Quantitative Characterization of Cyclic Freezing and Thawing in Stabilized Pavement Materials

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Frost action parameters (cooling rate, freezing temperature, duration of freezing, warming rate, thawing temperature, and duration of thawing) for a typical pavement section with a stabilized base course were developed for 30 years of climatic data for five separate locations in Illinois. All calculations were accomplished with the multilayered pavement heat-transfer model developed at the University of Illinois. An idealized freeze-thaw cycle was established for analysis purposes. The frost action parameter data showed substantial variability as related to the effects of geographical location, year, and month. Comparisons of the data with the standard ASTM and AASHO freeze-thaw testing procedures indicated that the standard procedures did not adequately simulate field service conditions in Illinois. The substantial discrepancies between test and field conditions present just cause for careful scrutiny of the standard test procedures and the interpretation of the test results. It is apparent from the results of this study that more realistic and rational freeze-thaw durability testing procedures should be developed for stabilized materials. Appropriate frost action parameter data, similar to those generated in this study, should be considered in the development of such improved testing procedures.

•STABILIZED MATERIALS such as soil-cement, lime-fly ash aggregate mixtures, and lime-soil mixtures are used extensively as base and subbase layers in pavement construction. In the areas where frost action occurs, these materials must retain their integrity and maintain adequate residual strength at all times in order to provide adequate structural performance. Repetitive cycles of freezing and thawing are detrimental, particularly as related to volume change and strength loss.

To achieve maximum efficiency in mixture design and pavement analysis, it is essential to properly assess the freeze-thaw action that the pavement system and stabilized materials will experience during the service life of the pavement. The ASCE Committee on Structural Design of Roadways (1) has recently emphasized the inadequate attention generally given to environmental variables during the pavement design process. The extreme variability of climatic factors as related to geographical location and time (year to year and within year) must be taken into account. It is also desirable to have the capability of evaluating the effect of other important factors such as thickness of various pavement layers and thermal and physical properties of constituent materials.

CURRENT PRACTICE

Freeze-thaw testing is currently considered in the design of soil-cement and lime-fly ash aggregate mixtures. The suggested test procedures, as outlined in ASTM D 560-57 (AASHO T 136-57) and ASTM C 593-66T, are quite similar. Twelve freeze-thaw cycles are required. Freezing is at < -10 F for 24 hours and thawing at 70 F for 23 hours in both procedures.

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Packard and Chapman (2) indicate that in the standard tests "8 hours at most are required to bring the specimen's temperature (interior) to -10F." This corresponds to a rate of cooling of 10 F per hour. According to Norling (3), "The number of cycles of testing and their duration was evolved by exploratory tests on freezing temperatures, freezing time, drying time, and soaking time. Twelve cycles for each test produced interpretable data and also met the requirements of a practical time limit."

Thompson (4) has proposed a mixture design procedure for lime-soil mixtures that considers freeze-thaw action. However, no standard freeze-thaw test procedure has yet been developed by ASTM or AASHO for lime-soil mixtures.

There is a dearth of factual information concerning the nature of the freeze-thaw action that occurs in field pavement systems. It is not surprising that current laboratory testing procedures and techniques are quite empirical in nature and are not assumed to be truly representative of field service conditions. Mielenz (5, p. 32), in a paper concerning the accelerated durability testing of concrete, stated:

> The value of any accelerated test lies in the degree to which the service condition is simulated and the extent to which the physical, chemical, and mechanical responses of the concrete in the service condition are reproduced in the method of test. Any substantial departure from reality in these respects is likely to produce erroneous decisions in the approval or rejection of the proposed concrete mixture or the treatment that is under investigation.

Cordon (6), in his ACI Monograph on freezing and thawing of concrete, suggested, "Where specific materials are being considered for a particular structure. . . it may be desirable that freezing and thawing tests simulate actual field exposure."

It is apparent that the freeze-thaw environment must be quantitatively characterized if pavement service life and performance are to be adequately predicted. This paper describes the use of a theoretical heat-transfer model for developing such quantitative data.

