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Review of Improved Subgrade and Stabilized Subbases to Evaluate Performance of Concrete Pavements

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16. Abstract

This report presents findings on the evaluation of foundation layers under concrete pavements in the state of Illinois. It also provides recommendations and scenarios where unbound granular layers can be safely used under concrete pavements as economical and well-performing subbase layers. The current practice and mechanistic design methods for constructing concrete pavements in Illinois was first evaluated, including historical studies that led to the current design procedures and policies. The performance of concrete pavements with unbound granular layers in Illinois were then evaluated, and several case studies of well-performing concrete pavements with granular subbases, high traffic levels, and low distress levels and severity were realized. Next, the practices of surrounding states were evaluated, and several Midwest states, i.e., Wisconsin, Minnesota, Iowa, and Michigan, were found to regularly use unbound granular layers under concrete pavements with no issues. A literature review on the most recent requirements and recommendations for designing granular subbases under concrete pavements was then presented. It is concluded that subbase layers under concrete pavements are mainly used to provide uniform support and prevent pumping. Based on the case study evaluations and literature, a stable, drainable, and durable daylighted granular subbase design is recommended for traffic factors up to 10.0. Stability is ensured by limiting the ratio of gravel-to-sand fractions in the aggregate mix between 1.3 and 1.9. Drainability requirements can be met by limiting the percentage of fines passing the No. 200 sieve (0.075 mm) to 4% and by checking the quality of drainage is at least fair based on the time required to drain 50% of the water. Lastly, a geotextile fabric is recommended for use below the granular subbase for separation to ensure drainability throughout design life.

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

- Heather Shoup, TRP Chair, Illinois Department of Transportation
- Andrew Stolba, Illinois Department of Transportation
- Charles Wienrank, Illinois Department of Transportation
- Dennis Bachman, Federal Highway Administration
- John Senger, Illinois Department of Transportation
- LaDonna Rowden, Illinois Department of Transportation
- Megan Swanson, Illinois Department of Transportation
- Michael Brand, Illinois Department of Transportation
- Mike Ayers, Illinois Chapter of the American Concrete Pavement Association
- Mike Copp, Illinois Department of Transportation
- Scott Kassel, Illinois Department of Transportation

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Trademark or manufacturers' names appear in this report only because they are considered essential to the object of this document and do not constitute an endorsement of product by the Federal Highway Administration, the Illinois Department of Transportation, or the Illinois Center for Transportation.

EXECUTIVE SUMMARY

This report presents findings on the evaluation of foundation layers (subgrade and subbase) under concrete pavements in the state of Illinois. The goal is to provide recommendations and scenarios where unbound granular layers could be safely and economically used under concrete pavements. The objective of this research effort is to provide a more economical subbase design for concrete pavements without jeopardizing performance over the design life. In the Illinois Department of Transportation's (IDOT's) current concrete pavement design procedure, a stabilized subbase layer with a 4 in. minimum thickness is required under concrete pavements for all road classes when the design traffic factor (TF) is higher than 2.0, which is equal to a traffic level of 2 million equivalent single axle loads (ESALs). This layer may be omitted for urban sections with curb and gutter and a storm sewer system.

The current practice and mechanistic-based design methods for constructing concrete pavements in Illinois were evaluated, including historical studies and research findings that led to the current design procedures and policies. The policies on the use of stabilized subbase dated back to findings from the American Association of State Highway Officials (AASHO) Road Test and to studies conducted by IDOT in the 1960s and 1970s related to the use of stabilized and granular subbases under concrete pavements. Some of the designs that the policies are based on, which required using a stabilized subbase for TF exceeding 0.7, are now outdated and seldom used in Illinois. The traffic factor for using a stabilized subbase was recently increased from 0.7 to 2.0 after the recommendations of a white paper research synthesis submitted to IDOT in 2010 by Jeffery Roesler (University of Illinois at Urbana-Champaign).

The performance of concrete pavements constructed in Illinois on interstates and state highways as well as roadways with unbound granular subbases and subgrade remediation involving aggregate subgrade improvement were evaluated. Most evaluated cases showed very low distress levels, mostly of low to medium severity. On a few projects, cases with traffic levels exceeding 20 million ESALs and showing good performance trends/low distresses were also observed in the state. This indicated the suitability of using granular subbases for traffic factors above the current 2.0 limit, particularly under jointed plain concrete pavements for which most cases were evaluated. The use of open-graded drainage layers (OGDL) in the state was also evaluated. Studies and test sections installed on in-service highways and exposed to real traffic and environmental conditions either showed that OGDL did not improve performance or resulted in issues because of the loss of cement paste (mortar) into large voids. The results and recommendations were also in line with studies from other states, thus discouraging the use of OGDLs because of lack of stability.

Next, the practices of surrounding states were evaluated. Several Midwestern states with similar climatic conditions to Illinois, i.e., Wisconsin, Minnesota, Iowa, and Kansas, were found to use unbound granular layers under concrete pavements as their common practice, and some states use granular subbases for considerably high traffic levels (e.g., 9 million ESALs in Kansas and 20 million ESALs in Iowa). These states, however, were found to request relatively stringent aggregate quality requirements for aggregate materials used in subbases under concrete pavements in order to ensure

performance. For example, Iowa limits the fines content, passing No. 200 sieve size, in aggregates to 6% for arterial concrete roads to minimize pumping and loss of support.

A literature review on the most recent requirements and recommendations for designing granular subbases under concrete pavements were then evaluated. The literature review included national case studies, recommendations of other states and national institutions, and more specialized research studies related to the use of subbases/granular materials under concrete pavements. From the literature, it was concluded that subbase layers under concrete pavements are mainly used to provide uniform support and prevent pumping. For uniformity, the subbase needs to be stable and resistant to erosion to prevent loss of support. The subbase needs to be drainable to prevent the accumulation of water, which facilitates pumping, and needs to remain clean from the intrusion of fines from the underlying subgrade. The three characteristics of relevance for these well-performing subbase functions were stability, drainability, and durability.

Based on the case study evaluations and the literature, a stable, drainable, and durable daylighted granular subbase design was proposed for use under concrete pavements in Illinois. The proposed daylighted subbase will have a minimum thickness of 4 in. and will be used for traffic factors between 2.0 and 10.0 for all road classes. The daylighted subbase will be underlain by a geotextile fabric for separation and drainage. An aggregate subgrade improvement or a Type A granular improvement on top of modified soil will be used as subgrade remediation methods under the daylighted subbase with geotextile separation to provide enough thickness for drainability and to ensure the functions of the subbase are properly served. Table 1 lists the proposed grain size distribution of the daylighted subbase under concrete pavements.

Table 1. Proposed Coarse Aggregate Gradation for Granular Subbase under Concrete Slab

	Sieve size and percent passing									
Gradation	2″	1 1/2″	1″	3/4″	1/2″	3/8″	#4	#10	#50	#200
CA 21	100	100	90 ± 10	78 ± 12	–	60 ± 10	40 ± 5	26 ± 6	13 ± 4	2 ± 2

The stability of the daylighted subbase was ensured by controlling the gravel-to-sand (G/S) ratio and limiting its value between 1.3 to 1.9. The G/S ratio is defined as the percent of gravel-sized particles (smaller than 3 in. and retained on sieve No. 4 or 4.75 mm as per the unified soil classification system, USCS) divided by the percent of sand-sized particles (passing sieve No. 4 and retained on No. 200 or 0.075 mm). Limiting the G/S ratio ensures a proper quantity of large gravel-sized particles are in contact for maximizing shear strength and proper sand content to fill the voids, provide stability, and packing.

Drainability requirements were met by limiting the percentage of fines passing the No. 200 sieve to 4% and by checking that the quality of drainage is excellent, good, or fair based on the time required to drain 50% of the water. The hydraulic conductivity and quality of drainage were calculated using the Moulton equation and DRIP (drainage requirements in pavements) software developed for the Federal Highway Administration, respectively. A recommendation was made to check drainage requirements more reliably for a specific material and grain size distribution using laboratory constant head permeameters or field-testing methods.

Lastly, the use of a geotextile fabric underneath the granular subbase was recommended as a separation layer to ensure the daylighted subbase remains clean and drainable throughout the design life. The use of a nonwoven geotextile was recommended unless a woven geosynthetics product (geotextile) is needed for providing enhanced lateral drainage and additional suction flow capacity in addition to gravity flow. For the geotextile, strength properties following the requirements of AASHTO M 288 Class 2 geotextile separator were recommended. A maximum apparent opening size of No. 70 sieve (0.212 mm) and a permittivity of 0.1 sec^{-1} or higher were specified. Manufacturers' specification sheets were revised to ensure a wide variety of manufacturers have multiple products meeting these requirements readily available for use in IDOT projects.

