Evaluation of Freeze-Thaw Durability of Stabilized Materials

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A suggested procedure for evaluating the freeze-thaw durability of stabilized materials is developed. Pertinent background information and previous related studies are summarized. The residual strength concept is used in the suggested evaluation procedure. Quantitative characterization of cyclic freeze-thaw action, freeze-thaw testing procedures and techniques, durability criteria, and construction influences are considered. Detailed data are presented for Illinois conditions, and the applicability of the proposed procedure is illustrated. It is demonstrated that current technology is sufficient to develop a realistic approach for evaluating the freeze-thaw durability of stabilized materials.

Methods of durability testing of stabilized materials were studied to develop a satisfactory and realistic procedure for evaluating the freeze-thaw (FT) durability of partially cemented highway materials such as soil-cement, lime-fly ash-aggregate, and soil-lime mixtures.

An illustrative example for a typical Illinois condition is presented.

DEVELOPMENTAL ACTIVITIES

Freeze-Thaw Cycles and Testing Procedures

A heat-transfer model for evaluating frost action and temperature effects developed for multilayered pavement systems (1) was used to establish relevant quantitative frost-action parameters for stabilized pavement systems for five locations in Illinois. The frost-action parameters were determined by statistically analyzing pavement temperatures for 30 years of past climatic data (2). The parameters generated by the model (a standardized FT cycle) were programmed into a unique FT testing unit (3, 4, 5, 6). The FT cycle was representative of field conditions in the more severe environments of Illinois (the central to northern parts of the state).

A vacuum saturation durability testing procedure was also developed (6). This procedure is much more rapid than the rather lengthy (48-h) FT test.

Laboratory Testing Program

A wide range of typical Illinois stabilized materials (soils, gravels, and crushed stone) was included in the laboratory testing program (6). The stabilizing agents considered were lime, lime-fly ash, and cement. Other factors considered were compaction density effects, curing time effects, and percent additive effects.

The various soil-stabilizer mixtures were subjected to 5 and 10 cycles of the standard FT cycle. The evaluation techniques used to measure the durability included measures of compressive strength, length change, and moisture change.

The laboratory data have shown that 5 and 10-cycle FT strengths can be predicted based on the strength of the stabilized material after curing (prior to FT testing) or on the vacuum saturation strength of the cured material. Figures 1 and 2 show the 10-cycle FT relations developed. Those factors that influence the cured strength (density, percent additive, curing time) affect the FT strength in the same manner.

DEVELOPMENT OF FREEZE-THAW DURABILITY CRITERIA

General

The results of the early phases of the FT durability project provided valuable information and data concerning field conditions and the response of typical stabilized materials to realistic FT exposure. However, in the development of tentative FT durability criteria, it is not only important that use be made of laboratory data and information but also essential that consideration be given to the many aspects of stabilized material use such as mix design, construction operations, pavement behavior, climatic factors, and curing conditions.

The Residual Strength Concept

The concept of residual strength has been used in estab-

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lishing quality requirements for soil-lime stabilization (7). The residual strength is the strength of a stabilized material following the equivalent of the first winter FT cycles. If the residual strength is adequate to ensure the desired level of structural pavement response, and the material displays a projected strength-time history that will ensure that the field strength will always be greater than some minimum strength requirement, then pavement performance will be satisfactory. The residual strength concept is illustrated in Figure 3. Field experience with partially cemented highway materials has shown that if the cured material possesses sufficient durability to survive the first winter FT cycles, the probability of durability problems during subsequent years is quite low. The additional curing and autogenous healing that may develop during the summer following construction and during subsequent summers are beneficial in developing additional strength in the stabilized mixture (especially in properly designed lime-fly ash and soil-lime mixtures).

Residual Strength Durability Criteria

The development of durability criteria based on the residual strength concept requires several steps.

1. Establish the minimum tolerable strength.
2. Estimate the cured strength of the stabilized material prior to cyclic FT action.
3. Estimate the residual strength following the first winter cyclic FT action.
4. Consider the projected strength-time profile for the material.
5. Check the adequacy of the residual strength and the strength-time profile.

The various factors are discussed in detail below.

Minimum Tolerable Strength

If a given set of pavement design parameters such as subgrade support, traffic loading, and design life is assumed, most pavement thickness design procedures consider the strength of the component pavement layers in establishing the required layer thicknesses. The strength of the stabilized materials must therefore be established for field service conditions. For such materials as soil-cement and lime-fly ash-aggregate mixtures, the most critical field service condition in FT areas is during the spring following the first winter of exposure to FT cycles. The strength during that period is therefore probably the strength that should be considered as a minimum strength for assessing the structural capacity of the pavement section.

Regardless of the thickness design procedure used to design a pavement section containing a stabilized layer, it should be possible (assuming the design procedure has some quasi-rational basis) to establish some minimum tolerable strength that corresponds to the lowest strength required to ensure the structural adequacy of the pavement during the critical spring period. An alternate approach for establishing minimum tolerable strength levels is to consider field performance and job history data.

