Establishing a Construction Cutoff Date for Placement of Aggregate-Lime-Pozzolan

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Aggregate-lime-pozzolan has been, for the most part, successfully used as a base course and shoulder material in flexible pavement construction in Pennsylvania. However, a number of recent failures associated with late-season construction have occurred. These failures prompted the Pennsylvania Department of Transportation to impose a construction cutoff date for the placement of the material. In this paper, failure criteria based on attained tensile strengths and the probabilities of attaining these tensile strengths before the freezing season are established. Total probabilities of failure of a typical 3 percent lime, 15 percent fly ash, and 82 percent limestone aggregate (regular mix) are determined and plotted against placement dates. An acceptable failure probability is chosen, and the corresponding placement date is designated as the cutoff date for placement of the typical aggregate-lime-pozzolan material. Two field demonstration projects were monitored for one freezing season to verify the chosen cutoff date.

As part of a program of testing and evaluation of troublesome materials, the Bureau of Materials, Testing and Research of the Pennsylvania DOT conducted in-depth research on aggregate-lime-pozzolan (ALP) material. This research confirmed that the poor performance of ALP resulted because the material had not been placed far enough in advance of probable freezing conditions to allow adequate strength gain (curing). Consequently, the bureau decided to determine a construction cutoff date to be incorporated into Pennsylvania DOT specifications on the use of ALP material in highway construction.

The research work presented here was performed to develop a failure criterion for ALP, based on strength characteristics, with which to statistically evaluate actual temperature data in certain areas of the state and to determine ALP material failure probabilities given a placement date and location. Ultimately, the work was done to develop a technique for establishing realistic construction cutoff dates that when implemented would eliminate or substantially reduce recently experienced material failures.

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TENSILE STRENGTH FAILURE CRITERION

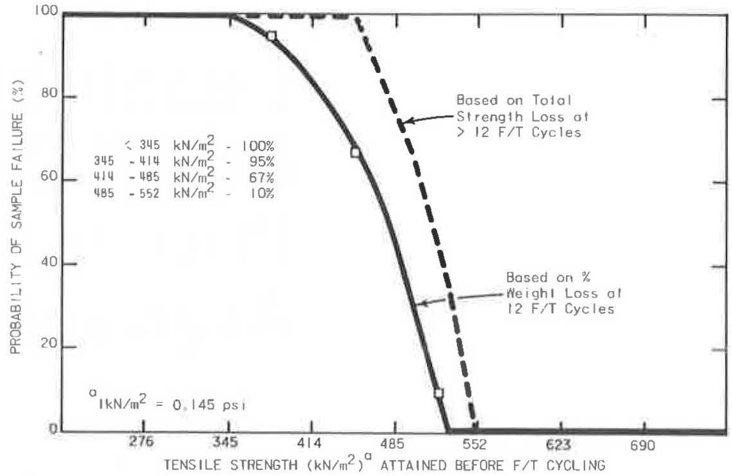
For tensile strength testing, the double punch test developed at Lehigh University (2) is a relatively quick and reproducible test that simulates actual field failure conditions better than the more commonly used unconfined compression test (1). Failure during freezing occurs when interparticulate, cementitious bonds break under tensile stresses induced by freezing pore water or the formation of ice lenses or both. Consequently, 231 cylinders were tested to determine a relationship between double punch tensile strengths and the number of freeze-thaw (F-T) cycles at failure as described in a previous publication (1).

Figure 1 shows probability curves for a sample failing during F-T cycling for any tensile strength value achieved prior to freeze-thaw testing. The solid and dashed curves shown in this figure were deduced from the results of tests on the 231 samples mentioned above.

1. The solid line represents failure defined as 14 percent weight loss after 12 freeze-thaw cycles (AASHO T-136-70). The probability of failure was determined by dividing the number of samples having initial tensile strengths in a particular range 345 to 414, 414 to 483, and 483 to 552 kPa (50 to 60, 60 to 70, and 70 to 80 psi) that failed by the total number of samples in the same range. For example, approximately 67 percent of the samples with tensile strengths prior to F-T cycling of 414 to 483 kPa (60 to 70 psi) failed.
2. The dashed line represents failure defined as eventual total loss of tensile strength after some reasonable number of F-T cycles greater than 12. A probability of failure was determined as previously described by using the same range of tensile strengths before F-T cycling. By this failure definition, all samples in the range of 414 to 483 kPa (60 to 70 psi) or lower failed.