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CHAPTER 1: INTRODUCTION

BACKGROUND AND MOTIVATION

Illinois Department of Transportation's (IDOT's) mechanistic and mechanistic-empirical (M-E) pavement design procedures for concrete pavements have continually incorporated significant advances in material characterization, climate effects, performance prediction, and other elements of pavement design over the years. Thus, the modernization of design and construction methods employed for foundational layers of pavements, including subgrade soil modifications and subbase courses under concrete pavements, needs to keep up a similar pace. The guidelines provided in IDOT's *Geotechnical*, *Design and Environment*, *Local Roads and Streets*, and *Subgrade Stability Manuals* as well as its *Standard Specifications for Road and Bridge Construction* may require revisions. The parts related to foundational layers under concrete pavements may need to catch up with M-E pavement design procedures for concrete pavements to provide sustainable and resilient concrete pavement designs with satisfactory performance over the design life. These manuals and specifications detail design and construction methods for foundation layers, embankments, bases, subbases, etc. using soil, sand, gravel, crushed gravel, crushed stone, crushed concrete, crushed slag, crushed sandstone, etc. Generally, these documents are also not as integrally related or tied to M-E design practices and procedures as they could be.

One important aspect where IDOT's design and construction manuals need to be studied for economical pavement designs is related to the improved subgrade and subbase requirements for constructing rigid pavements. Construction of a working platform provides sufficient stability and adequate immediate support for equipment mobility and paving operations without developing excessive rutting. Note that subgrade stability refers to soil strength and repeated loading behavior of this lowest, and most often the weakest, layer of the pavement structure. Subgrade stability influences both pavement construction operations and long-term pavement performance.

IDOT's *Subgrade Stability Manual* (2005) recommends that minimum levels of strength and stiffness be achieved in the subgrade soil to a depth influenced by construction traffic to ensure adequate equipment mobility and to prevent excessive rutting under vehicle tires. To be stable, the finished subgrade must have a minimum Illinois bearing value (IBV) of 6% if untreated, or 10% if treated, and a maximum rut depth of 0.5 in. under construction traffic. For untreated soils with IBV less than 6%, the *Subgrade Stability Manual* presents guidelines for several remedial options. Subgrade removal and aggregate placement as a cover or capping layer is one of the most commonly used options in Illinois for treating soft, unstable soils. Figure 1 presents the required aggregate cover thickness, or the subgrade treatment/replacement thickness depending on the other remedial options such as admixture stabilization, determined as a function of the soil's IBV, cone index, shear strength, or unconfined compressive strength (Q_u). This figure is adapted from Figure A-2 of IDOT's *Subgrade Stability Manual* (2005). Note that the required remedial thickness does not distinguish between different aggregate types or aggregate qualities.

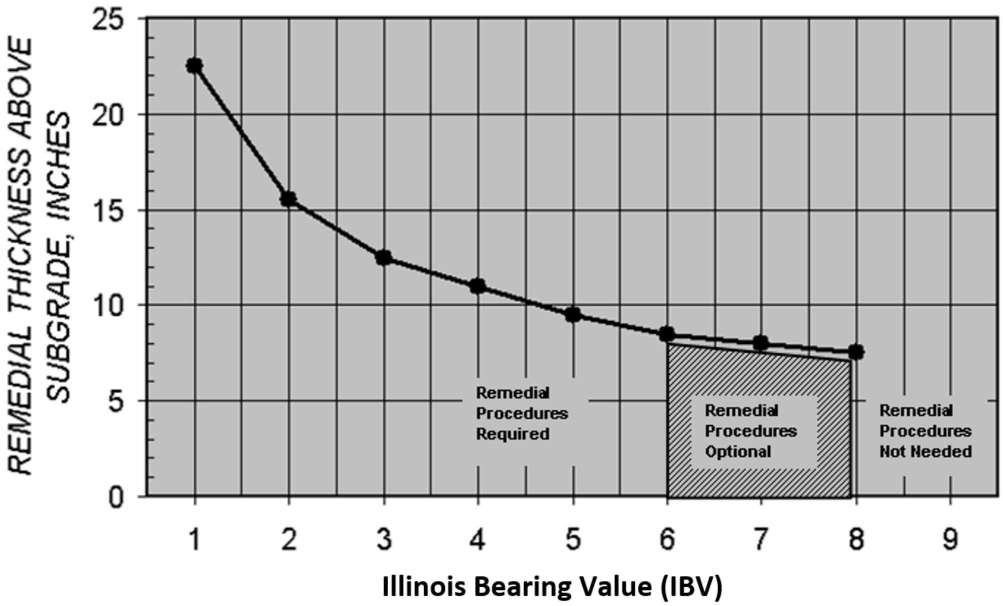


Figure 1. Graph. IBV or unsoaked California Bearing Ratio (CBR)-based remedial action.

IDOT (2005)

In the past few years, IDOT's Central Bureau of Materials has made efforts to develop guidelines on the types and properties of aggregate subgrade materials for use as aggregate/granular subbase. "Aggregate subgrade" is a term used in IDOT's *Standard Specifications for Road and Bridge Construction* that is linked to furnishing, transporting, and placing granular materials for subgrade improvement and subbase. Aggregate subgrade materials can be virgin aggregates, recycled materials such as crushed concrete and reclaimed asphalt pavement (RAP), or combinations of both. They are often used for subgrade replacement and construction of granular subbase layers over soft, unstable Illinois subgrade soils for building pavement construction working platforms, which eventually become part of the pavement structure. For example, on very soft subgrades with IBV below 3, large top-size aggregate subgrade materials such as primary crushed rocks (PCR) are often constructed as the pavement subgrade/granular subbase layer (12 to 24 in. thick) with a minimum 3 in. CA 6/CA 10 dense-graded capping layer placed on top. Note that these aggregate subgrade materials may also include RAP and/or crushed concrete blended with virgin aggregates. Several past Illinois Center for Transportation (ICT) projects characterized performance and alternative sustainable options for subgrade remediation. These will be discussed in Chapter 2 as readily implementable options for subgrade improvements.

Specifically related to the design and construction of rigid pavements, IDOT's *Bureau of Design and Environment* (*BDE*) *Manual* (2021) lists treatment options for improved subgrade as well as requirements for subbase type and thickness under jointed plain concrete pavements (JPCP). These requirements have undergone changes over time, following studies conducted by IDOT personnel and researchers as well as pavement performance evaluation of concrete pavements constructed in Illinois. The changes are related to the use of granular subbase materials under JPCP and minimum traffic levels (traffic factors) that require using a stabilized hot-mix asphalt (HMA) or Portland cement concrete (PCC) stabilized subbases. Table 2 presents the most up-to-date requirements, as listed in Figure 54-4.D in the *BDE Manual*. The stabilized subbase is currently required for all road classes and facility types with a design traffic factor (TF) exceeding 2.0, except for urban sections with curb and gutter and a storm sewer system when a subgrade remediation method involving an aggregate subgrade improvements (ASI) or a granular layer over modified subgrade (GM) are allowed. These requirements are generally viewed as overly conservative for many scenarios, where these stabilized subbases may be replaced by a more economical option without adversely affecting performance over design life. Another issue is that the stabilized subbases are not given credit in the design and are not accounted for to reduce pavement thickness despite their high stiffness.

Table 2. Minimum Structural Design Requirements for Mechanistically Designed Rigid Pavements

Facility Type	Subbase (1)		Improved Subgrade Type (2) (3)
	Type	Minimum Thickness (in.)	
Class I			
Interstate / Freeway	HMA or PCC stabilized	4	ASI, GM, or MS
Other Marked Routes	HMA or PCC stabilized	4	ASI, GM, or MS
Unmarked Routes (TF $\geqslant$ 2.0)	HMA or PCC stabilized	4	ASI, GM, or MS
Unmarked Routes (0.7 < TF < 2.0)	Not required	n/a	ASI, GM (4)
Unmarked Routes (TF $\leqslant$ 0.7)	Not required	n/a	ASI, GM, or MS
Class II			
Marked Routes	HMA or PCC stabilized	4	ASI, GM, or MS
Unmarked Routes (TF $\geqslant$ 2.0)	HMA or PCC stabilized	4	ASI, GM, or MS
Unmarked Routes (0.7 < TF < 2.0)	Not required	n/a	ASI, GM (4)
Unmarked Routes (TF $\leqslant$ 0.7)	Not required	n/a	ASI, GM, or MS
Class III			
Marked Routes	HMA or PCC stabilized	4	ASI, GM, or MS
Unmarked Routes (TF $\geqslant$ 2)	HMA or PCC stabilized	4	ASI, GM, or MS
Unmarked Routes (0.7 < TF < 2.0)	Not required	n/a	ASI, GM (4)
Unmarked Routes (TF $\leqslant$ 0.7)	Not required	n/a	ASI, GM, or MS
Class IV			
Marked Routes	HMA or PCC stabilized	4	ASI, GM, or MS
Unmarked Routes (TF $\geqslant$ 2.0)	HMA or PCC stabilized	4	ASI, GM, or MS
Unmarked Routes (0.7 < TF < 2.0)	Not required	n/a	ASI, GM (4)
Unmarked Routes (TF $\leqslant$ 0.7)	Not required	n/a	ASI, GM, or MS

Figure 54-4.D, *BDE Manual* IDOT (2021)

Notes:

(1) For urban sections containing curb and gutter and a storm sewer system, the designer may omit the stabilized subbase when an ASI or GM improved subgrade is used, regardless of the traffic factor.