Cured Strength

The cured strength that a stabilized mixture develops prior to cyclic FT action is dependent on many factors, but particularly on the mixture proportioning and mixing, the density, and the curing.

1. Field correction factors. Field correction factors must be applied to laboratory strengths to correct for mixing inefficiencies and the nonuniformity of field-mixed material. For equivalent mixture proportions the strength of field-mixed material is less than that for laboratory-mixed: For mixed-in-place operations the ratio of the field-mixed strength to that of the laboratory-mixed strength ranges from about 0.6 to perhaps 0.8. Plant mixing is more efficient than field mixing, but although ratios approaching 1 are sometimes achieved, a realistic range is perhaps 0.75 to 0.95. The variability in field mixture strength due to deviations from mix design proportions (primarily of additive and water contents) is substantial. Unpublished data (Barenberg, Department of Civil Engineering, University of Illinois) for lime-fly ash-aggregate plant-mixed material indicated coefficients of variation of strength from 7.7 to 18.2 percent with an average of approximately 11.5 percent. Similar data (8) for a cement-treated base (California type A material plant mix) indicated a coefficient of variation of 16 percent. The coefficient of variation for the compressive strength of a California specification class C cement-treated base constructed by using blade mixing techniques was about 19 percent (8). [There are limited data concerning the strength variability of field-mixed materials, although another California study (9) considers in detail various items of mixed-in-place field operations including additive content and depth of mixing.] Thus it is reasonable to conclude that plant-mixed materials will be more uniform than mixed-in-place materials and to assume a coefficient of variation of 10 to 15 percent for plant-mixed material and 20 to 25 percent for mixed-in-place material.

2. Density effects. The compacted density of stabilized materials substantially influences their cured strength and FT durability (6, 10). Density effects must be carefully considered in the development of a durability evaluation system. If it is assumed that field quality control is adequate to ensure complete compliance with the applicable specifications, the minimum acceptable specification density should be used for the laboratory preparation of specimens. In most instances, the stabilized mixtures are field compacted at approximately optimum moisture content, and a similar moisture content should be used in laboratory specimen preparation. If extensive field data for compaction density and water content are available, such data should be considered in establishing laboratory preparation procedures.

3. Curing effects. The influence of time and temperature on the strength development of soil-lime, soil-cement, and lime-fly ash-aggregate mixtures is well documented. For adequately proportioned mixtures, increases in the temperature and time of curing result in higher strengths. The problem of accurately predicting the combined temperature-time influence on the strength development of a field-cured material is complex. The field temperature in the stabilized layer is quite variable within any 1 year and also shows substantial variability from year to year. The critical consideration in the use of stabilized materials in FT climates is that adequate curing must be provided to ensure sufficient strength development in the material prior to the cyclic FT action. If the cured strength is not adequate at this point, the residual strength of the material after it experiences FT cycles will not be adequate (i.e., the residual strength will be less than the minimum tolerable strength). It is possible to develop information for establishing construction cutoff dates, as illustrated by MacMurdo and Barenberg (11) for various materials and geographic locations. The heat-flow model is readily available for use, although it requires extensive labora-

tory testing of the different materials to establish the minimum curing necessary to ensure adequate strength development. Such a procedure is cumbersome, but it represents the best current approach for considering curing effects. In the absence of such quantitative data, it is necessary to arbitrarily set the cutoff construction date sufficiently early in the fall to ensure attaining the curing essential to achieving the desired cured strength.

Figure 1. Relation between strength after curing and 10-cycle freeze-thaw strength.