Using varying failure probabilities over a tensile strength range of 345 to 552 kPa (50 to 80 psi) is more realistic than using a single tensile strength of 483 kPa (70 psi) as the criterion for acceptance or failure. When the standard AASHO T-136-70 was used to define failure,

Figure 1. Probability of sample failure before freeze-thaw cycling given an initial tensile strength.



the results were as follows:

Strength (kPa)	Percentage of Failure
<345	100
345 to 414	95
414 to 483	67
483 to 552	10
>552	Negligible

Frequency Analysis

The goal was not only to determine material failure probabilities based on attained tensile strengths but also to determine what probabilities were associated with attaining a given tensile strength before the start of the freezing season in Pennsylvania. Because curing is primarily a function of temperature and time, a degree-day concept based on 255.4 K (0°F) was used in the prediction of tensile strength to combine the temperature and time parameters into a single unit.

A statistical analysis of frequency, typically used in hydrological studies, was performed on predicted tensile strengths with 26 years of maximum-minimum daily temperature data from nine first-order weather stations. Three weather stations (one with exceptionally cold temperatures, one with exceptionally warm temperatures, and one with moderate temperatures) were used from Pennsylvania DOT districts in the Philadelphia, Harrisburg, and Pittsburgh areas in which most of the ALP material is produced and placed. Average daily air temperatures (ADAT) were calculated for each day from August 1 through December 31. This period was chosen to ensure the ultimate construction cutoff date would be included. Because a 255.4 K base was used, the ADAT was simply equated to degree-days.

The temperature data were computerized so that the total tensile strength gained by December 31 was predicted for placement dates of August 1 and 15, September 1 and 15, and October 1 and 15 for each of the 26 years at each of the nine weather stations. Temperature data were manipulated as follows.

1. ADATs or degree-days were cumulated in three different registers beginning on the ninth day after placement. Because of a delay in the start of the chemical reaction, the initial cure rate is much slower; and, therefore, an average tensile strength gain of only 55 kPa (8 psi) resulted from the first 8 days of curing. The three registers correspond to the temperature ranges of 285.9 to 292.6, 292.7 to 297.0, and greater than 297 K (55 to 67, 68 to 75, and greater than 75°F) used in developing the cure rate curves depicted in Figure 2. At temperatures below 285.9 K (55°F), no appreciable gain in tensile strength was achieved under field conditions.

2. The cumulated real degree-days (heat energy index) in each temperature range were converted to a partial tensile strength for that range by means of a linear equation. Because all total cumulated degree-days were within the straight-line portions of the cure rate curves in Figure 2, the following linear equations were used.

$$\sigma x = 0.041x \qquad \sigma y = 0.049y \qquad \sigma z = 0.078z \tag{1}$$

where x, y, and z are the cumulated real degree-days for the temperature ranges 285.9 to 292.6, 293.2 to 297, and greater than 297 K (55 to 67, 68 to 75, and greater than 75°F) respectively and σx, σy, and σz are the associated partial tensile strengths. It should be noted that all lines (as indicated by these equations) intercept the ordinate axis at zero. The authors felt that the second linear portion of the curves for each temperature range was the true cure rate although the first linear portion was a result of the initial delay in the start of true curing. Compensation for strength gain during this initial delay period is made below.

3. The partial tensile strengths for each temperature range were then summed to obtain the total tensile strength (σ_t) gained. An additional 55 kPa (8 psi) was included in this total to represent the average strength gained during the first 8 days of curing.

$$\sigma_t = 55 + 6.89[0.041(x) + 0.049(y) + 0.078(z)] \tag{2}$$

4. The average of the tensile strengths for the three weather stations was obtained for each of the three districts. Therefore, an average tensile strength was tabulated for each of the three districts, for each of the six placement dates, and for each of 26 years.

