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Thickness Design for Cement-Treated Base Pavements

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A report of the findings of

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Thickness Design for Cement-Treated Base Pavements

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16. Abstract

This project developed a cement-treated base (CTB) thickness design procedure for the Illinois Department of Transportation based on CTB fatigue (stress ratio criterion). The researcher developed a comprehensive ILLI-PAVE database for a range of thickness design inputs (7-day compressive strength, CTB thickness, and subgrade modulus). A CTB flexural stress algorithm was derived from the comprehensive ILLI-PAVE database. Minimum CTB thicknesses for IDOT Class III and Class IV pavements were established, and the results were presented in tabular form. Falling weight deflectometer testing and project site reviews of several existing typical CTB projects indicated CTB compressive strengths are significant (average of 750 psi), and the projects are performing well. As expected, transverse shrinkage cracks have occurred in the projects.

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This publication is based on the results of **ICT-R27-235: Thickness Design for Cement-Treated Base Pavements**. ICT-R27-235 was conducted in cooperation with the Illinois Center for Transportation; the Illinois Department of Transportation; and the U.S. Department of Transportation, Federal Highway Administration.

Members of the Technical Review Panel (TRP) were the following:

- James Krstulovich, TRP Chair, Illinois Department of Transportation
- Tim Peters, TRP Co-Chair, Illinois Department of Transportation
- Dennis Bachman, Federal Highway Administration
- Ben Bland, Hampton, Lenzini and Renwick Consultants
- Greg Halsted, National Ready Mix Concrete Association
- Robert Rescot, Illinois Concrete Pavement Association
- John Senger, Illinois Department of Transportation
- Heather Shoup, Illinois Department of Transportation
- Filiberto Sotelo, Illinois Department of Transportation
- Charles Wienrank, Illinois Department of Transportation

EXECUTIVE SUMMARY

This project developed a cement-treated base (CTB) thickness design procedure for the Illinois Department of Transportation based on CTB fatigue (stress ratio criterion). A comprehensive ILLI-PAVE database (see Appendix A) was developed for a range of thickness design inputs:

- 7-day CTB compressive strength (CS): 300, 400, and 500 psi
- Subgrade modulus (E_{Ri}): 3, 7.7, and 12.3 ksi
- CTB thickness: 8, 9, 10, 11, 12, 13, 14, and 15 inches

Based on the database, a flexural stress algorithm for interior loading conditions was established:

$$\text{Log } \sigma = 2.397 - 0.059 \times T + 0.00019 \times E - 0.0091 \times E_{Ri}$$

- $R^2 = 0.98$
- σ = CTB flexural stress (psi)
- T = CTB thickness (inches)
- E = CTB modulus (ksi)
- E_{Ri} = Subgrade modulus (ksi)

Minimum CTB thicknesses for IDOT Class III (average daily traffic [ADT]) > 400 / < 2000) and Class IV pavements (ADT < 400) were established, and the results were presented in tabular form. Falling weight deflectometer testing and project site reviews of several existing typical CTB projects indicated CTB compressive strengths were significant (average of 750 psi), and the projects have displayed good performance. As expected, transverse shrinkage cracks were observed in the projects.

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CHAPTER 1: INTRODUCTION

The objective of R27-235: Thickness Design for Cement-Treated Base (CTB) Pavements is to develop in cooperation with Illinois Department of Transportation (IDOT) a CTB thickness design procedure and supporting policies. Project activities will focus on falling weight deflectometer (FWD) testing (per IDOT) and further performance surveillance of projects considered in previous projects and additional CTB projects identified by IDOT and the project's principal investigator.

PROJECT TASKS

The following tasks are included in R27-235:

- Task 1: Cooperate with IDOT in establishing a CTB Thickness Design Working Group (Quarter 1 [Q1]–Q2).
- Task 2: Cooperate with IDOT in selecting additional CTB projects for FWD testing and periodic monitoring and surveillance (Q1–Q10).
- Task 3: Review and evaluate FDRC (full-depth reclamation with cement) literature related to materials, thickness design, construction, and performance (Q1–Q12).
- Task 4: Prepare a white paper summarizing the current practice for CTB thickness design (Q1–Q3).
- Task 5: Develop a proposed CTB thickness design procedure and submit it to IDOT for review and modification as needed (Q3–Q9).
- Task 6: Cooperate with IDOT in the implementation of the approved CTB thickness design (Q9–Q12).