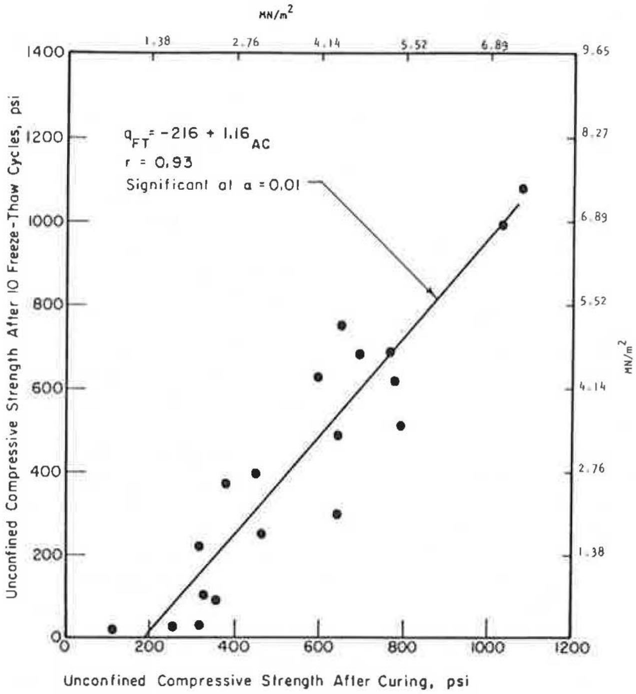
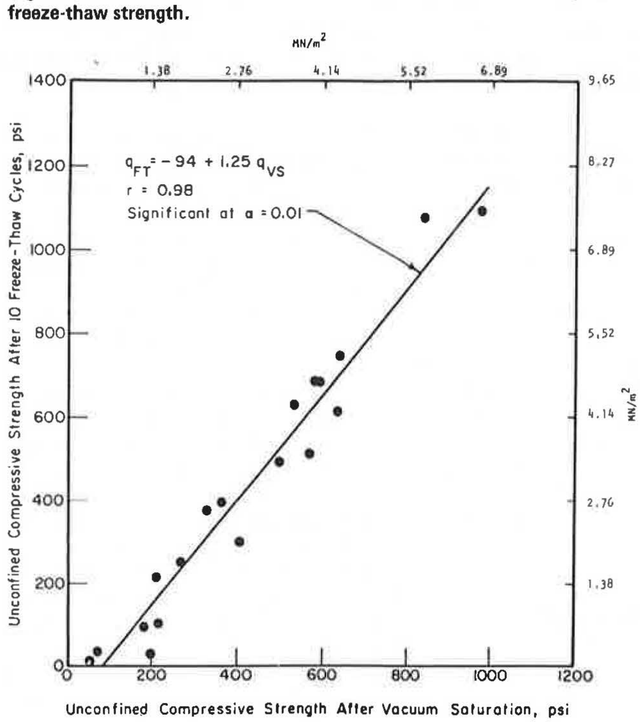


Figure 2. Relation between vacuum saturation strength and 10-cycle freeze-thaw strength.



Residual Strength

Two basic factors must be considered in predicting the residual strength of a stabilized material. The first factor is the determination of the number of FT cycles the material will experience during the first winter. The second is the prediction of the residual strength based on the number of FT cycles and some property(ies) of the stabilized mixture.

1. Prediction of the number of FT cycles. The number of FT cycles a particular point in a pavement will experience is affected by many factors, of which the major ones are geographic location and climatic variability, and the pavement system characteristics.

(a) For a given pavement system, the number of FT cycles for a particular reference point will depend on its geographic location. The intensity of cyclic FT action varies from year to year. Figure 4 (2) shows the degree of variability ($\bar{X}$) associated with cyclic FT for various Illinois locations: The standard deviations (σ) are approximately 5 to 6 for northern and central Illinois and

Figure 3. Residual strength concept of freeze-thaw durability.

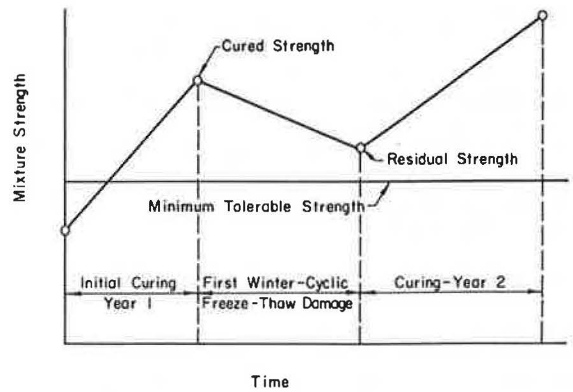
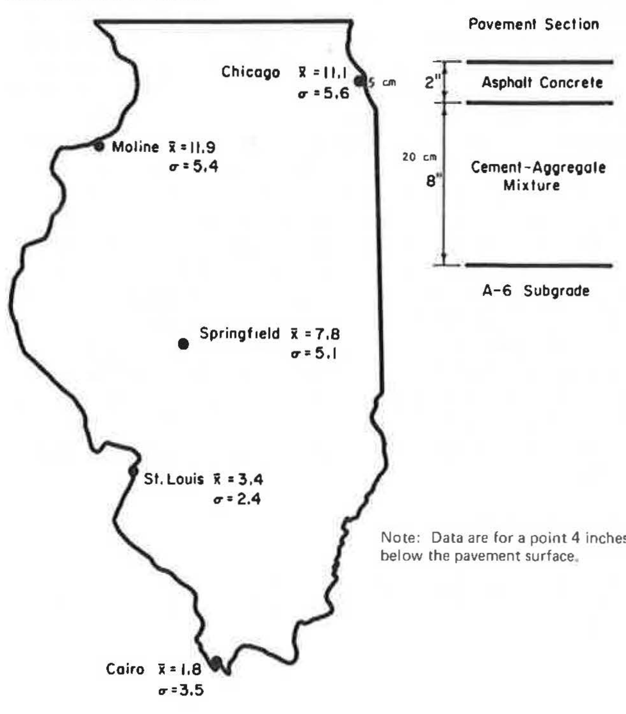


Figure 4. Freeze-thaw cycle data for a stabilized base with an asphalt concrete surface course.



about 3 for southern Illinois. The data developed in the Thompson-Dempsey study (2) were analyzed using the hydrologic statistical concepts employed by Dempsey (12). In this procedure, a relation between the number of FT cycles and the recurrence interval (in years) is established, and by using the recurrence interval concept, it is possible to determine in a rational manner the number of FT cycles that should be considered for FT durability evaluation purposes. The recurrence interval selection should be based on a comprehensive consideration of such factors as economy, field construction practices, pavement design, and performance factors. If a recurrence interval of 2 years is used, that number of FT cycles is exceeded on the average once every 2 years. As illustrated in Figure 5, the cyclic FT-induced strength decreases are not linearly related to the number of FT cycles (6), and later FT cycles are not as detrimental as those initially experienced. This means that FT cycle prediction errors are not necessarily critical.