Figure 3 shows theoretical frequency curves based on some of the cumulative tensile strength data described above. The data for each district and each date (one point for each of the 26 years) are placed in ascending numerical order and assigned a frequency or probability of occurrence based on a 26-point sample group. From Figure 3, a tensile strength of 310 kPa (45 psi) or higher should occur 50 percent of the time or every other year in District 6-0 if the material is placed on October 1. Likewise, the probability that the tensile strength will be 345 kPa (50 psi) or less is approximately 64 percent, and the probability that the tensile strength will be 414 kPa (60 psi) or less is 86 percent. Therefore, the probability that the tensile strength will be in the 345 to 414 kPa (50 to 60 psi) range for the October 1 placement date in District 6-0 is 86 percent minus 64 percent or 22 percent.

Air and Base Course Temperature Correlation

The initial frequency curves shown in Figure 3 were derived by using air temperatures; however, ALP cures from base course temperatures, which are generally

Figure 2. Tensile strength gain for various curing temperatures.

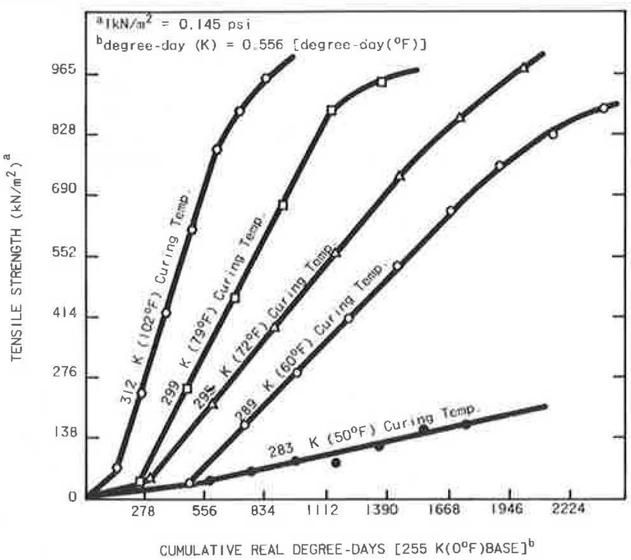


Figure 3. Cumulated tensile strengths versus frequency of occurrence (District 6-0).

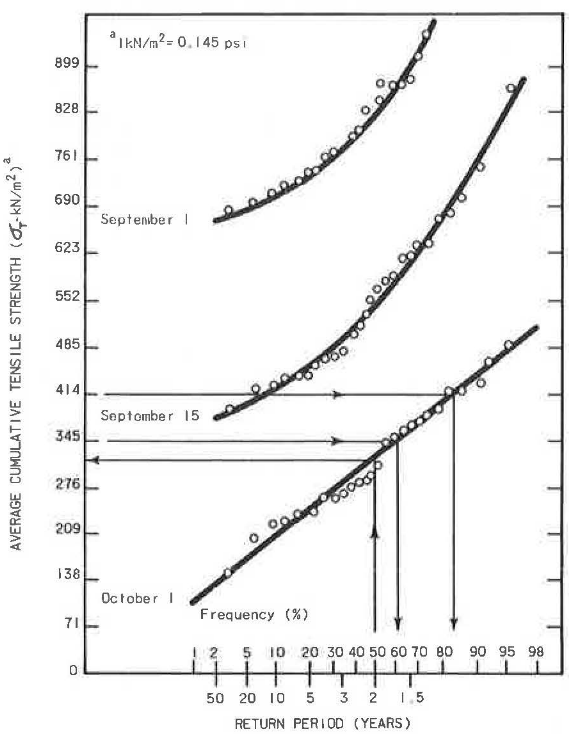


Figure 4. Relationship between monthly ADAT and average base temperature increase over air temperature for various depths to the midpoint of the base layer.