CHAPTER 2: ACCOMPLISHMENTS

Task 1: The project Technical Review Panel (TRP) served as the Working Group.

Task 2: Several projects were identified, and IDOT or their subcontractors conducted FWD testing. The FWD data were analyzed, and CTB modulus values were established through iterative back-calculation using the ILLI-PAVE model. Compressive strength (CS) was estimated from the modulus (CS (psi) = modulus (ksi)/1.25). Table 1 shows the analysis results. The age of the projects varied considerably. The average estimated CS was 750 psi. The low value for Compromise Township is due to the excess amount of fine-grained soil in the mixture.

Task 3: Relevant FDRC literature was reviewed. Pertinent information was utilized in Task 4.

Task 4: An unpublished white paper was prepared based on Task 3 information and submitted to the TRP for review and comment.

Task 5: Based on the white paper prepared in Task 4, a stress ratio CTB fatigue concept was utilized in developing the CTB thickness design procedure. The two elements of the procedure are as follows: (1) calculate the flexural stress at the bottom of the CTB layer, and (2) estimate the fatigue life of the CTB layer.

ELEMENT 1—CALCULATING FLEXURAL STRESS

A comprehensive ILLI-PAVE database (see Appendix A) was developed for a range of thickness design inputs:

- 7-day CTB compressive strength (CS): 300, 400, and 500 psi
- Subgrade modulus (E_{Ri}): 3, 7.7, and 12.3 ksi
- CTB thickness: 8, 9, 10, 11, 12, 13, 14, and 15 inches

Based on the database, a flexural stress algorithm for interior loading conditions was established:

$$\text{Log } \sigma = 2.397 - 0.059 \times T + 0.00019 \times E - 0.0091 \times E_{Ri}$$

Where,

$R^2 = 0.98$

σ = CTB flexural stress (psi)

T = CTB thickness (inches)

E = CTB modulus (ksi)

E_{Ri} = Subgrade modulus (ksi)

ELEMENT 2—ESTIMATING CTB FATIGUE LIFE

A “consensus” stress ratio CTB fatigue algorithm was developed in Task 4 (see Appendix B):

$$\text{Log } N = (0.91 - SR)/0.076$$

Where,

- N = Number of flexural stress repetitions to failure
- SR (stress ratio) = design flexural stress/“slab strength”

THE DESIGN MODEL

Some adjustments were necessary for establishing the design SR.

To accommodate the critical edge loading condition, the interior stress is multiplied by 1.3. Per Brand et al. (2013), the “slab strength” is equal to the modulus of rupture × 1.5. The modulus of rupture is ~0.25 × CS.

A factor of safety (FOS) is normally applied in routine pavement design. Typical FOSs range from 2–4. For lower traffic volume pavements (IDOT Class III and Class IV), two is a reasonable FOS choice and probably provides ~65%–75% design reliability.

An acceptable CTB thickness is achieved when the CTB fatigue life is larger than twice the 18-kip design traffic (ESALs—equivalent 18-kip single-axle loads).

Typical surface courses for CTB pavements are surface treatments, cape seals, and hot-mix asphalt (HMA). For HMA surfaces, the CTB thickness is reduced (per the Odemark transformation) by 0.7 × HMA thickness (minimum CTB thickness is 8 inches).

THE DESIGN PROCEDURE

The design CS is the 28-day CS. Per conversations with TRP Committee member Greg Halsted (formerly with the Portland Cement Association), the 28-day CS is conservatively 1.3 × 7-day CS.

Per LRS 400-9 (IDOT, 2024), the 7-day CS classes are: 300, 400, and 500 psi.

The subgrade classes are (see Figure 1): poor (ER_i = 3 ksi) and fair (ER_i = 7.7 ksi).

Check the appropriate thickness design table (Tables 2, 3, and 4) for the CTB design thickness. Adjust (reduce) the thickness if an HMA surface is utilized (minimum CTB thickness is 8 inches).

COMMENTS

- The 28-day CS (1.3 × 7-day CS) is a conservative estimate. The Wirtgen Manual (2012) indicates the 28-day strength is 1.8 × 7-day strength. CS will typically increase beyond 28 days of curing and the 28-day strength is ~0.9 × ultimate strength.