(2) Improved subgrade types include:

ASI—aggregate subgrade improvement (minimum of 12 in.)

GM—granular over modified Soil (4 in. CA 6 or CA 10 over 12 in. modified soil)

MS—modified soil (minimum of 12 in.)

(3) The minimum thickness of improved subgrade shall be according to Section 54-2.01(f).

(4) Modified Soil may be used for the improved subgrade if a minimum 4 in. stabilized subbase is used.

This report aims to provide geotechnical solutions for rigid pavement designs in Illinois. It mainly deals with the review and evaluation of critical aspects of improved subgrade requirements, specifically Figure 54-4.D of the *BDE Manual* (IDOT 2021), presented in Table 2. This project will revise these requirements and recommend more economical and sustainable designs as well as assess the scenarios and TF levels for which these alternative options will be deemed suitable.

In summary, to ensure adequate performance under construction traffic as well as a structural layer of the constructed pavement structure, improved subgrade and subbase requirements for constructing rigid pavements need to be adequately established through performance-based specifications involving modern testing techniques and state-of-the-art mechanistic-based design procedures. Project design and construction solutions require further guidance and improvements for site-specific considerations of these special geotechnical issues (e.g., dealing with soft and/or problematic soils, compaction, geosynthetics, drainage, stabilization, sustainable materials use, and working platform design).

OBJECTIVE AND SCOPE

The objective of this research project is to provide IDOT with geotechnical solutions for highway and pavement applications that will advance current practice and ensure that the pavements in Illinois are constructed to the needed levels of performance, economy, and durability, without being overly conservative. A more specific goal is to review the use of improved subgrade and stabilized subbase considerations under concrete pavements. Current pavement designs are evaluated based on performance records of constructed field projects, and recommendations are made, as needed, to revise certain design aspects currently adopted by IDOT that may be considered conservative and uneconomical. Specifically, the main objective and outcome of this project is to come up with an alternative design to replace (or reduce the thickness of) the stabilized subbases currently required under concrete pavements, assess traffic levels for which the alternative design is deemed suitable, and evaluate aspects to ensure performance and cost are optimized for the proposed design. To achieve the overall objective of this project, the following specific tasks are conducted:

- Task 1—Review and evaluate improved subgrade and subbase requirements for IDOT’s pavement design procedures.
- Task 2—Compile field projects and performance records.
- Task 3—Develop alternatives for IDOT’s design and construction methods that are overly conservative and provide other geotechnical solutions.
- Task 4—Recommend changes to IDOT’s manuals and specifications.

REPORT ORGANIZATION

This report consists of four chapters, including this introductory chapter.

Chapter 2, titled “Review of Literature and Practice,” provides details for the design methods of concrete pavements in Illinois, presents a review of the performance of concrete pavements with granular subbases, and discusses the practices of surrounding states related to the use of granular subbases underneath concrete pavements. This chapter presents a discussion of available and up-to-date literature on the design of granular subbases for concrete pavements, including important aspects for ensuring uniformity, stability, pumping prevention, drainability, and durability throughout the design life.

Chapter 3, titled “Proposed Subbase Design,” provides details on the effort of the research team to propose a daylighted, stable, drainable, and durable granular subbase design underlain with a geotextile fabric to be put into use under concrete pavements for IDOT traffic factors ranging from 2.0 to 10.0. Details on the selection of the grain size distribution to ensure stability and drainability of the subbase layer, aggregate quality requirements, constructability requirements, and geotextile separator properties and specifications are all discussed and justified in this chapter.

Chapter 4, titled “Summary and Conclusions,” provides a summary of the research results and recommendations as well as conclusions related to constructing a durable and well-performing granular subbase for concrete pavements. This chapter also discusses some recommendations for future research, such as monitoring the performance of the proposed subbase in future implementation projects for IDOT.

CHAPTER 2: REVIEW OF LITERATURE AND PRACTICE

IDOT DESIGN METHODS AND REQUIREMENTS FOR CONCRETE PAVEMENTS

IDOT's *Bureau of Design and Environment* (*BDE*) *Manual* (2021) presents standard design procedures for concrete pavements in the state of Illinois. Chapter 54 of the *BDE Manual* presents the design procedures for jointed plain concrete pavements (JPCP), jointed reinforced concrete pavements (JRCP), and continuously reinforced concrete pavements (CRCP). The design of JPCP pavements follows a mechanistic design approach, while the design of CRCP and JRCP follows a modified AASHTO design procedure. JRCP is only used to match existing pavement and use of CRCP is limited to designs with a TF greater than 60.

IDOT's Subgrade Requirements for Concrete Pavements

According to the *BDE Manual* (IDOT 2021), most Illinois soils are weak and do not provide a subgrade that meets the criteria for a stable working platform. The negative effects of less satisfactory soils can be reduced by increasing pavement thickness, but there may still be a need to treat in situ soils to ensure adequate subgrade support for construction equipment operations. At minimum, it is required that a 12 in. improved subgrade layer be provided. Where in situ soils are found to be inadequate such that the 12 in. improved subgrade layer will not provide a stable working platform, the designer should include provisions to address the need for deeper treatment or removal and replacement as per the requirements of IDOT's *Subgrade Stability Manual* (2005). The *BDE Manual* allows three options for improved subgrades: aggregate subgrade improvement (ASI), granular over modified soil (GM), and modified soil (MS). Figure 2 presents these required options and minimum required treatment depths.

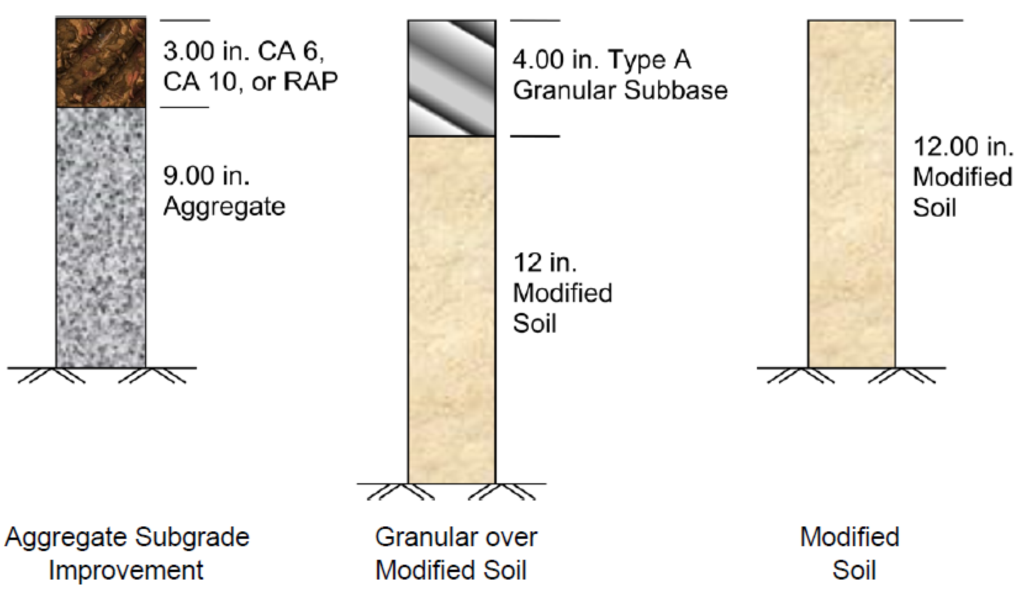


Figure 2. Illustration. IDOT's treatment options for improved subgrade.

IDOT (2021, Figure 54-2.D)

The mechanistic design methodology for both rigid and flexible pavements assumes that a stable subgrade is present (in situ or improved). If an improved subgrade is utilized, then the assumption is that the subgrade is constructed with the highest quality material. Further, if a modified subgrade is utilized, then the *BDE Manual* does not give it any additional credit during design nor is the cost of providing an improved subgrade included in the pavement selection process. If an improved subgrade layer is needed to provide a stable working platform, no change will be made to the subgrade support rating (SSR) that is used during design.

IDOT Design Procedure for Jointed Plain Concrete Pavements

Chapter 54 of the *BDE Manual* (IDOT 2021) presents the detailed procedure for designing JPCP pavements. The design follows a multi-step approach to select and adjust the concrete layer thickness based on the design requirements, which include design period, traffic factor (TF), SSR, and road/street class, among other design parameters. The design period for concrete pavements is typically 20 years. Table 3 summarizes the road classes in Illinois based on the average daily traffic (ADT) and the number of lanes.

Table 3. IDOT Road and Street Classes as Defined by the *BDE Manual*

Road and Street Class	ADT and Number of Lanes
Class I	Roads with four or more lanes, and all one-way streets with structural design traffic greater than 3,500 ADT
Class II	Two-lane facility with structural design traffic greater than 2,000 ADT, and all one-way streets with structural design traffic less than 3,500 ADT
Class III	750 ≤ ADT ≤ 2,000
Class IV	ADT < 750

IDOT (2021)

The steps for selecting the thickness of concrete pavements start by determining the TF and SSR. The TF is calculated based on ADT and the volume of passenger vehicles (PV), as well as single-unit (SU) and multiple-unit (MU) vehicles that will be in the design lane in the year that is one-half the design period from the established date of construction. The full details are presented in section 54-2.01(c) of the *BDE Manual* (IDOT 2021). The equations for determining the TF are presented in Figure 54-4.C of the *BDE Manual* based on the class of the road.