HEAT-TRANSFER MODEL

There are a large number of variables that influence freeze-thaw action in a pavement system. It is prohibitive and impractical to gather field data in the hope of quantitatively characterizing freeze-thaw action (7). The only realistic procedure that can be used to develop sufficient data for characterizing frost action is the development of a model that accurately simulates the temperature regime in a pavement system. Input data for the model should consist of pertinent past climatic data (maximum and minimum daily air temperature, percentage of possible sunshine, and average daily wind velocity) and appropriate parameters for describing the pavement section and its constituent materials. Utilization of the model to analyze several years of past climatic data would provide a sufficient quantity of information for adequately characterizing the frost action in a pavement system.

A heat-transfer model with the capabilities described has been developed and verified at the University of Illinois. Model development and details have been presented elsewhere (7).

CYCLIC FREEZE-THAW

Considerable study has been devoted to the mechanism of frost action in concrete. These studies, recently summarized by Kennedy (8), have resulted in the development of theoretical models for explaining the behavior of freezing cement paste.

The theoretical models, as well as experimental data, suggest that the rate of freezing is a significant factor affecting deterioration due to hydraulic pressure. The length of time the concrete remains frozen and the temperature to which it is frozen relate to the extent of deterioration associated with development and growth of ice bodies within the cement paste.

Because of the similarity in the nature of the cementing products (primarily hydrated calcium silicates and calcium aluminates) in concrete, soil-cement, lime-fly

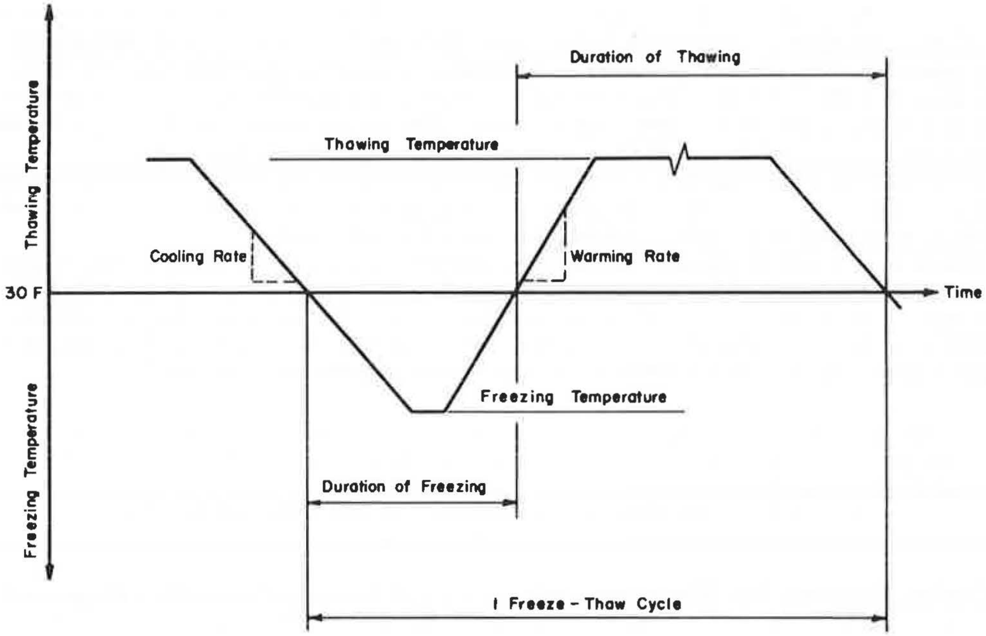

Figure 1. Idealized freeze-thaw cycle.

ash aggregate, and lime-soil mixtures, it is probable that the theories relating to cement paste would also be qualitatively applicable for other materials.

Based on the available theories for explaining frost action in concrete, the idealized freeze-thaw cycle shown in Figure 1 appears to include all the pertinent features of importance as follows:

1. Cooling rate,
2. Freezing temperature,
3. Duration of freezing temperature,
4. Warming rate,
5. Thawing temperature, and
6. Duration of thawing temperature.