(b) The thickness of the component pavement layer, the characteristics such as thermal properties and color of the paving materials, and the subgrade soil properties all affect the number of FT cycles experienced by a pavement system. The major uses of stabilized materials are for base courses in flexible pavements with asphalt concrete surface courses or bituminous surface treatments, or for stabilized subbases beneath PCC pavements. Only flexible pavements are considered here. Many subgrade soils are fine-grained, and subgrade soil is not considered as a variable in the following discussions. The FT cycle data shown in Figure 4 were developed for a 20-cm (8-in) base course of a stabilized aggregate mixture (cement-aggregate mixture, pozzolanic aggregate mixture). Similar data were also developed (13) for 30 years of climatic data at three locations (Chicago, Springfield, and St. Louis) and for 1 year of climatic data for Moline for a pavement section in which the base course was 20 cm (8 in) of a stabilized fine-grained soil (soil-cement, soil-lime). Fewer FT cycles were experienced in the stabilized fine-grained soil base. On the average, the ratio of the number of FT cycles for a stabilized fine-grained soil to the number of FT cycles for a stabilized granular soil was 0.70. The effect of the base course thickness was also evaluated (13). The basic pavement section examined is that shown in Figure 4. The thickness of the stabilized granular base was varied from 10 to 20 cm (4 to 8 in). Ten years of climatic data for Springfield, Illinois, were evaluated. The data indicated an insignificant effect (0.7 FT cycle maximum difference) of base course thickness on the number of FT cycles. Thus, no adjustment is required for base course thickness variations if the thickness is within the 10 to 20-cm (4 to 8-in) range. The thickness of the asphalt concrete surface course overlying the stabilized base also influences the number of FT cycles experienced by the base course. As the surface course thickness increases, fewer FT cycles are experienced. If the reference surface course thickness is taken as 5 cm (2 in), an adjustment factor (FT cycles for x inches of surface course/FT cycles for 2 in of surface course) can be developed as shown in Figure 6. The surface course thickness and stabilized material type will substantially affect the number of FT cycles for a pavement system with an asphalt concrete surface course and a stabilized base course. These effects should also be considered in evaluating FT durability.

2. Prediction of residual strength. Three techniques have been developed for predicting residual strength (6). Any of the procedures (FT testing, FT strength-cured strength relations, FT strength-vacuum saturation strength relations) can be used.

(a) The standard FT testing procedure outlined by Dempsey and Thompson (6) is the most realistic and direct procedure for evaluating the FT durability of a stabilized material. The major constraints of the proposed procedure are that the programmable FT testing unit is not a common piece of laboratory equipment, and that the procedure is very time consuming (48 h/cycle).

(b) Cured strength data for the mixture can be used to predict the 5 and 10-cycle FT strength as shown in Figure 1. The standard error of estimate for the regression equation given in Figure 1 is 869 kPa (126 lb/in^2) for 10 cycles.

(c) Vacuum saturation strength data developed according to the testing procedures of Dempsey and Thompson (14) can also be used to predict the 5 and 10-cycle FT strengths, as shown in Figure 2. The standard error of estimate here is 462 kPa (67 lb/in^2) for 10 cycles.

The most direct approach for evaluating residual strength is obviously the FT testing procedure. However, in view of its limitations, the cured strength and vacuum saturation strength correlations are both very attractive. However, since the errors of estimate for the vacuum saturation strength correlations are lower than those for the cured strength correlations, better predictions can be made based on vacuum saturation strength data. Also since the time and equipment required to conduct the vacuum saturation test are nominal, the FT strength-vacuum saturation strength correlations are better (more accurate predictions of FT strength that are only slightly more expensive) than the cured strength correlations.

The major advantage of using the cured strength correlation is that cured strength criteria are commonly used in materials and construction specifications. If FT strength-cured strength correlations are used, residual strengths can be estimated quite readily (assuming that the specification strength is equal to the cured strength).

Strength-Time Profile

A major premise of the residual strength concept is that the stabilized material is capable of developing additional strength following the first winter of FT action. The additional curing (provided favorable temperature conditions prevail) experienced after the first winter is beneficial in developing additional strength in the stabilized material.