Next, the SSR of the in situ soil is determined to evaluate existing soil conditions. SSRs are based on information provided in the project geotechnical report and are divided into three categories—poor, fair, and granular—based on the grain size distribution of the in situ soil materials and the percentages of clays, silts, and sands. Figure 3 presents the methodology adopted in the *BDE Manual* to determine the SSR as the point of intersection based on the percentage of clay, silt, and sand in the in situ soil.

The edge support (e.g., tied or untied shoulder) and pavement thickness are determined next. For all Class I, II, III, and IV marked roads and streets as well as for Class I, II, and III unmarked roads and streets, the concrete thickness is determined based on SSR from several graphs presented in the *BDE*

Manual (mechanistic design graphs). Figure 4 presents a sample graph for determining the pavement thickness for a fair SSR and a TF up to 10.0. For Class IV unmarked routes, the thickness is determined with a different procedure using Figure 54-4.H in the *BDE Manual* and assuming a standard case of untied shoulders, no subbase, poor subgrade (k = 50 psi/in.), panel length of 12 ft, and no dowels. The pavement thickness is then adjusted according to Figure 54-4.I of the *BDE Manual*. Note that Figures 54-4.H and 54-4.I are not shown here.

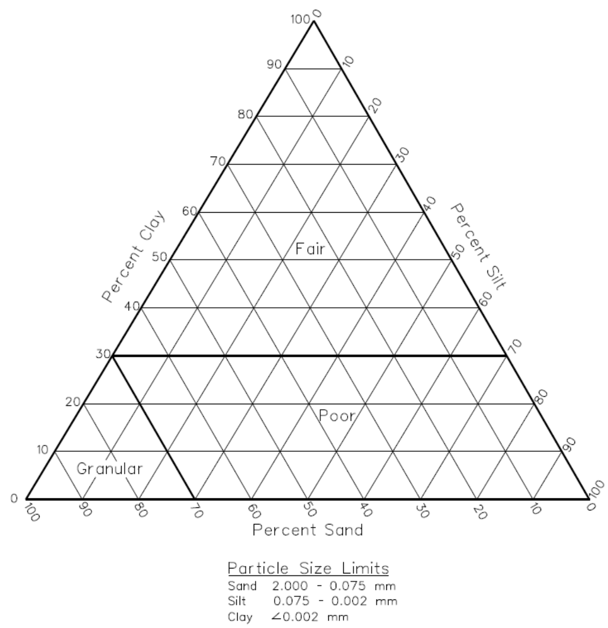


Figure 3. Diagram. Determining the subgrade support rating of in situ soil.

IDOT (2021, Figure 54-2.E)

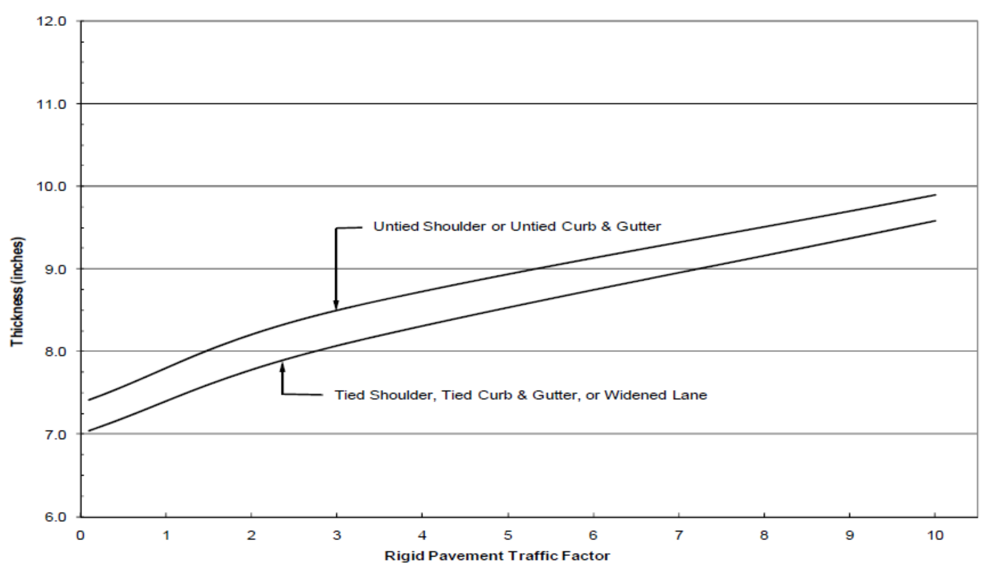
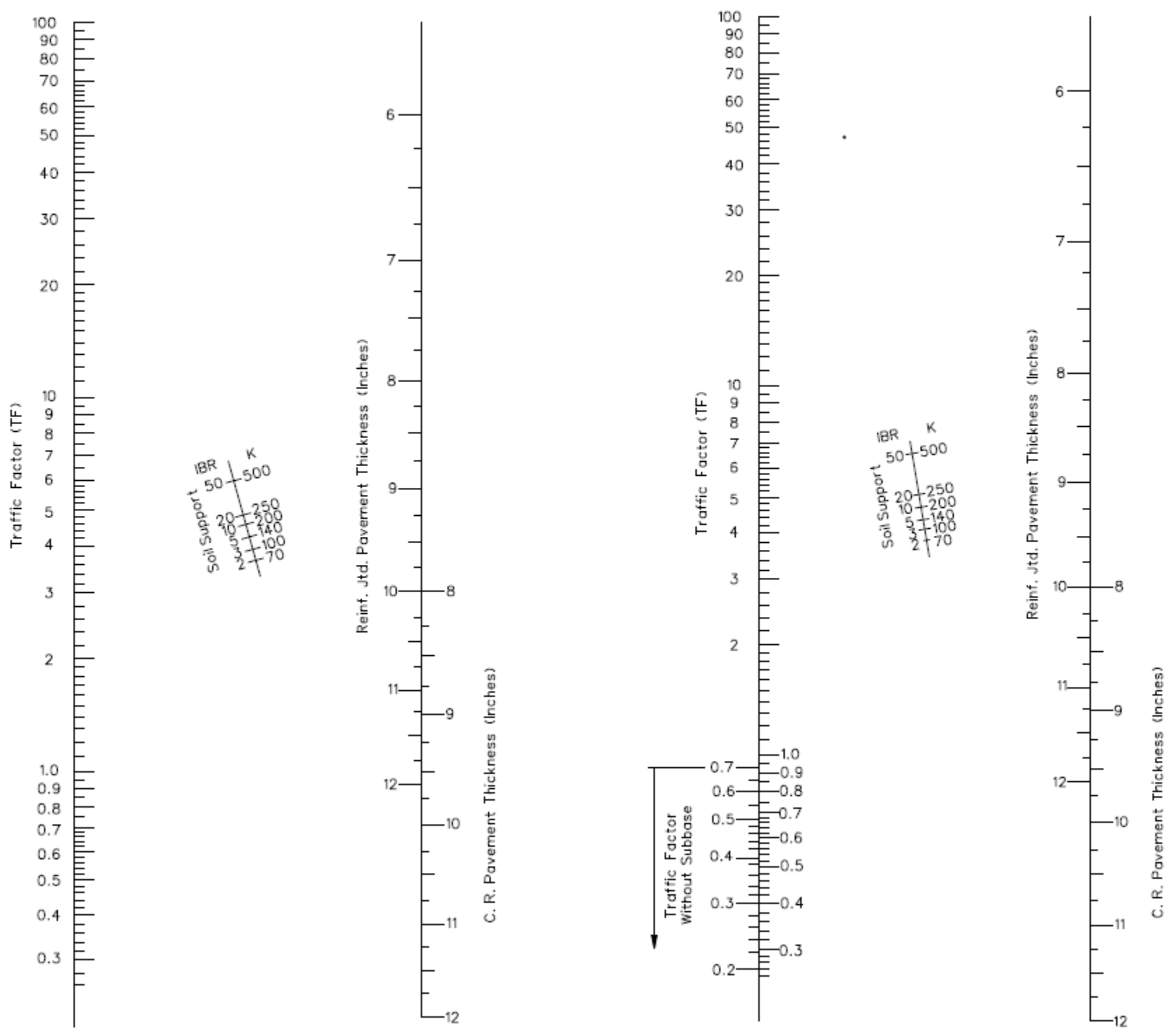


Figure 4. Graph. IDOT pavement thickness design graph for JPCP with a fair subgrade support rating.