- All of the traffic loading is not "edge loading." Many low-volume roads are not "center striped," and edge loading is infrequent.

SUMMARY

FWD testing and project site reviews of several existing typical CTB projects (see Table 1) indicated CTB compressive strengths are significant (average of 750 psi), and the projects are performing well. As expected, transverse shrinkage cracks have occurred in the projects. A CTB flexural stress algorithm was derived from the comprehensive ILLI-PAVE database that was developed. A CTB thickness design procedure based on CTB fatigue (stress ratio criterion) was developed. Minimum CTB thicknesses for IDOT Class III and Class IV pavements were established, and the results were presented in tabular form.

Table 1. FWD Testing Summary

PROJECT	SECTION*	SUB MOD/KSI	CTB E/KSI	CS/PSI
Kinoka Road	3 HMA+10(8%)	8.9	860	687
Coles County	A-2+10(8%)	8	1210	890
Cumberland County / CH1	2.5 HMA+12(7%)	9.7	970	775
Cumberland County / CH3	3 HMA+12(7%)	10.3	1070	850
Fulton County / CH2	4 HMA+12(7%)	9.6	930	745
Compromise Township	A-2+12(6%)	2.1	260	208
Grundy County / CH3	A-2+12(6%)	6.5	1200	960
Jasper County				
A	A-2+8(8–9%)	4.3	715	572
C	A-2+8(9%)	8	1280	1025
F	A-2+8(9%)	3.9	590	472
I	A-2+8(8%)	6.5	1215	972
J	A-2+8(8%)	6.6	1035	827
White County	A-3+12(8%)	11	925	740

* SURFACE (HMA/A − 2/A − 3) + CTB THICKNESS – INS (% CEMENT)

Table 2. Class IV Minimum Thickness Requirements

7-Day Compressive Strength (psi)	ADT	ESALS (KESALS)	Minimum CTB Thickness (inches)
300	200	54	12*/11**
300	400	108	13/12
400	200	54	11/10
400	400	108	11/10
500	200	54	10/9
500	400	108	10/9

*Subgrade Modulus = 3 ksi

** Subgrade Modulus = 7.7 ksi

ADT = Average Daily Traffic

Table 3. Class III Minimum Thickness for Subgrade Modulus of 3 ksi

ADT	ESALS (KESALS)	Minimum CTB Thickness (inches)
400	108	13*/11**/10***
800	216	13/11/10
1,200	324	13/12/11
1,600	432	13/12/11
2,000	540	14/12/11

*7-day compressive strength: 300 psi

** 7-day compressive strength: 400 psi

*** 7-day compressive strength: 500 psi

Table 4. Class III Minimum Thickness for Subgrade Modulus of 7.7 ksi

ADT	ESALS (KESALS)	Minimum CTB Thickness (inches)
400	108	11*/10**/9***
800	216	12/11/10
1,200	324	13/11/10
1,600	432	13/11/10
2,000	540	13/11/10