Items 1, 2, and 3 are the most significant features relative to cyclic freeze-thaw damage.

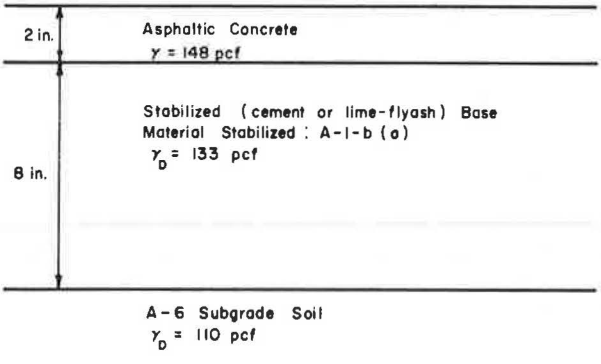

Figure 2. Pavement section analyzed.

The quantitative parameters for the idealized cycle, for a given point in the pavement system, would vary depending on geographical location, month of the year during the freezing period, and the year.

A freeze-thaw history for a given point in a pavement could be simulated by (a) developing an idealized freeze-thaw cycle for each freezing month for each year of available climatic record, and (b) determining how many freeze-thaw cycles occurred during the month. Statistical analyses of the

TABLE 1

Frost Action Parameter Data

Station	October			November			December			January			February			March			Year		
	Avg.	$\sigma^{(a)}$	V,%$^{(b)}$	Avg.	$\sigma^{(a)}$	V,%$^{(b)}$	Avg.	$\sigma^{(a)}$	V,%$^{(b)}$	Avg.	$\sigma^{(a)}$	V,%$^{(b)}$	Avg.	$\sigma^{(a)}$	V,%$^{(b)}$	Avg.	$\sigma^{(a)}$	V,%$^{(b)}$	Avg.	$\sigma^{(a)}$	V,%$^{(b)}$
Cooling Rates, °F/hr																					
Chicago	0.54	0.05	9.97	0.35	0.04	11.49	0.19	0.06	32.12	0.21	0.07	32.91	0.22	0.10	43.36	0.46	0.08	17.59	0.33	0.02	7.13
Moline	0.55	0.06	11.20	0.35	0.05	13.16	0.19	0.06	29.48	0.23	0.08	36.19	0.23	0.10	43.13	0.48	0.08	17.61	0.34	0.02	7.26
Springfield	0.59	0.06	10.71	0.40	0.50	12.28	0.23	0.06	27.17	0.23	0.07	30.89	0.32	0.09	28.12	0.53	0.07	12.88	0.38	0.02	6.19
St. Louis	0.58	0.07	12.65	0.43	0.05	10.67	0.27	0.06	23.20	0.27	0.07	26.05	0.38	0.09	28.69	0.56	0.07	11.96	0.41	0.03	7.71
Cairo	0.66	0.08	11.94	0.48	0.04	8.81	0.34	0.06	18.06	0.34	0.06	16.78	0.45	0.08	17.65	0.62	0.05	7.79	0.48	0.03	6.45
Below Freezing Temperatures, °F																					
Chicago	None	-	-	26.24	1.44	5.47	26.46	1.70	6.41	25.45	2.65	10.41	26.08	2.33	9.93	27.56	0.50	1.80	25.41	1.94	7.63
Moline	None	-	-	26.42	2.08	7.89	25.79	2.20	8.51	24.33	2.75	11.31	25.84	2.90	11.21	26.80	1.09	4.08	24.45	2.25	9.60
Springfield	None	-	-	26.98	None	None	26.81	1.42	5.29	25.82	2.22	8.58	26.32	2.04	7.76	28.27	1.16	4.12	25.94	1.77	6.82
St. Louis	None	-	-	None	-	-	27.77	0.96	3.46	26.50	1.78	6.72	27.39	1.52	5.54	None	-	-	26.94	1.44	5.33
Cairo	None	-	-	None	-	-	27.44	0.95	3.45	27.24	1.28	4.70	28.82	1.27	4.42	None	-	-	27.42	1.16	4.24
Duration of Freezing, Days																					
Chicago	0.0	0.0	0.0	0.10	0.29	305.15	1.81	2.17	119.87	2.75	3.29	119.91	1.90	4.22	222.60	0.14	0.33	227.52	2.25	1.38	61.39
Moline	0.0	0.0	0.0	0.09	0.28	306.04	2.05	2.52	123.05	3.43	3.14	91.52	2.60	4.86	186.67	0.15	0.33	229.60	2.61	1.43	54.53
Springfield	0.0	0.0	0.0	0.03	0.16	547.72	0.87	0.90	103.36	1.60	1.80	112.50	0.94	2.08	221.63	0.07	0.23	308.48	1.65	1.35	81.89
St. Louis	0.0	0.0	0.0	0.0	0.0	0.0	0.39	0.54	144.19	1.10	1.70	161.78	0.43	1.25	291.73	0.0	0.0	0.0	1.24	1.21	97.74