IDOT (2021, Figure 54-4.F)

IDOT's Design Procedure for Continuously Reinforced and Jointed Reinforced Concrete Pavements

For JRCP and CRCP, IDOT uses a modified AASHTO design procedure. For JRCP, the maximum joint spacing is typically 50 ft. CRCP designs, in contrast, are typically used for high traffic levels, i.e., traffic factors exceeding 60.0. The procedure for determining the traffic factor is the same as that used for JPCP. The main discrepancy in the determination of the concrete thickness is that it is based on the Illinois bearing ratio (IBR) instead of SSR for in situ subgrade rating. The IBR is determined from laboratory tests on four-day soaked samples of the soils to be used in construction or are estimated based on AASHTO soil classification for the existing soils. Once the IBR and the traffic factor are determined, the required pavement thickness is determined using design nomographs presented in the *BDE Manual*. Figure 5 presents design nomographs for CRCP and JRCP from the *BDE Manual*.



CRCP and JRCP design nonograph for Class I roads

CRCP and JRCP design nonograph for Class II, III, and IV roads

Figure 5. Nomographs. IDOT pavement thickness design graphs for CRCP and JRCP.

IDOT (2021)

IDOT's Gradation Requirements for Granular Subbases

According to Article 1004.04 of the *Standard Specifications for Road and Bridge Construction* manual (IDOT 2016b), several coarse aggregate gradations are permitted by IDOT for granular subbases. Table 4 presents a list of allowable subbase materials. Note that Types A, B, and C refer to construction requirements, which govern density requirements and maximum thickness per lift, with Type A subbase material being the most stringent in terms of requirements and quality control. Table 5 presents the grain size distribution of four of the most commonly used subbase materials. CA 6 and CA 10 are the two most commonly used coarse aggregate materials by the state of Illinois and are commonly used for embankments, capping layers, subbases, bases, and surface courses. CA 10 has a smaller nominal maximum aggregate size and higher allowable maximum fines content passing the No. 200 sieve (0.075 mm).

Table 4. Allowed Gradations for Granular Subbase Materials

Granular Subbase	Gradation
Subbase Granular Material, Type A	CA 6 or CA 10 [1/]
Subbase Granular Material, Type B	CA 6, CA 10, CA 12, or CA 19 [1/]
Subbase Granular Material, Type C	CA 7, CA 11, or CA 5 & CA 7 [2/]

Adapted from IDOT (2016b)

Notes:
1/ Gradation CA 2 or CA 4 may be used if approved by the Engineer.
2/ If the CA 5 and CA 7 blend is furnished, proper mixing will be required either at the source or at the jobsite according to Article 1004.02(d).

Table 5. Grain Size Distribution of Selected IDOT Coarse Aggregate Materials

	Cumulative percent passing (%)									
Gradation	3 in.	1.5 in.	1 in.	0.75 in.	0.5 in.	3/8 in.	No. 4	No. 16	No. 50	No. 200
CA 6		100	95±5		75±15		43±13	25±15		8±4
CA 10			100	95±5	80±15		50±10	30±15		9±4
CA 12				100	95±5	85±10	60±10	35±10		9±4
CA 19	100		95±5				60±15	40±15	20±10	10±5

Historical Changes for Design Requirements and Traffic Factors

Table 2 in Chapter 1 (Figure 54-4.D of the IDOT *BDE Manual*) presented the current IDOT requirements for subbase materials under concrete pavements (IDOT 2021). These requirements have been refined over time based on recommendations of several studies and field evaluations at the state. Roesler (2010) performed a historical review of key IDOT documents and selected outside literature to determine the rationality of IDOT's current policy on the use of granular or stabilized subbases under concrete pavements, and the traffic factor thresholds for different design requirements.

The white paper by Roesler (2010) presented a summary of the testing results of the American Association of State Highway Officials (AASHO) Road Test, which had concrete pavements with 2.5, 3.5, 5, 6.5, 8, 9.5, 11, and 12.5 in. slab thicknesses constructed on top of granular subbases of various thickness (no subbase, 3, 6, and 9 in.). The granular bases conformed to IDOT's CA 6 gradation requirements and had approximately 7.5% fines content passing No. 200 (0.075 mm)—specification limits were 5% to 9% fines content. Constructed JPCP had 15 ft transverse joint spacing and JRCP had 40 ft joint spacing, with all joints doweled. Roesler concluded that the granular subbases showed some erosion and washouts because of the accumulation of water underneath the slabs, creating high water pressure and leading to pumping and material washouts. Subbase material was removed by horizontal water movement at the interface of the subbase layer and slab. Subbase thickness was not a variable in the failure, and there was no clear evidence that the soil layer entered the voids in the subbase.

Several follow-up studies by IDOT succeeded the AASHO Road Test to further investigate the performance. These studies contributed to some of the current specifications and requirements of traffic factor assignments for different road classes and concrete pavement subbase requirements. According to Roesler (2010), the main studies and contributions can be summarized as follows.

- Chastain et al. (1964) established design slab thickness charts for Class I with a terminal present serviceability index (PSI) of P_t = 2.5 and Class II and III roadways with P_t = 2.0. The designers could use a 4 in. stabilized or 6 in. granular subbase thickness under Portland cement concrete (PCC). On Class I roads, a stabilized base was required for ESALs exceeding 130,000 per year (TF = 2.6). On residential streets with drainage and local traffic, no subbase was required, and the minimum required slab thickness is 6 in.

- Burke (1968) developed further guidelines for concrete pavement design and for the use of granular subbases under PCC. He concluded that for thinner PCC sections (5 in.), the use of granular subbases made a difference in pumping performance, but not for thicker concrete slabs (6.5 in. or 8 in.). Accordingly, the study suggested that for Class III roadways, no subbase would be required for a traffic factor (TF) below 0.8 because of the low amount of pumping anticipated over the design life.

- Chastain et al. (1973) determined a need to apply a 1.3 multiplication factor for the thickness charts to adjust for actual performance (Illinois-modified AASHO). The study concluded that stabilized subbases were now required on Class I roads, granular materials now required only 4 in. thickness, and the use of a subbase was no longer needed for a TF less than 0.7 or in urban areas with curb and gutter and storm sewer.

- Little and McKenzie (1977) and McKenzie et al. (1977) studied several original AASHO Road Test sections put into service on I-80 to extend the scope of the AASHO Road Test variables. Subbase materials used included cement aggregate mixtures (CAM) and bituminous aggregate mixtures (BAM) of 4 in. thickness, various thickness sand-gravel subbases, and crushed stone subbases (6 in. thickness), and no subbase. The study found most transverse cracking and faulting occurred on granular subbases relative to stabilized ones. BAM subbases outperformed other subbase types when used under JRCP with 40 ft and 100 ft slab sizes. The study also concluded that the type of granular subbase did not make a statistical difference in pavement performance. Further, the presence of durability cracking (D-cracking) skewed the conclusion to better-performing pavements having fewer joints. Note that this study had mostly 40 ft and 100 ft joint spacing, which is no longer implemented in the state. Thus, the conclusions in this study are based on longer joint spacing, which is not comparable to current design and practice. Also, a missing part from this study is that no stabilized sections were installed under the shorter slabs (15 ft) for comparison.

Roesler (2010) made the following recommendations for improving the design:

- IDOT could raise the required traffic level for granular base layers to 2 or 3 million ESALs and still maintain their current network performance for concrete pavements. Because pumping and erosion is the biggest concern, slower moving traffic would allow this required traffic threshold to rise. This recommendation is currently implemented in the February 2021 *BDE Manual*.

- A further increase of the allowable traffic level for granular materials would likely require use of a separation layer, a drainage system, minimum quality requirements of the granular material, and higher compactive effort during construction (also recommended by Tutumluer et al. 2009). These requirements are further investigated by this research project to recommend best practices and further increase the allowable traffic factor for using granular subbases under concrete pavements in Illinois.

REVIEW OF ICT PROJECTS THAT STUDIED SUBGRADE AND SUBBASE IMPROVEMENTS

Mishra and Tutumluer (2013) in the project R27-81 characterized in the laboratory the strength, stiffness, and deformation behaviors of three aggregate types commonly used in Illinois for subgrade replacement and subbase applications. They validated their field performance trends through accelerated loading of full-scale pavement working platform test sections. Six test “cells” were constructed at different combinations of aggregate material quality and subgrade strength and were tested to failure using the University of Illinois’ Accelerated Transportation Loading Assembly (ATLAS). Each cell was tested along two different wheel paths representing two aggregate layer moisture contents (cells 1–5) or geotextile reinforcement conditions (cell 6). Performances under loading were monitored through surface profile measurements as well as transverse scanning with ground-penetrating radar. Field and laboratory test results highlighted the importance of considering aggregate quality in the thickness design of aggregate layers for construction platforms. Thick layers of uncrushed gravel placed over a weak subgrade mainly underwent internal shear failure owing to excessive movement of the aggregate particles. Crushed aggregate layers constructed with high relative compaction, in contrast, showed significantly higher resistance to internal shear deformation and permanent deformation accumulations. Prolonged exposure to moisture and freeze-thaw effects was found to be beneficial for a crushed dolomite material with high amounts of nonplastic fines, probably owing to carbonate cementation within the fine fraction. Failure of test sections under flooded conditions was primarily caused by excessive deformation in the subgrade layer. Recommendations were made based on the study's findings for improved material selection and thickness designs of aggregate working platforms.