Typical strength relations (field data for areas with FT action) for soil-cement and lime-fly ash-aggregate mixtures have shown that the net effect of cyclic FT action and additional curing is a general strength increase (13). Cyclic FT damage is therefore not cumulative on a year-to-year basis. The general increasing strength with time relation for stabilized materials is further supporting evidence for the earlier statement that "if the cured material possesses sufficient durability to survive the first winter FT cycles, the probability of experiencing durability problems during subsequent years is quite low."

It is essential in developing mixture designs for stabilized materials that the mixture be capable of developing additional strength following the first winter. It may be appropriate to use laboratory curing conditions to simulate (a) curing prior to the first winter and (b) additional curing. The additional strength increase must be achieved with increased curing to ensure an adequate mixture design.

If the residual strength of the mixture is greater than the minimum tolerable strength and the mixture is capable of developing additional strength following the first winter of FT action, then the durability properties of the mixture should be considered adequate.

Other Considerations

In using the residual strength concept, due consideration must be maintained for good mixture design, quality control, and construction practices. If it is assumed that acceptable quality stabilizing additives (lime, cement, and fly ash) are used, and that adequate quality control is being achieved in mixture preparation and construction, then the mixture design becomes a very important and key process.

Freeze-thaw durability evaluation is but one aspect of the mixture design problem, but it is a critical part of the process. An acceptable mixture must meet not only durability requirements, but also other applicable criteria. For properly proportioned and constructed stabilized mixtures, the cured strength normally correlates well with FT durability.

The mixture durability is controlled primarily by the

Figure 5. Effect of cycle interval on freeze-thaw strength decrease.

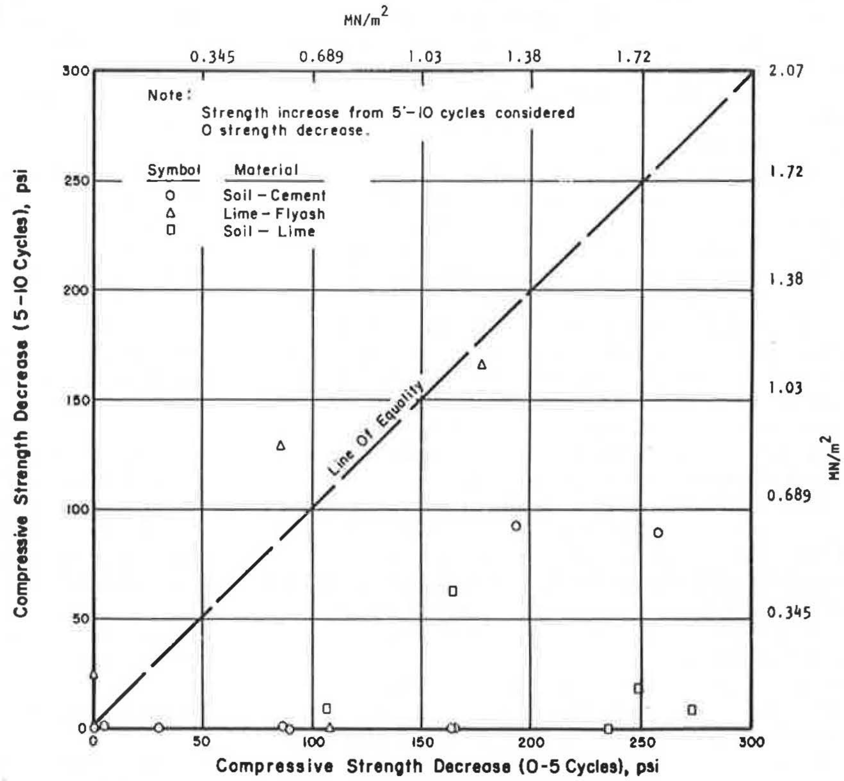


Figure 6. Adjustment factor for asphalt concrete surface course thickness effect.