Cairo	0.0	0.0	0.0	0.0	0.0	0.0	0.09	0.28	305.27	0.31	0.63	206.00	0.05	0.17	381.57	0.0	0.0	0.0	0.38	0.63	165.90
Warming Rates, °F/hr																					
Chicago	0.88	0.11	12.08	0.54	0.07	13.29	0.30	0.10	34.57	0.32	0.12	35.54	0.36	0.16	45.02	0.81	0.15	18.53	0.54	0.04	8.08
Moline	0.90	0.11	12.62	0.54	0.09	16.83	0.31	0.10	32.21	0.34	0.02	36.35	0.39	0.17	43.13	0.83	0.15	17.60	0.57	0.04	7.40
Springfield	0.97	0.12	11.95	0.62	0.09	14.64	0.36	0.11	30.09	0.36	0.13	35.69	0.53	0.16	30.00	0.95	0.12	13.20	0.63	0.04	6.44
St. Louis	0.97	0.13	13.29	0.67	0.08	11.27	0.44	0.12	26.95	0.45	0.13	28.20	0.65	0.15	23.70	0.99	0.11	11.48	0.70	0.06	7.95
Cairo	1.10	0.13	11.87	0.76	0.70	9.82	0.54	0.10	18.28	0.57	0.10	17.06	0.76	0.14	18.03	1.08	0.07	6.79	0.80	0.05	6.28
Above Freezing Temperatures, °F																					
Chicago	59.69	3.03	5.07	44.42	2.56	5.94	35.19	2.94	8.37	32.76	2.31	7.04	34.32	2.49	7.26	43.69	4.16	9.51	42.93	1.49	3.48
Moline	60.00	3.38	5.98	44.12	2.88	6.53	34.70	2.81	8.09	32.23	1.95	6.05	34.13	2.68	7.87	44.56	4.11	9.23	43.15	1.39	3.23
Springfield	62.25	3.06	4.92	46.93	2.84	6.05	37.09	3.22	8.67	34.74	3.02	8.69	37.95	3.14	8.27	48.29	4.30	8.91	45.27	1.37	3.02
St. Louis	64.57	3.16	4.90	49.86	2.74	5.48	40.11	3.55	8.85	37.94	3.64	9.60	41.54	3.70	8.91	51.50	4.36	8.46	47.94	1.49	3.11
Cairo	66.57	2.73	4.10	52.68	2.61	4.96	43.10	3.43	7.96	41.19	3.54	8.59	45.00	4.10	9.11	55.02	4.10	7.45	50.76	1.40	2.76
Duration of Thawing, Days																					
Chicago	30.38	0.0	0.0	28.11	5.82	20.72	10.91	9.44	86.47	7.13	8.95	125.57	12.38	10.23	82.60	27.64	7.95	28.77	16.80	10.99	65.43
Moline	30.38	0.0	0.0	28.45	4.72	16.58	10.60	11.03	104.12	6.69	8.88	132.74	9.59	8.80	91.76	27.05	9.06	33.49	14.76	8.47	57.37
Springfield	30.38	0.0	0.0	29.49	2.82	9.56	15.64	12.93	82.67	10.62	10.91	102.73	19.17	10.61	55.37	29.41	4.84	16.46	35.40	44.15	124.75
St. Louis	30.38	0.0	0.0	30.00	0.0	0.0	22.40	11.74	52.48	17.68	11.71	66.24	23.06	8.56	37.10	31.00	0.0	0.0	61.28	51.24	83.62
Cairo	30.38	0.0	0.0	30.00	0.0	0.0	28.73	6.96	24.22	24.54	11.11	45.26	26.22	5.69	21.71	31.00	0.0	0.0	130.52	69.36	53.14
Number of Freeze-Thaw Cycles																					
Chicago	0.0	0.0	0.0	0.17	0.53	318.48	3.17	2.60	82.13	4.93	3.37	68.36	2.40	2.47	103.00	0.43	1.28	294.93	11.10	5.57	50.15
Moline	0.0	0.0	0.0	0.10	0.31	305.13	3.93	3.03	76.98	4.37	3.03	69.48	2.93	2.64	89.94	0.60	1.65	275.43	11.93	5.35	44.83
Springfield	0.0	0.0	0.0	0.03	0.18	547.72	2.83	2.89	101.99	3.70	3.26	88.12	1.13	1.72	151.48	0.10	0.31	305.13	7.80	5.10	65.41
St. Louis	0.0	0.0	0.0	0.0	0.0	0.0	1.23	1.94	157.46	1.70	1.90	115.56	0.47	0.86	184.36	0.0	0.0	0.0	3.40	2.40	70.62
Cairo	0.0	0.0	0.0	0.0	0.0	0.0	0.27	0.87	325.63	1.23	2.81	228.03	0.30	1.29	430.18	0.0	0.0	0.0	1.80	3.46	192.12