*7-day compressive strength: 300 psi

** 7-day compressive strength: 400 psi

*** 7-day compressive strength: 500 psi

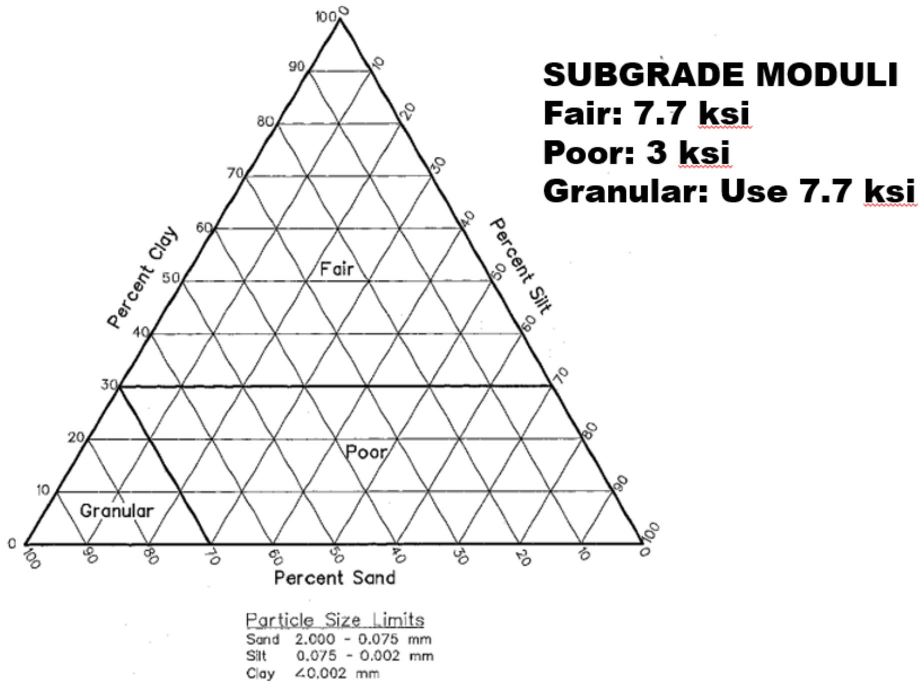

Figure 1. Subgrade modulus values (per IDOT).

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APPENDIX A: ILLI-PAVE DATABASE

Table 5. ILLI-PAVE Database: CTB Strength of 300 psi

Subgrade Modulus (ksi)	CTB Modulus (ksi)	CTB Thickness (inches)	CTB Strength (psi)	CTB Flexural Stress (psi)
3	375	8	300	92.4
3	375	9	300	80.6
3	375	10	300	70.3
3	375	11	300	61.3
3	375	12	300	53.5
3	375	13	300	46.6
3	375	14	300	40.7
3	375	15	300	35.5
7.7	375	8	300	83.7
7.7	375	9	300	73
7.7	375	10	300	63.7
7.7	375	11	300	55.6
7.7	375	12	300	48.5
7.7	375	13	300	42.3
7.7	375	14	300	36.9
7.7	375	15	300	32.1
12.3	375	8	300	76.1
12.3	375	9	300	66.3
12.3	375	10	300	57.9
12.3	375	11	300	50.5
12.3	375	12	300	44
12.3	375	13	300	38.4
12.3	375	14	300	33.5
12.3	375	15	300	29.2

Table 6. ILLI-PAVE Database: CTB Strength of 500 psi

Subgrade Modulus (ksi)	CTB Modulus (ksi)	CTB Thickness (inches)	CTB Strength (psi)	CTB Flexural Stress (psi)
3	625	8	500	103.1
3	625	9	500	89.9
3	625	10	500	78.4
3	625	11	500	68.4
3	625	12	500	59.7
3	625	13	500	52
3	625	14	500	45.4
3	625	15	500	39.6
7.7	625	8	500	93.4
7.7	625	9	500	81.5
7.7	625	10	500	71.1
7.7	625	11	500	62
7.7	625	12	500	54.1
7.7	625	13	500	47.1
7.7	625	14	500	41.1
7.7	625	15	500	35.9
12.3	625	8	500	84.8
12.3	625	9	500	74
12.3	625	10	500	64.5
12.3	625	11	500	56.3
12.3	625	12	500	49.1
12.3	625	13	500	42.8
12.3	625	14	500	37.3
12.3	625	15	500	32.6

Table 7. ILLI-PAVE Database: CTB Strength of 750 psi

Subgrade Modulus (ksi)	CTB Modulus (ksi)	CTB Thickness (inches)	CTB Strength (psi)	CTB Flexural Stress (psi)
3	937.5	8	750	118.2
3	937.5	9	750	103.1
3	937.5	10	750	89.9
3	937.5	11	750	78.4
3	937.5	12	750	68.4
3	937.5	13	750	59.7
3	937.5	14	750	52
3	937.5	15	750	45.4
7.7	937.5	8	750	107.1
7.7	937.5	9	750	93.4
7.7	937.5	10	750	81.5
7.7	937.5	11	750	71.1
7.7	937.5	12	750	62
7.7	937.5	13	750	54.1
7.7	937.5	14	750	47.1
7.7	937.5	15	750	41.1
12.3	937.5	8	750	97.3
12.3	937.5	9	750	84.8
12.3	937.5	10	750	74
12.3	937.5	11	750	64.5
12.3	937.5	12	750	56.3
12.3	937.5	13	750	49.1
12.3	937.5	14	750	42.8
12.3	937.5	15	750	37.3

APPENDIX B: CEMENT-TREATED MATERIAL FLEXURAL FATIGUE BEHAVIOR

Cement-treated material (CTM) flexural fatigue behavior is typically characterized in terms of the stress ratio or strain ratio. Stress ratio is defined as:

Repeated Flexural Tensile Stress / Modulus of Rupture

Strain ratio is defined as:

Tensile Strain @ Break / Repeated Flexural Strain

The Tensile Strain @ Break typically is in the range of 125 to 300 microstrain and varies for various CTM strengths. The Tensile Strain @ Break decreases as the CTM strength/modulus increases.