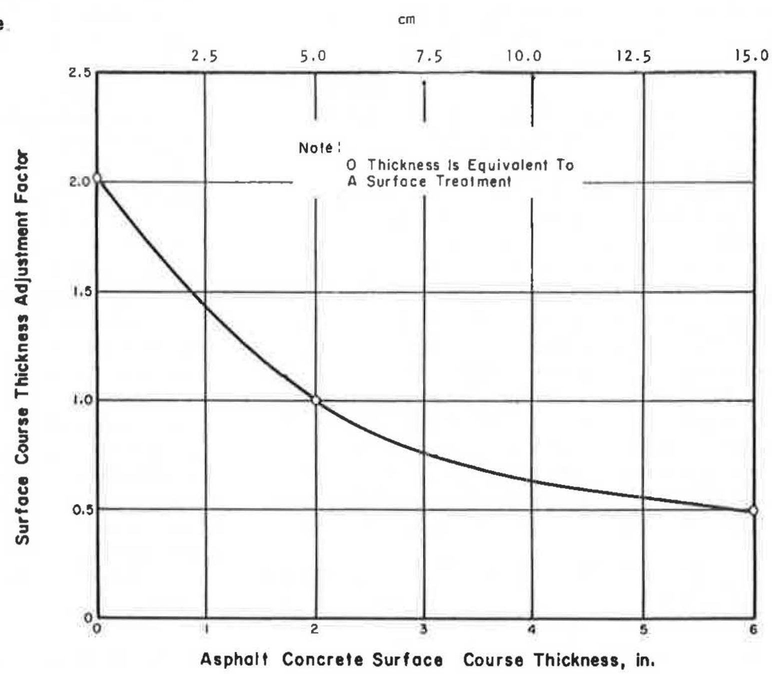
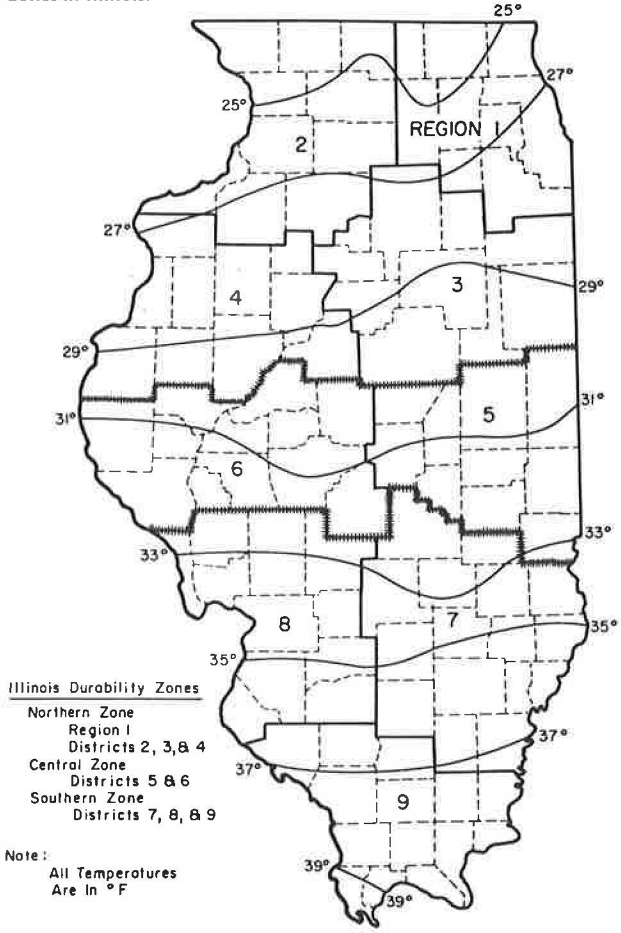


Figure 7. Mean winter temperature data and freeze-thaw durability zones in Illinois.



quality of the matrix material in the stabilized granular materials (cement-aggregate mixtures and lime-fly ash-aggregate mixtures). In order to ensure the development of a highly durable matrix fraction in the mixture, it is essential to ensure the development of a floating aggregate mixture in which the larger aggregate particles are separated and the matrix material (the stabilizing additives plus the fraction passing through a No. 4 sieve) is a continuous phase.

The gradation criteria shown below have been developed for cement-aggregate mixes to ensure a floating aggregate mixture.

Sieve	Percentage Passing
No. 4	55
No. 10	37
Nos. 10 to 200	25

Good quality lime-fly ash-aggregate mixtures normally contain sufficient quantities of fines, fly ash, and lime to achieve a floating aggregate condition. In some cases, for example with a uniformly graded sand, increased quantities of lime and fly ash are required to fill the voids in the sand and form a continuous phase, high-quality matrix material.

PROPOSED ILLINOIS PROCEDURE

The following procedure, which is based on the residual strength concept, has been developed for Illinois conditions:

1. Establish the minimum tolerable strength.
2. Determine the number of FT cycles to be expected during the first winter following construction.
3. Establish minimum field-cured and laboratory-cured strength requirements.

Durability Zones

To develop reasonable and realistic durability criteria for Illinois, it is essential to subdivide the state into various durability zones. Based on a consideration of the FT cycle data for various locations in Illinois (Figure 4) and the mean winter temperature data for December, January, and February, the state was divided into the three durability zones (northern, central, and southern) shown in Figure 7. The corresponding FT cycle-recurrence interval relations are shown in Figure 8 (13).

Minimum Tolerable Strengths

A key element in a residual strength-based durability concept is the establishment of a realistic minimum tolerable strength. Various approaches to establishing minimum tolerable strength levels have been discussed earlier in this report.

Cured strength requirements (laboratory conditions) and estimated 10-cycle FT strengths (based on the relation shown in Figure 1) are summarized in Table 1 for typical stabilized materials used by the Illinois Department of Transportation. The approximate 10-cycle FT strength groupings are 1.03 MPa (150 lb/in^2), 1.72 MPa (250 lb/in^2), 2.41 MPa (350 lb/in^2), and 3.79 MPa (550 lb/in^2). These strengths can be used as minimum tolerable strength groupings. (These values could also be based on material properties for pavement thickness design or on field performance data.)