a - Standard deviation

b - Coefficient of Varation = $\frac{(\sigma)(100)}{Avg}$

data would provide satisfactory information for quantitative characterization of the freeze-thaw environment. The data would be invaluable as input for laboratory testing procedures where it is desirable to simulate field conditions.

DATA DEVELOPMENT

The typical pavement cross section shown in Figure 2 was analyzed using the heat-transfer model. The typical section is characteristic of the type used for local and secondary roads in Illinois.

Only the data for the freezing months (October to March) were used. Thirty years of climatic data (1918-1947) were analyzed for five locations in Illinois (Chicago, Moline, Springfield, East St. Louis, and Cairo). These stations provide excellent north-south coverage of the state. The basic temperature trends in Illinois are from north to south.

Statistics, based on 30 observations, for the mean values of the various segments of the idealized freeze-thaw cycle (Fig. 1) are presented in Table 1. The statistics are for node 3, which is located 4 in. beneath the surface of the pavement and 2 in. below the surface-stabilized base course interface. Node 3 conditions are considered to be representative of the more intensive frost action occurring near the upper surface of the stabilized base course.

DATA ANALYSIS

Table 2 gives mean values based on 30 years of data for all months (October to March) by station and by month. Grand mean values, based an all the data, are also given in Table 2.

The frost action parameters for the five stations were compared statistically to determine if there were significant differences. Results of the analysis indicated the following:

1. There was a statistically significant (α = .01) difference for all of the frost action parameters relative to the influence of months. Thus, the parameters are not the same for all of the months (October to March).
2. There was a statistically significant (α = .01) difference for all of the frost action parameters relative to the influence of station (location in Illinois). Thus, the frost action parameters are not the same for the various Illinois locations.