Kazmee and Tutumluer (2015) in the project R27-124 evaluated and validated the existing IDOT "aggregate subgrade" gradation bands through full-scale field testing. The project utilized a state-of-the-art image analysis technique to characterize the size and shape as well as the texture and angularity properties of the studied aggregate subgrade materials. For field evaluation, 24 combinations of pavement test sections were constructed over subgrade with controlled low IBV or unsoaked CBR strength properties. Construction quality control was achieved through in-place density and modulus measurements on aggregate layers using a nuclear gauge, lightweight deflectometer, and soil stiffness gauges. Periodic rut measurements were carried out on the pavement surface through the accelerated loading process using ATLAS. Contributions of the underlying pavement layers to the total rut accumulation were evaluated through innovative applications of ground-penetrating radar, a lightweight variable energy penetrometer device known as PANDA, and a geo-endoscopy probe. Layer intermixing and material migration at the aggregate subgrade–subgrade interface improved the foundation layer stiffness properties and pavement performance results significantly. Construction platforms capped with reclaimed asphalt pavement (RAP) consistently exhibited a higher magnitude of rutting. Performances of flexible pavement sections were governed by the as-constructed HMA thicknesses, which varied considerably during the paver operation because of RAP subbase sinkage and the weak subgrade. Adequate validation and potential revisions to current IDOT specifications were recommended.

As part of the findings of R27-124, penetration of large rocks, i.e., aggregate subgrade, into very soft subgrade was demonstrated to be effective in improving the weak subgrade and preparing a fairly stable working platform layer in pavement construction (Kazmee and Tutumluer 2015). Nevertheless, the uniformly graded materials, such as the railway ballast–size RR01 aggregates or the primary crusher run aggregates (IDOT CS01 or CS02 specifications), exhibited wider variation in rutting performance because of the presence of large inherent voids. Without the presence of smaller sized particles, aggregate interlock was minimal at the interface of aggregate subgrade, which eventually affected the subgrade load distribution and resulted in less than desirable rutting performance. A clear recommendation from the project was to consider inclusion of smaller sized aggregate materials to fill voids and improve performance of the uniformly graded large-size aggregate subgrade materials. Low-cost quarry by-products (QB) or nonplastic fines were especially recommended for such beneficial and sustainable pavement applications. The challenge was to ensure uniformity by avoiding segregation among different blended aggregate sizes. As a result, an in-depth study was recommended to optimize the composition, handling, and compaction of such blended applications of QB with coarse aggregate fractions of virgin and recycled materials and other additives, such as fibers, etc., for use as subbase/base.

Qamhia et al. (2018) in project R27-168 utilized excess aggregate quarry fines by incorporating QBs in sustainable pavement applications to adequately evaluate their field performance through accelerated pavement testing (APT). The project selected new and sustainable applications of QB or QB mixed with other marginal, virgin, or recycled aggregate materials in pavements, as unbound or chemically stabilized pavement layers. Sixteen full-scale test sections were constructed to evaluate the use of QB in base, subbase, and aggregate subgrade applications. The chemically stabilized test sections utilizing QB were stabilized with 3% cement or 10% Class "C" fly ash by dry weight and were constructed over a subgrade having an engineered unsoaked CBR of 6% to study their effectiveness in low- to medium-volume flexible pavements. The unbound applications of QB investigated the use of QB to fill the voids between large aggregate subgrade rocks commonly used for rockfill applications on top of very soft subgrade soils, as well as using dense-graded aggregate subgrade layers with higher fines content up to 15% passing No. 200 sieve (0.075 mm) for soft subgrade remediation. These unbound test sections were constructed over a CBR = 1% subgrade soil to investigate their effectiveness in both construction platforms and low-volume road applications. All field test sections were evaluated in rutting and fatigue by applying traffic loading using a super-single wheel in APT. In general, results from APT and forensic analyses indicated that satisfactory results and improved rutting performance were obtained from all test sections utilizing QB applications. The studied QB pavement applications were deemed readily implementable into standard pavement construction and rehabilitation practices.

In project R27-SP43, Qamhia et al. (2021) evaluated a case study for constructing aggregate subgrade improvement (ASI) layers using quarry by-product aggregates (QBA)—a quarry mix of large rocks and sand-sized quarry fines. The construction took place at Larry Power Road at Bourbonnais Township in Kankakee County, Illinois, where the research team and IDOT placed two QBA mixes. The first mix (QBA_M1) consisted of 45% quarry by-products and 55% railroad ballast–sized 3×1 primary crushed rocks (PCR). The second mix (QBA_M2) consisted of 31% and 69% quarry by-products and large rocks, respectively. IDOT and the researchers also constructed two conventional ASI sections conforming to IDOT's CS02 gradation. All sections consisted of a 9 in. QBA/PCR topped with a 3 in. dense-graded CA 6 capping layer. They monitored the quality and uniformity of the construction using nondestructive techniques such as dynamic cone penetrometer, lightweight deflectometer, and falling weight deflectometer. They also monitored the segregation potential by visual inspection and imaging-based techniques. Laboratory studies preceded the construction to recommend optimum QB content in the QBA materials and construction practice. Short-term field evaluation of the constructed QBA layers, particularly QBA_M2 with a 31% quarry by-product content, showed no evidence of abnormal segregation and did not jeopardize the structural integrity of the QBA ASI layers, which had slightly lower but comparable strength and stiffness profiles to the conventional ASI sections. The use of QBA materials in ASI was field validated as a sustainable construction practice to provide stable pavement foundation layers.

In a recently completed ICT project R27-157, Osouli et al. (2018) found that the plasticity requirements of unbound aggregate pavement layers and fines content (passing No. 200 sieve size or finer than 0.075 mm) characteristics influence the aggregate matrix strength as well as the modulus and deformation behavior. A laboratory investigation was conducted to identify the effects of fines content, plasticity index, dust ratio (percent passing No. 200 to No. 40 sieve size), and gradations on the strength, modulus, and deformation characteristics of crushed gravel and limestone aggregates. A series of moisture-density and CBR tests were conducted on considered configurations. Furthermore, triaxial strength and resilient modulus tests were conducted on selected samples. A series of guide charts were presented to show the effects of various fines content characteristics on the strength, modulus, and deformation behavior of aggregates. Some of the configurations that are in compliance with existing IDOT specifications provided unacceptable strength values. For example, the use of aggregates with low dust ratio and high fines content resulted in a weak aggregate matrix. In general, the detrimental effect of a high plasticity index was more pronounced on crushed gravels. The findings of this study relate to Article 1004.04 of IDOT's standard specifications (IDOT 2016b). For any modification to be applied to this specification, it is recommended that these laboratory results be further validated using field- or full-scale tests.

REVIEW OF CONCRETE PAVEMENT PERFORMANCE IN ILLINOIS

IDOT published a 2016 report to verify and validate the design procedures and life-cycle cost models used in the pavement selection process (IDOT 2016a). The report entailed detailed surveys on 105 mechanistically designed flexible and rigid pavements across the state. Of these pavements, the rigid pavements constructed on unbound subbases were selected with the help and input from the TRP members of this project to investigate their performance and recommend best practices.

Table 6 and Table 7 present details about these pavements, including subbase type and thickness, pavement age, percent patching, and cumulative ESALs upon last survey in 2014. All nine surveyed pavement sections with unbound granular subbases were JPCP. Pavements had a 4 in. to 12 in. subbase thickness, and three pavements were constructed on top of a 12 in. aggregate subgrade improvement layer. Concrete thickness ranged between 9.5 in. and 10.25 in., and percent patching of all nine pavements was minimal (0%–0.6%) at a pavement age of 11 to 14 years. Further, cumulative ESALs is reported at the pavement age upon last survey and ranged between 0.938 to 11.476 million ESALs. The cumulative ESALs and low percent patching for the surveyed pavements is an indicator of a proper mechanistic pavement design with unbound subbases and provides a starting point to recommend using granular subbases for long-lasting and low-maintenance concrete pavements in the state of Illinois.

The report also provided details on the types and severity of distresses in the surveyed pavements. All sections with unbound subbases were examined in detail, and this report will present details for two sections with JPCP because they had the highest traffic accumulated at the time of surveying. The first section involved two westbound lanes on IL-64 in DuPage County (milage 5.81 to 7.06), which were constructed in 2002 and have an annual average daily traffic (AADT) of 38,980 vehicles, comprising of 35,360 passenger vehicles, 2,080 single-unit trucks, and 1,540 multiple-unit trucks. The second section involved two northbound lanes on I-74 in Rock Island County (milage 3.75 to 4.51), which were constructed in 2003 and have an AADT of 36,500 vehicles, comprising of 34,725 passenger vehicles, 875 single-unit trucks, and 900 multiple-unit trucks. The IL-64 section had an average condition rating survey (CRS) value of 6.9, an international roughness index of 120 in/mi, and an average rut depth of 0.1 in. at the time of the survey; while these values were 8.1, 109 in/mi, and 0.1 in., respectively, for the I-74 section at the time of survey.

