	Oct. 10	Oct. 1
1967	-1.7	-51	-3	Oct. 10	Oct. 1
1968	+0.6	+18	+1	Oct. 14	Oct. 5
1969	+0.2	+6	+0	Oct. 13	Oct. 4
1970	+0.7	+21	+1	Oct. 14	Oct. 5
1971	+7.1	+213	+12	Oct. 25	Oct. 16
1972	-4.9	-147	-8	Oct. 5	Oct. 27
12-year average				Oct. 14	Oct. 5

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