TABLE 2

Mean Values for Frost Action Parameters-Station and Month Effects

Effects	Frost Action Parameter						
	Cooling Rate, °F/ hr	Below Freezing T, °F	Duration of Freezing, days	Warming Rate, °F/hr	Above Freezing T, °F	Duration of Thawing days	No. of F-T Cycles/month
Station							
Chicago	0.326	28.20	1.12	0.534	41.74	19.42	1.85
Moline	0.338	27.79	1.39	0.553	41.63	18.79	1.99
Springfield	0.383	28.79	0.59	0.632	44.54	22.45	1.30
E. St. Louis	0.415	29.40	0.32	0.695	47.59	25.75	0.57
Cairo	0.481	29.82	0.07	0.803	50.59	28.48	0.30
Month							
October	0.583	30.00	0.0	0.965	62.62	30.38	0.0
November	0.401	29.83	0.04	0.625	47.68	29.21	0.06
December	0.244	28.07	1.04	0.391	38.04	17.66	2.29
January	0.254	26.89	1.84	0.408	35.77	13.33	3.19
February	0.321	28.22	1.18	0.538	38.59	18.08	1.45
March	0.528	29.78	0.07	0.931	48.61	29.22	0.23
Grand Mean	0.389	28.80	0.70	0.643	45.22	22.98	1.20

Although significant statistical differences were detected, a careful study of the data in Table 2 indicates that the mean values for many of the various frost action parameters fall within a rather limited range.

DISCUSSION OF FINDINGS

Frost action parameters are quite variable as indicated by the data presented. It is apparent that adequate simulation of frost action in a pavement system requires careful consideration of many factors. Such factors should include geographical location, time (month and year), and the nature of the pavement system (material properties and layer thicknesses).

Comparisons of typical data in this paper with the cooling rate, below freezing temperature, duration of freezing, and number of freeze-thaw cycles used in the standard ASTM and AASHO freeze-thaw durability test procedures show that the procedures are not reasonable simulations of the frost action that occurs under field conditions. For example, the following differences were noted:

1. The cooling rates are an order of magnitude higher than field cooling rates.
2. The 12 freeze-thaw cycles prescribed in the standard test may be exceeded quite frequently in many locations. At Moline and Chicago, for example, more than 12 freeze-thaw cycles will occur annually 50 percent of the time.
3. The data for the northern stations (Chicago, Moline, and Springfield), where freeze-thaw durability is of prime concern, indicate that the average duration of freezing is substantially longer than the 24 hours used in the standard tests.
4. Average freezing temperatures for the state (range of 24.5 to 27.4 F) are substantially higher than the < -10 F required by the standard ASTM or AASHO procedure.

Although no one has claimed that the standard AASHO and ASTM tests truly simulate field conditions, the substantial discrepancies between test and field conditions are just cause for careful scrutiny of the procedures and the interpretation of the test results. The major advantage generally cited for using the standard test is that a substantial body of field experience and performance data has been gathered and correlated with results obtained for the standard testing procedures. Although soil-cement has a long service record, some of the newer materials (lime-fly ash aggregate and lime-soil mixtures) have service records of limited length, especially in the northern area of the United States where freeze-thaw durability is a major consideration. The empirical nature of the standard test is obvious.

With the increasing interest displayed in stabilized materials and their effective and economical use in pavement construction, it would seem appropriate to pursue the development of more realistic and rational freeze-thaw durability testing procedures and criteria. The data presented in this paper and similar data that can be generated by the heat-transfer model provide the basic information required to develop improved durability testing procedures; such data were not previously available.

It should be emphasized that, even though all of the frost action parameters were statistically different for the various months and locations studied, practically speaking the ranges of the average values were quite small for some of the parameters. An extensive laboratory testing program is currently being conducted at the University of Illinois to determine if, for the range of values observed, the freeze-thaw durability of typical stabilized materials (lime-fly ash aggregate, soil-cement, and lime-soil mixture) is significantly influenced by the magnitude of the various frost action parameters. A sophisticated automatic freeze-thaw cabinet has been developed for use in the study. The cabinet can be programmed to accurately control both the top and bottom temperatures on a specimen, and either a closed or open system moisture condition can be provided. Results from the testing program will be used to determine whether constant or variable frost action parameters should be used in freeze-thaw durability testing.

Ultimately, a detailed testing procedure, based on heat-transfer model data and laboratory test results, will be proposed. The procedure should much more accurately simulate field conditions than any present procedure.

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The opinions, findings, and conclusions expressed in this report are those of the authors and not necessarily those of the State of Illinois, Division of Highways, or the Bureau of Public Roads.

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