First Winter FT Cycles

Only pavements with asphalt concrete surface courses and stabilized bases are considered in this paper. A similar approach has been developed for stabilized subbases beneath portland cement concrete pavements (13). The FT cycle predictions are based on data previously generated in the University of Illinois study (6) although it may be desirable, in some applications, to actually consider a particular pavement system and the local climatic conditions in more detail by using the heat-flow model techniques developed by Dempsey and Thompson (1).

The following FT cycle prediction procedure is proposed:

1. Select an appropriate frequency-of-return period. (If a 2-year return period is used, that number of FT cycles will be exceeded on the average once every 2 years).
2. From the FT frequency-of-return chart (Figure 8) for the appropriate durability zone, determine the number of FT cycles for the standard pavement structure.
3. Modify the FT cycle value by using the materials factor. (This factor is 1.0 for stabilized granular material and 0.70 for stabilized fine-grained soils.)
4. For an asphalt concrete surface course thickness different from 5 cm (2 in), modify the FT cycle value in accordance with Figure 6. [The thickness of the stabilized base or subbase material is not a significant factor (within normal ranges of thickness), and a modifying factor for this is not needed.]

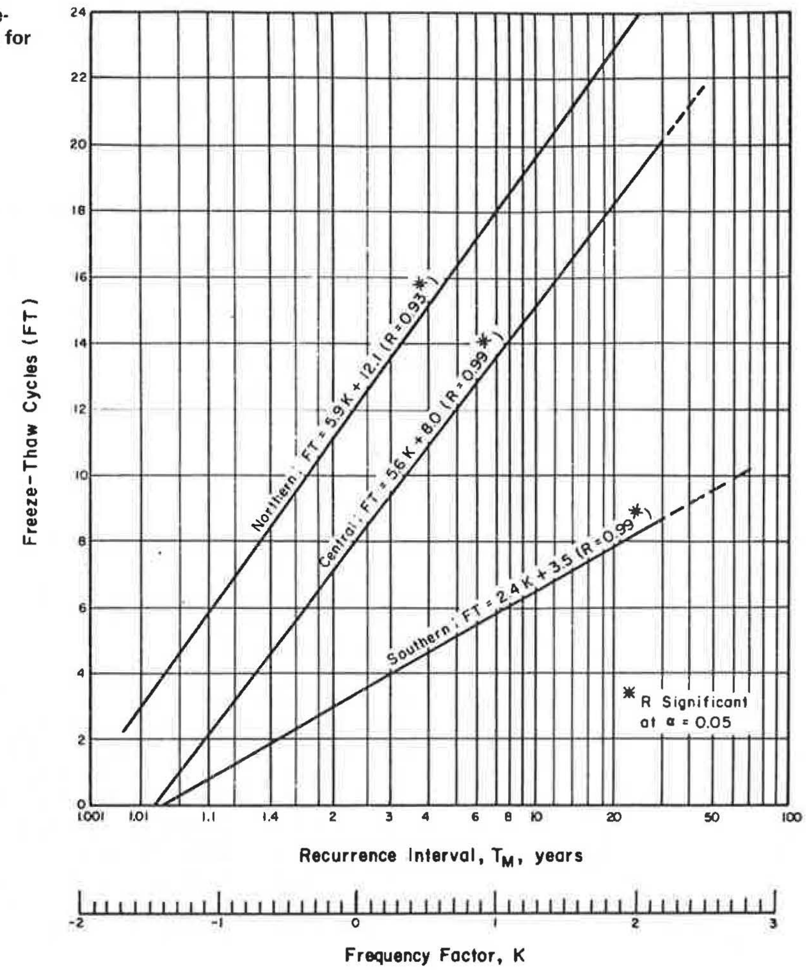


Figure 8. Freeze-thaw cycle-recurrence interval relations for Illinois durability zones.

Table 1. Minimum laboratory strengths and estimated residual strengths for stabilized materials.

Material	Minimum Laboratory Compressive Strength (MPa)	Curing Conditions	10-Cycle FT Strength[a] (MPa)
Cement aggregate base course (bureau of local roads and streets)	"Not less than the design strength specified" (4.48)	7 days—moist	3.71
Pozzolanic base course, type A	2.76	7 days at 38°C	1.71
Soil cement (Illinois DOT flexible pavement design)	2.07	7 days—moist	0.91
Soil cement (bureau of local roads and streets)	2.07 or 3.45	—	0.91 or 2.51
Stabilized shoulders and subbases, cement-aggregate mixture, pozzolan-aggregate mixture	2.76 (FT durability criteria)	7 days at 38°C	1.71

Note: 1 MPa = 145 psi; 1°C = (1°F - 32) 1.8.
[a]Estimate based on the relation shown in Figure 1.