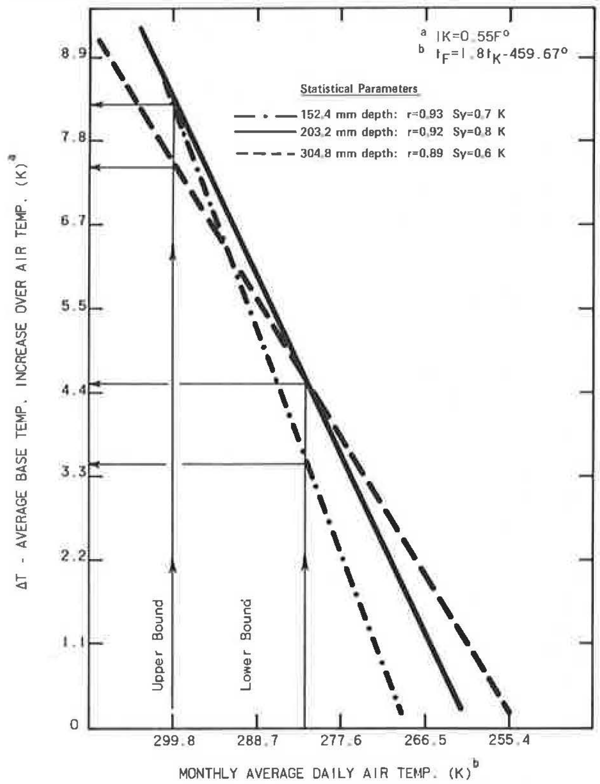
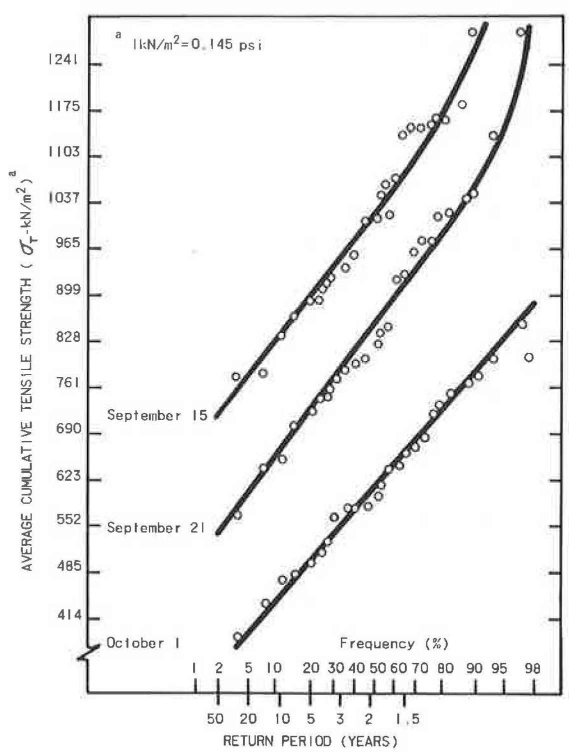


Figure 5. Cumulative tensile strength versus frequency of occurrence.



higher during the investigated season. Air, surface, and pavement profile temperatures (available from a research project entitled Freezing Indices and Regional Climates) were compared statistically to provide a method for legitimately adjusting air temperatures within the pavement system. Four years of data were collected at 14 flexible pavement installations located throughout the state. Monthly ADATs were regressed with average increases of base temperatures (thermocouple measurements at the top, midpoint, and bottom of the base layer) over air temperatures. Initially, the data were grouped according to surface layer thicknesses; however, this procedure resulted in low correlation coefficients. Grouping of the data according to total depths from the surface to the base layer midpoints resulted in good correlation (Figure 4).

Figure 4 shows that average temperature increases at 152.4, 203.2, and 304.8-mm-deep (6, 8, and 12-in) base midpoints are very similar within the range of monthly average daily temperatures used. When the figure is entered on the abscissa at 281.5 K (47°F) (lower bound), increases of approximately 3.3 K to 4.4 K (6 to 8°F) are realized. Therefore, by increasing an ADAT of 281.5 K (47°F) by 4.4 K (8°F) to simulate base temperature, the minimum temperature of 285.9 K (55°F) for appreciable curing to take place is obtained. Moreover, an average daily air temperature of 299.8 K (80°F), which corresponds to increases of approximately 7.2 to 8.3 K (13 to 15°F) in the pavement system, was never exceeded in the investigated ADAT data.

A second frequency analysis of tensile strengths, using simulated base temperatures, was performed and resulted in the curves shown in Figure 5. This frequency analysis was made as previously described except that each average daily air temperature of 281.5 K or greater (47°F or greater) was adjusted up by the maximum temperature increase (ΔT) corresponding to the 203.2-mm (8-in) depth to base midpoint line shown in Figure 4.