Table 6. Surveyed Concrete Pavements in Illinois: Subbase and Subgrade Information

County	District	Route	Pavement Type	Pavement Thickness	Subbase Type	Subbase Thickness	Subgrade Type	Subgrade Thickness	Overlay
Kendall	3	US 34	JPCP	9.5	Granular Type A	12.00″	–	–	
Kendall	3	US 34	JPCP	9.5	Granular Type A	12.00″	–	–	
Jo Daviess	2	US 20	JPCP	9.5	Granular Type A	12.00″	–	–	
Lee	2	IL-2	JPCP	9.5	Granular Type A	12.00″	–	–	
DuPage	1	IL-64	JPCP	10.25	Granular Type B	4.00″	Aggregate	12″	
DuPage	1	IL-64	JPCP	10.25	Granular Type B	4.00″	Aggregate	12″	
Lake	1	US 45	JPCP	9.75	Granular Type B	4.00″	Aggregate	12″	
Winnebago	2	IL-2	JPCP	9.75	Granular Type A	12.00″	–	–	
Rock Island	2	I-74	JPCP	10	Granular	6.00″	0	0	Yes (1)

Adapted from IDOT (2016a)

Table 7. Surveyed Concrete Pavements in Illinois: Percent Patching and Traffic Levels

County	District	Route	Pavement Type	Pavement Thickness (in.)	Survey Year	Pavement Age (years)	Percent Patching	Cumulative ESALs (million)
Kendall	3	US 34	JPCP	9.5	2014	11	0	3.296
Kendall	3	US 34	JPCP	9.5	2014	11	0.02	2.85
Jo Daviess	2	US 20	JPCP	9.5	2015	12	0.22	2.86
Lee	2	IL-2	JPCP	9.5	2014	14	0.33	1.863
DuPage	1	IL-64	JPCP	10.25	2014	12	0.03	9.599
DuPage	1	IL-64	JPCP	10.25	2014	12	0	11.476
Lake	1	US 45	JPCP	9.75	2014	12	0.03	2.955
Winnebago	2	IL-2	JPCP	9.75	2014(A)	13	0.01	0.938
					2014(B)	13	0	1.341
Rock Island	2	I-74	JPCP	10	2014	11	0.6	6.231

Adapted from IDOT (2016a)

The distress types and severities, i.e., low, medium, or high, observed for the IL-64 section in DuPage County are presented for the passing lane (PL) and driving lane (DL) in Table 8. At the time of the survey, the section had 11.476 million cumulative ESALs and had 0% patching. Most of the distresses were low-severity longitudinal cracks or areas with permanent patch deterioration. Only a few medium- and high-severity distresses were observed, in particular a few areas with spalling. This JPCP pavement was constructed on a 4 in. unbound subbase on top of a 12 in. aggregate subgrade improvement. The pavement survey results indicate that this design provides sufficient support uniformity and drainability and is likely adequate for a TF exceeding 10, with minimal issues with durability and longevity.

Table 8. Distress Levels for IL-64 Section in DuPage County

Distress+	PL Low	PL Medium	PL High	DL Low	DL Medium	DL High
8	1	0	0	2	0	0
13	0	0	0	46	0	0
16	72	0	0	0	0	0
18	5	18	0	4	2	0
26	0	1	0	0	0	0
28	4	9	2	8	4	2
30	4	1	0	2	1	0

Adapted from IDOT (2016a) *+ Distress types are as follows—8: corner break (number); 13: longitudinal cracking (lineal ft); 16: permanent patch deterioration (ft²); 18: pothole and localized distress (number); 26: scaling and map cracking or crazing (highest severity); 28: spalling (number); 30: transverse cracking (number).*

The distress types and severities for the I-74 section in Rock Island County are presented for the passing and driving lanes in Table 9. At the time of the survey, the section had 6.231 million cumulative ESALs and 0.6% patching. Most of the distresses were low- or medium-severity permanent patch deterioration. Only a few medium- and high-severity distresses were observed for the other types of distresses, in particular a few areas with medium- and high-severity spalling and transverse cracking. This JPCP pavement was constructed on a 6 in. unbound subbase, and the maintenance records indicate it had the first overlay before 2010. This pavement was selected to showcase because of the high ESAL level accumulated. The low percent patching and generally low distress severity indicate the design is suitable for a traffic level higher than the 2.0 TF currently requiring a stabilized subbase in the IDOT *BDE Manual*. In summary, the performance data collected by IDOT for JPCP pavements in Illinois indicate the design traffic factor for JPCP with granular subbases can be safely increased above 2 million ESALs.

Table 9. Distress Levels for I-74 Section in Rock Island County

Distress+	PL_Low	PL_Medium	PL_High	DL_Low	DL_Medium	DL_High
8	3	0	0	5	0	0
16	432	0	0	504	144	0
28	3	2	1	4	9	1
30	8	8	1	10	9	0

Adapted from IDOT (2016a). *+ Distress types are as follows—8: corner break (number); 16: permanent patch deterioration (ft²); 28: spalling (number); 30: transverse cracking (number).*

Next, the experience of IDOT with open-graded drainage layers (OGDL) was examined. Most of the information were obtained from two reports published by IDOT that summarize projects and research/implementation efforts to examine the effectiveness and cost-benefit of building OGDL in the state. The first is Physical Research Report (PRR) No. 114 (IDOT 1993), and the second is PRR No. 147 (IDOT 2004); both reports were published by IDOT's Bureau of Materials and Physical Research. The 1993 report stated that Illinois experimented with OGDL during the late 1980s and early 1990s in the following projects:

- I-39 near Bloomington was constructed in the fall of 1989. For a test section length of 1,220 ft, a 16 in. lime-modified subgrade was topped with 6 in. cement-treated OGDL (CTOGDL) and 10.75 in. hinge-jointed plain concrete pavement. The OGDL extended 18 in. out under the tied plain concrete shoulders. Geocomposite underdrains were placed at the shoulder. The performance monitoring records indicated that the CRS value remained within the "Excellent" category for the first 10 years. Further, the IRI, falling weight deflectometer (FWD) deflections, and load transfer efficiency (LTE) were within normal ranges. The 2003 visual distress survey indicated three spalled joints, two transverse cracks, and approximately 50% of the joints with some degree of faulting, and no rehabilitation measured were necessary.

- I-39 at Lostant was constructed in the fall of 1990. Test sections were 500 ft long each. A 16 in. lime-modified subgrade was topped with a 4 in. lean concrete base in the control section. The OGDL sections experimented with the type and thickness of OGDL layers. In the northbound lanes, 4 in. and 5 in. asphalt-treated OGDL (ATOGDL) were constructed. In the southbound lanes, 4 in. and 5 in. CTOGDL were constructed. Additional sections with 4 in. ATOGDL on top of 3 in. dense-graded aggregates in both directions were also constructed. All sections were topped with 10 in. CRCP and had plastic pipe underdrains placed outside the shoulder edge with outlets every 500 ft. Performance monitoring records revealed that no significant difference in performance was observed for sections with OGDL layers with different thicknesses, or with the addition of an aggregate separation layer below the OGDL. Further, FWD deflections indicated no significant difference between CTOGDL, ATOGDL, and the control (lean concrete base).

- I-39 at El Paso was constructed in 1992 with a length of 9.5 miles (north- and southbound) having OGDL sections and no control section. The 10 in. CRCP pavement was constructed on top of OGDL and a 16 in. lime-modified subgrade. Some of the sections had a 3 in. layer of aggregate material topped with 4 in. CTOGDL, while others had a 4 in. CTOGDL placed directly on subgrade. Plastic pipe underdrains were placed 1 ft from outside the shoulder edge with outlets every 500 ft. Premature failure shortly after construction was observed, with high FWD deflections recorded and evidence of pavement settlement in some locations. This required corrective undersealing measures to restore pavement profile. According to performance monitoring records in 2003, the corrective measures worked, and only low-severity cracks were observed, with no spalling at the transverse cracks. Further, "Excellent" CRS values were measured, and the IRI values were below the state average. Maintenance and rehabilitation measures also included placement of numerous full-depth concrete patches throughout the project in the driving lane. The OGDL section placed directly on the lime-modified subgrade required the most patching.

- I-80 between mileposts 105 and 111 west of Morris was completely reconstructed in 1993 with a 12 in. lime-modified subgrade topped with 4 in. CTOGDL and an 11.5 in. CRCP. Recycled concrete aggregates from the existing road were used to construct the OGDL. The pavement encountered premature cracking and failure because of the use of an open-graded layer under the concrete. Performance monitoring records until 2003 revealed that 10% to 20% of the transverse cracks were moderate in severity, with between 10% and 50% of the joints spalled. Below average to average IRI levels were recorded. CRS values had a sharp decline after construction, then a slower decline. An increase in cracks after pavement undersealing maintenance measures performed in 1995–96 was observed. In addition to the undersealing, several full-depth concrete patches were placed, but the percent of patched area was considerably low.

- Macon County Highway 1 was constructed as three sections between 1994 and 1997 (3 miles) on top of a 12 in. lime-modified subgrade. The pavement section consisted of a 4 in. ATOGDL topped with 12 in. JRCP, with a doweled joint spacing of 40 ft, and a 6 in. by 12 in. welded wire fabric reinforcement. The pavement was a curb and gutter section, and no underdrains were installed. Performance monitoring in 2003 revealed that 99% of the 40 ft slabs had a mid-panel crack, and 9% of those mid-panel cracks were considered medium severity. Further, 5% of the mid-panel cracks had positive faulting exceeding 0.25 in. and some low-severity spalling. No maintenance and rehabilitation activities were undertaken in the first nine years of the age of the project, i.e., until 2003.