Strength Requirements

It is possible to establish a field-cured strength requirement based on the minimum tolerable strength level and the predicted number of FT cycles. The relations shown in Figure 9 can be used to estimate the field-cured strength requirement (i.e., the strength corresponding to 0 FT cycles). This should then be adjusted (increased) sufficiently to account for mixing efficiency, field variability, and curing considerations. The adjusted strength requirement can be considered as a laboratory strength requirement for the material when it is cured under simulated field conditions; and as more information and experience are developed concerning these important factors, further refinements in strength requirements should be made.

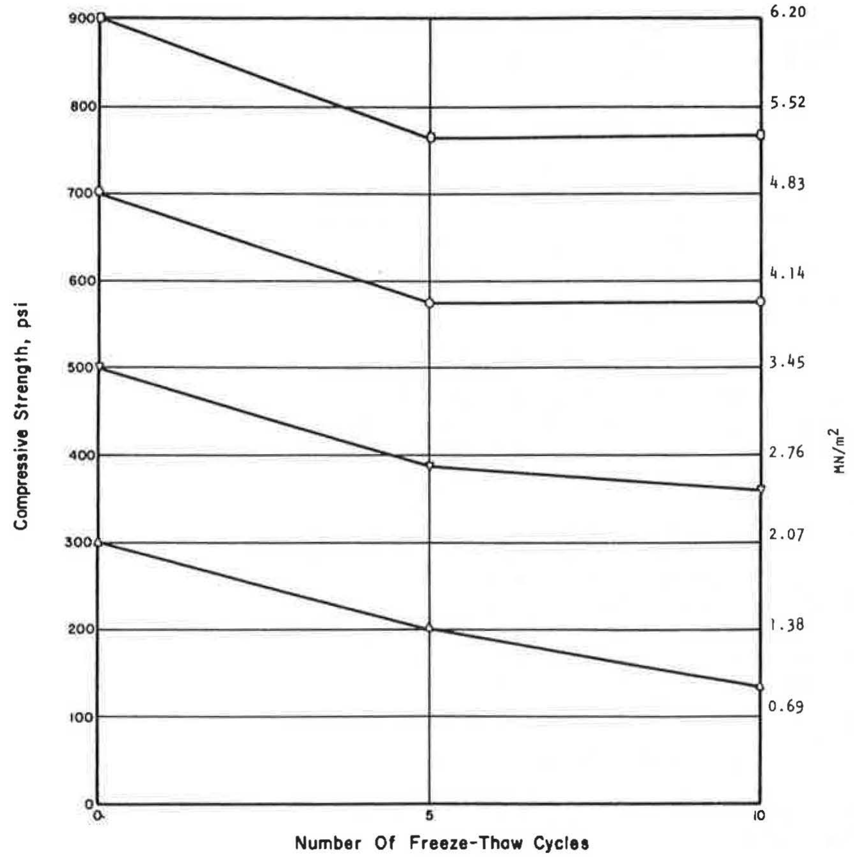
Illustrative Example

The following example of the application of the residual strength procedure is illustrative in nature. A similar approach could be used to establish cured and laboratory strength requirements for different applications. The tools and concepts have been developed, but careful study and judgment are required to establish specific requirements.

Assume the following conditions: (a) The minimum tolerable strength = 1.72 MPa (250 psi), (b) the predicted number of FT cycles (first year) = 10, and (c) the material is plant mixed. In accordance with the suggested procedure:

1. Estimate the required field-cured strength. From Figure 9, the field-cured strength (prior to the first

Figure 9. Generalized relation between compressive strength of stabilized materials and number of freeze-thaw cycles.



winter) should be approximately 2.76 MPa (400 psi).

2. Adjust for field variability. If the coefficient of variation for the field compressive strength is assumed to be 15 percent, in order for 84 percent of the material to have a strength greater than 2.76 MPa (400 psi), the average field-cured strength should be

$\overline{X} - 1\sigma = 2.76$ MPa (400 psi)

$\sigma = 0.15\,\overline{X}$

$\overline{X} - 0.15\overline{X} = 2.76$ MPa (400 psi)

$\overline{X} = 2.76/0.85 \cong 3.24$ MPa (470 psi)

3. Adjust for mixing efficiency. For plant mixing operations with a mixing efficiency of 0.85, the adjusted strength is

$3.24/0.85 = 3.81$ MPa (553 psi)

It it is assumed that field density and curing will be approximately equivalent (i.e., develop similar strength) to laboratory conditions, then the 3.81-MN/m^2 (550-psi) strength requirement can be considered as the laboratory strength requirement for the field material to have a strength of 1.72 MN/m^2 (250 psi) after 10 FT cycles for the conditions and assumptions previously stated.

SUMMARY

Freeze-thaw durability evaluation of stabilized materials and the development of durability criteria are considered by using the residual strength concept. Since so many factors influence the FT durability of stabilized materials and the field FT environment is so variable, the use of this type of procedure is justified. Freeze-thaw durability is not an inherent material property, but relates to the conditions (geographic location, position in the pavement, type of pavement, mixture variables, construction variables, and curing) under which the material is used.

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