Failure Probabilities for Particular Placement Dates

The overall probability that a material would fail given a particular placement date was calculated by multiplying the probability of failure during freeze-thaw cycling for an initial tensile strength by the probability of attaining that initial tensile strength before the freezing season under Pennsylvania temperature conditions (Table 1). For example, if ALP material is placed on October 1 in District 6-0, the probability that it will have a tensile strength value between 414 and 483 kPa (60 and 70 psi) by December 31 is 15 percent less 8 percent or 7 percent; and the probability that a material with an initial strength of 414 to 483 kPa will fail is 67 percent. Therefore, the partial probability of failure associated with a strength range of 414 to 483 kPa is 7 times 67 or 4.7 percent. The total probability that a material placed on October 1 in District 6-0 will fail is the sum of all the partial probabilities for the tensile strength ranges. A summary of total probability data is given in Table 1 for all three districts. A plot of these total probabilities of failure against the corresponding material placement dates for each district is shown in Figure 6.

Choice of Construction Termination Date

The curves of construction cutoff dates versus total probability of failure shown in Figure 6 indicate a negligible probability of failure for material placed on September 15. However, excessive failure probabilities of 10 to 16 percent exist for the October 1 placement date. An evaluation using September 21 as the placement date resulted in probabilities of failure of approximately 0.5 to 1.0 percent. Acceptance of slightly higher probabilities of failure could have been tolerable; however, upon consideration of the possibly idealized optimum mix design and maximum densities used in developing these failure probabilities, the choice of the September 21 construction cutoff date and the apparently low failure acceptance seems justified. Moreover, an increase of the accepted total probability of failure to as much as 5 percent would have extended the construction season by only a few days. Therefore, September 21 has been specified by the Pennsylvania DOT as the termination date for construction with ALP material in Districts 6-0, 8-0, 11-0, and 12-0. This construction cutoff date is intended for the remaining mountainous and northern portions of the state when increased use of ALP material in those areas justifies it. Until additional investigation is completed, a September 1 construction cutoff date has been specified for the remaining colder portions of the state.

These cutoff dates are based on the regular ALP mix as stated earlier. Adding small percentages of cement or other agents that substantially increase the rate of curing enables acceptable strengths to be attained in shorter time periods. Hence, the construction termination date may be extended to later in the season in these situations.

Field Demonstration Projects

Two demonstration test sections were installed during fall of 1974 to verify the specified September 21 cutoff date and to observe the performance of new mix designs with special additives. One project was a 305-m-long (1000-ft) section of County Line Road in North Philadelphia (District 6-0) where two sections of the regular ALP mix and three sections of new mixes with additives to increase the rate of curing were placed. The second field installation was located in Ephrata Borough, Lancaster County (District 8-0), where 90-m-long (300-ft) sections of the regular mix and a new mix design were placed.

Regular mix ALP material was placed at the County Line Road project on September 14 before the specified construction cutoff date. The computer model, using actual maximum and minimum daily air temperatures at the site, predicted that this material would attain a tensile strength of 931 kPa (135 psi). The material placed on September 14 had an in-place tensile strength of 593 kPa (86 psi) by December 31 (Figure 7). This in-place tensile strength was obtained by averaging the strengths of a minimum of three core samples for each drilling date. Although the ALP material placed before the cutoff date did develop adequate tensile strength by December 31, this strength was only about two-thirds of that predicted by the model. Two possible reasons for this discrepancy are (a) lack of sufficient moisture to propagate the hydration process during the latter stages of the ALP field curing and (b) an alteration of the curing characteristics of ALP after the 4-day cold period during the third week in October. Laboratory cure rate curves were developed under ideal conditions in which environmental moisture was controlled. If the material dried too rapidly under field conditions, all of the potential chemical reaction would not take place and slower cure rates would result. During the fifth week of curing, subfreezing air temperatures occurred on 4 consecutive days. The ADATs on these days were 276.5 to 277.6 K (38 to 40°F). The cure rate after this cold period was apparently slower than the rate before. This slower rate may have been caused by a delay in the resumption of the curing process after the cold period or a breakdown of some of the previously formed bonds. Some adjustments to the computer model appear warranted and will be made

Table 1. Total probabilities of material failure by placement dates and districts.