There is considerable variability in CTM fatigue life predictions. There is no consensus on which algorithm is "best." A complicating consideration is that the CTM strength/modulus properties will be changing (normally increasing) as curing time progresses.

Several reasonable options have been proposed to characterize CTM fatigue behavior:

- The fatigue algorithm originally proposed by Thompson (1994) for IDOT and is now the algorithm in the AASHTO *Mechanistic-Empirical Pavement Design Guide* (2011). The stress ratio (SR) algorithm is:

  $$\text{Log } N = (0.972 - SR) / 0.0825$$

  - SR = Repeated flexural stress/flexural strength
  - N = Number of stress repetitions to failure
- The PCA algorithm (Larsen & Nussbaum, 1967) is based on a "curvature ratio" approach.
  - For granular CTMs: $N^{0.028} = (R/R_C) \times (1.05 - 0.042 \times h)$
  - For fine-grained soil CTMs: $N^{0.054} = (R/R_C) \times (1.05 - 0.042 \times h)$
  - R = CTM Radius of Curvature associated with the repeated load
  - R_C = Critical R (R at failure of the beam)
  - R_C = ~7,350 inches for granular CTM
  - R_C = 4,000 inches for fine-grained CTM
  - h = Fatigue beam thickness (inches)

NOTES:

- The PCA study indicated a thickness (h) effect.
- R_C/R is equivalent to a stress ratio if stress = E × ε.
- R can be used to calculate the CTM strain:

$$\varepsilon = h/2R$$

h = layer thickness

- The Australian Road Research Board has developed "presumptive algorithms" based on strain ratio. After extensive studies and analyses (ARRB, 2013; Jameson, 2014), ARRB concluded that lab fatigue testing is necessary to reliably establish a CTM fatigue algorithm. However, acknowledging that in some projects lab testing is not feasible/possible, ARRB proposed the following presumptive algorithms of the form $N = (k/\varepsilon)^{12}$:

ARRB (2013)

UCS – 800 psi

$$N = (311/\varepsilon)^{12}$$

González et al. (2013)
(For "in-service" conditions)

UCS – 800 psi

$$N = (272/\varepsilon)^{12}$$

UCS – 700 psi

$$N = (270/\varepsilon)^{12}$$

UCS – 575 psi

$$N = (304/\varepsilon)^{12}$$

$$(k = 384 - 0.15 \times UCS)$$

Where,

- ε = repeated flexural strain (microstrain)
- UCS = unconfined compressive strength (psi)

Information presented by ARRB (Jameson, 2014) indicated that the SR for 10^5 load repetitions is 0.64.

ALGORITHM COMPARISONS

- The fatigue algorithms were compared based on the "slope" (change in stress ratio for one log cycle / 10^5 to 10^6) of a semi-log stress ratio (SR) concept (the IDOT algorithm).
- The CTM baseline conditions were:
    - Compressive strength = 500 psi; E(flexure) = 500 ksi
    - Flexural strength = 125 psi
- The PCA and ARRB [$N = (311/\varepsilon)^{12}$] stress ratios were calculated based on stress = $\varepsilon \times E$.
- The PCA slope is 0.064 for an 8-inch CTM layer and 0.072 for a 10-inch CTM layer. The ARRB slope is 0.085. The IDOT slope is 0.083.
- The average slope is 0.076.
- The SRs for 10^5 load repetitions are:
    - IDOT = 0.56
    - PCA = 0.52 (8-inch CTM)
    - PCA = 0.46 (10-inch CTM)
    - ARRB (2013) = 0.48
    - ARRB (Jameson, 2014) = 0.64.
- The average SR for 10^5 load repetitions is 0.53.
- Thus a "consensus" CTM fatigue algorithm is:

$$\text{Log } N = (X - SR)/0.076$$

Solving for "X" with $N = 10^5$

and SR = 0.53

$$\text{Log } N = (0.91 - SR)/0.076$$

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