Placement Date	Tensile Strength Range (kPa)	Probability That Cumulative Tensile Strength Will Be Within Range (%)			Probability of Failure Given a Strength Within the Range (%)			Total Probability of Failure (%)		
		6-0[a]	8-0[a]	11-0[a]	6-0[a]	8-0[a]	11-0[a]	6-0[a]	8-0[a]	11-0[a]
September 15	<345	0.0	0.0	0.0	100	100	100	—	—	—
	345 to 414	0.0	0.0	0.0	95	95	95	—	—	—
	414 to 483	0.0	0.0	0.0	67	67	67	—	—	—
	483 to 552	<1.0	<1.0	<1.0	10	10	10	<0.1	<0.1	<0.1
								<0.1	<0.1	<0.1
September 21	<345	<0.1	<0.1	<0.1	100	100	100	—	0.1	—
	345 to 414	0.1	0.2	0.1	95	95	95	0.1	0.2	0.1
	414 to 483	0.4	0.6	0.5	67	67	67	0.2	0.4	0.3
	483 to 552	1.1	1.7	1.5	10	10	10	0.1	0.2	0.2
								0.4	0.8	0.6
October 1	<345	1.3	2.3	2.3	100	100	100	1.3	2.3	2.3
	345 to 414	3.0	5.0	4.3	95	95	95	2.8	4.8	4.1
	414 to 483	7.0	11.0	9.0	67	67	67	4.7	7.3	6.0
	483 to 552	13.0	17.7	14.4	10	10	10	1.3	1.8	1.4
								10.1	16.2	13.8
October 15	<345	38.0	51.0	38.0	100	100	100	38.0	51.0	38.0
	345 to 414	23.0	23.0	24.0	95	95	95	21.9	21.8	22.8
	414 to 483	20.0	15.0	21.0	67	67	67	13.4	10.0	14.0
	483 to 552	11.0	8.0	11.0	10	10	10	1.1	0.8	1.1
								74.4	83.6	75.9

Note: 1 kPa = 0.145 psi.
[a]District of Pennsylvania Department of Transportation.

Figure 6. Total probabilities of material failure by material placement date.

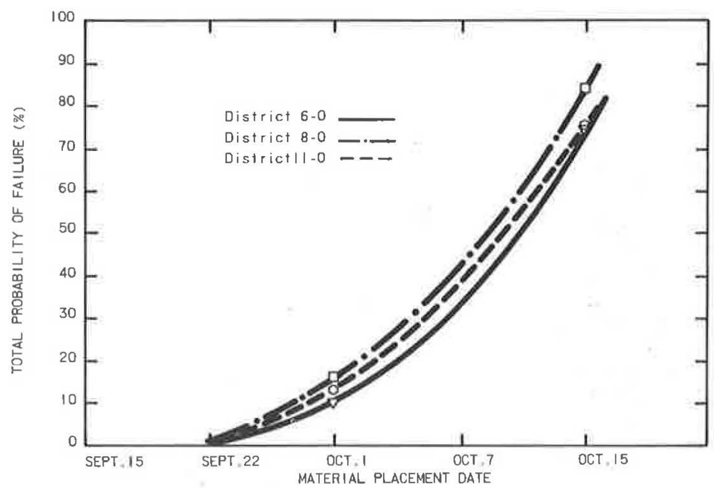
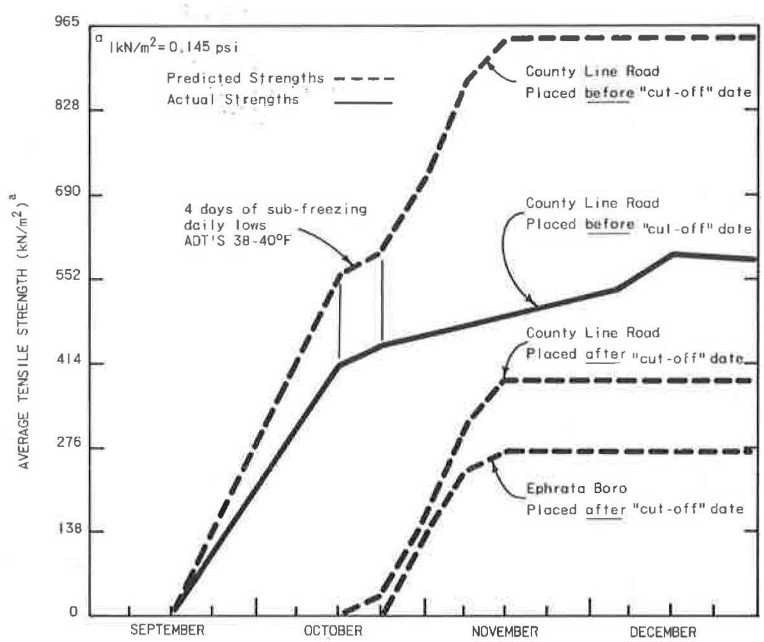


Figure 7. Predicted and actual tensile strengths at field demonstration sites.



as additional field curing data become available.

A second section of regular mix ALP material was placed at the County Line Road project on October 14, 3 weeks after the specified construction cutoff date. A tensile strength gain to December 31 of only 386 kPa (56 psi) was predicted for this material. The material placed after the cutoff date never attained a tensile strength high enough to obtain cores suitable for actual tensile strength testing. At least three attempts to obtain cores were made in each test section on a biweekly schedule. Previous drilling experience has shown that ALP with tensile strengths of about 345 kPa (50 psi) or less breaks apart when cored.

Cores obtained after the spring thaw on April 24, 1975, showed that the regular mix placed before the cutoff date had an average tensile strength of 580 kPa (84 psi), i.e., no appreciable strength loss during the freezing season. It was still impossible on April 24 to obtain cores of the ALP placed after the cutoff date. Moreover, all the lime and fly ash fines were washed from the limestone aggregate by the drill water, which indicated that few or no cementitious bonds remained. The material was apparently degraded by the freeze-thaw action of the previous freezing season.

The results were similar on the demonstration project in Ephrata Borough where the regular ALP mix was placed on October 22, approximately 1 month after the cutoff date. A tensile strength gain by December 31 of 267 kPa (39 psi) was predicted. Again, only broken pieces of cores were obtained after numerous drilling attempts. Again, almost total disintegration of the cementitious bonds was apparent during coring operations after the spring thaw.

These two field demonstration projects did verify that the cutoff date of September 21 for regular mix ALP is reasonable for Districts 6-0 and 8-0. The material placed 1 week before the cutoff date achieved adequate strength to withstand the freeze-thaw action of the initial freezing season. However, the material placed 3 and 4 weeks after the cutoff never attained a suitable tensile strength and deteriorated substantially from the freeze-thaw action of the initial freezing season.

The four sections of new mix designs with special additives for late-season construction provided significant data. These new designs showed accelerated early strength gains but attained ultimate strengths the same as or slightly lower than those of the regular mix. It appears that these new mix designs may be used for late-season construction after the currently specified September 21 cutoff date. However, further testing and analyses of curing properties at the considerably lower curing temperatures of October and November and of long-term effects of multiple freezing seasons on the new designs are warranted before the use of these materials is specified by the Pennsylvania DOT.

CONCLUSIONS

Based on the results of this research work, the following conclusions have been drawn.

1. Tensile strengths gained by in-place ALP material before exposure to any freezing temperatures provide a good criterion for material acceptance or failure. Materials with tensile strengths less than 345 kPa (50 psi) have a negligible chance of surviving a moderate freezing season in Pennsylvania. Materials with tensile strengths ranging from 345 to 552 kPa (50 to 80 psi) have varying probabilities of failure according to curves shown in Figure 1. Materials with tensile strengths greater than 552 kPa (80 psi) before freeze-thaw cycling have a negligible chance of failure.

2. A frequency analysis based on readily available daily air temperature data may be used to predict construction termination dates for any material that requires temperature-time dependent curing. Cure rates for various temperature ranges must initially be established. A degree-day concept (based on any appropriate temperature) may then be used to convert temperature data to strength gain. Finally, a reasonable amount of tolerable failure (based on a strength criterion) must be chosen.

3. Air temperatures should be converted to pavement system temperatures to simulate realistic curing conditions for pavement materials. Because average pavement temperatures are substantially higher than air temperatures (Figure 4) during most of the investigated curing season, the strength gains from actual pavement temperatures will be accelerated over those predicted from air temperatures.

4. Based on two field demonstration projects that were monitored for one freezing season in Districts 6-0 and 8-0, the choice of the September 21 construction cutoff date appears reasonably good. Comparisons of predicted and in-place tensile strengths indicated some discrepancies; therefore, some adjustments to the computer model appear warranted.

5. Additives that increase rates of curing and strength development should be investigated when construction after the cutoff date is necessary. Economic analyses of additive costs versus longer construction seasons should be made.

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

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