The 2004 IDOT report No. 147 concluded the following regarding the use of OGDL under concrete pavements:

- The use of an OGDL is more expensive than the use of a standard stabilized subbase material or lime-modified soil. The limited benefits of using an OGDL do not outweigh the cost, construction difficulties, and maintenance requirements on CRCP.

- The intrusion of fines from the subgrade and the aggregate separation layer into the OGDL resulted in settlement, faulting, and eventually premature failures, particularly with CRCP.

- An unexpected permanent bond between the CRCP and the OGDL reduced steel depth with regards to total pavement cross section, reducing the effective steel percentage and leading to premature CRCP failures.

- The benefits of using either type of OGDL (cement or asphalt treated) over the other could not clearly be determined.

REVIEW OF PAVEMENT PERFORMANCE—OTHER STATES

Rao et al. (2019) evaluated case studies for a range of conditions wherein the foundation layers, i.e., base and subbase layers, contributed significantly (positively or negatively) to overall pavement performance. They sought to develop guidelines for proper design and construction of quality bases and subbases for concrete pavements. Ten case studies were evaluated by the authors, four of which were related to drainage aspects, and summarized in their paper:

- Case 1: US 460 Bypass in Appomattox County, Virginia, is a 9.0 in. doweled JPCP, with 4.0 in. cement-stabilized OGDL, underlain by 6.0 in. of cement-treated soil with 10% hydraulic cement by volume. The section had 6.0 in. to 9.0 in. variable depth jointed concrete with tied shoulder and is designed for 8 million ESALs (annual daily traffic was 13,000 in 2003, including 10% truck traffic). Subgrade soil was classified as A-7-5 red clay and silt with a California bearing ratio (CBR) of 9%. This section experienced premature failure after five years of paving: 24% of eastbound slabs and 12% of westbound slabs were distressed, and distress types included mid-slab cracks, broken joint seals, lane-shoulder drop-off, pumping, and joint faulting. Upon characterization, the drainage layer was found clogged and filled with red soil, and water was trapped underneath the slab and was observed during coring. Learning outcomes from this premature failure is that poor drainage can be a key for premature failure. In this case, the OGDL was not continued to the edge drain, so trapped water seeped vertically and abraded the soil cement subbase, leading to localized loss of support, disintegration, and pavement distresses.

- Case 2: US 63 in Callaway County, Missouri, was originally constructed as a 9 in. JRCP with 61 ft. joint spacing on top of a 4 in. dense-graded crushed rock subbase on top of A-6 and A-7 soils. The section completely washed away because of flooding in 1993. The modified enhanced design afterwards consisted of 12 in. JPCP with 15 ft. joint spacing on top of a 24 in. daylighted subbase to increase structural capacity and improve drainage during heavy rain or flood periods. After reconstruction, the section experienced another flood in 1995 but maintained a good condition. For 24 years of performance monitoring (1994–2018), the section exhibited minimal cracking, faulting, and roughness increase. The main learning outcome from this case study is that stability and drainability of subbase material is essential to enhance the performance during heavy rain or flooding incidents. The 4 in. dense-graded rock filled with sand and jeopardized the structural capacity, leading to failure, while the 24 in. daylighted subbase facilitated drainage and improved performance.

- Case 3: US 23 in Monroe County, Michigan, had 10.5 in. JRCP test sections with 27 ft. joint spacing constructed from concrete mixtures having different coarse aggregates (crushed limestone, blast furnace slag, and gravel). Half of each section was built on an impermeable subbase and the other half on a well-draining sand-permeable subbase with a hydraulic conductivity of 198 to 288 ft/day. Sections were constructed on a 4 in. asphalt-treated permeable base on top of a 3 in. gravel separator layer, separating the drainage layer from the wet clayey subgrade. The JRCP sections did not exhibit any distresses related to freeze-thaw (e.g., joint deterioration or D-cracking). After 23 years, all sections performed well except the one with blast furnace slag. Joints did not exhibit any pumping issues, and the measured joint faulting was less than 0.04 in. Further, smaller mid-panel deflections were measured underneath the well-draining subbase compared to the other subbase. The learning outcome from this study is that a well-draining base / subbase structure can improve pavement performance. The satisfactory freeze-thaw performance can be attributed to the well-draining asphalt-treated permeable base layer preventing water from accumulating at the bottom of the PCC.

- Case 4: Highway 115 in Ontario, Canada, was constructed of 8 in. JPCP on 4 in. of OGDL underlain by 4 in. of aggregate base over 12 in. of aggregate subbase. Three types of OGDL were used: untreated, asphalt cement treated, and Portland cement treated. The 4 in. aggregate base was used as a filter layer between OGDL and the subgrade. In 2005, at a pavement age of 13 years and a traffic level of 4.67 million ESALs, a pavement evaluation condition survey revealed only 0.5% cracked slabs eastbound and 2.4% westbound. From initial laboratory testing, all three types of OGDL met the initial permeability and stability requirements. FWD deflection testing was carried out on the different sections, and the cement-treated OGDL had 17% lower deflection than the asphalt-treated one and 28% lower deflection than the untreated OGDL. All sections showed excellent performance, and the major learning outcome is that OGDL layers should be separated from the subgrade using a separation layer (granular layer or a geotextile) to prevent/minimize the intrusion of fines.

From the four case studies by Rao et al. (2019), the drainability of the subbase under a concrete pavement is an essential feature to ensure good performance. The main highlights and learning outcomes are as follows. Subbases need to have enough capacity (thickness) to drain water, especially in areas prone to flooding or high rainfall intensities. Daylighted subbases are a good option for unbound subbases under concrete pavements to move the water away from underneath the slabs. OGDL under concrete pavements showed mixed performance, but the performance can be enhanced by ensuring they are well draining and clean from fines intrusion. The use of a separation layer between the subgrade and the draining subbase is essential to maintain the drainability of the subbase over the design life and reduce the intrusion of fines from the underlying fine-grained subgrades. The findings of this study are in line with many other studies, and the learning outcomes will be incorporated in this project’s findings for the proposed design improvements for subbases under concrete pavements in the state of Illinois.

PRACTICES OF SURROUNDING STATES

To provide a conclusion on the suitability of the use of unstabilized granular bases under concrete pavements as well as the acceptable traffic levels (traffic factors) to allow the use of granular subbases for IDOT, the practices and design requirements for surrounding states were reviewed. Roesler (2010) highlighted a brief review of the practices of surrounding states:

- Kansas DOT has the closest policy to Illinois and uses a 9 million ESAL criterion to move from granular to stabilized subbase usage—equivalent to a TF of 9.0 for IDOT.
- Missouri, Indiana, Ohio, and Michigan DOTs do not appear to use stabilized subbases under their concrete pavements.
- Minnesota employs thick granular base and subbase layers, probably to combat frost penetration.
- Wisconsin employs unbound granular bases under concrete pavements, and typically these are open-graded layers to facilitate drainage.

Further, Iowa, the state that has the highest percentage of concrete roads in the United States, typically uses granular subbase materials under concrete pavements. Iowa DOT (IADOT) allows aggregate of the following types/properties: (1) crushed stone, (2) gravels of which 30% or more of the particles are retained on the 3/8 in. (9.5 mm) sieve and have at least one fractured face, (3) crushed Portland cement concrete (PCC) pavement meeting the requirements of Materials I.M. 210 specifications, or (4) uniformly blended combinations of these materials (IADOT 2012). Table 10 shows the design requirements for PCC thicknesses for arterial roads in Iowa, as presented in the design manual published by the Institute for Transportation at Iowa State University (ISU 2019). Note that the use of granular subbases is permitted for traffic levels up to 20 million ESALs.

Table 10. IOWA Design Requirements for PCC Thicknesses for Arterial Roads

	Subgrade CBR = 3%						Subgrade CBR = 5%					
ESAL/Subbase thickness (in.)	Natural	4″ Granular	6″ Granular	8″ Granular	10″ Granular	12″ Granular	Natural	4″ Granular	6″ Granular	8″ Granular	10″ Granular	12″ Granular
1,000,000	7.5	7	7	7	7	6.5	7.5	6.5	6.5	6.5	6.5	6.5
1,500,000	8	7.5	7.5	7.5	7.5	7	8	7	7	7	7	7
2,000,000	8	8	7.5	7.5	7.5	7.5	8	7.5	7.5	7.5	7.5	7.5
3,000,000	8.5	8	8	8	8	8	8.5	8	8	8	8	8
4,000,000	9	8	8	8	8	8	8.5	8	8	8	8	8
5,000,000	9	8.5	8.5	8.5	8	8	9	8	8	8	8	8
7,500,000	10	9	9	9	9	9	9.5	8.5	8.5	8.5	8.5	8.5
10,000,000	10	9.5	9.5	9.5	9	9	10	9	9	9	9	9
12,500,000	10.5	9.5	9.5	9.5	9.5	9.5	10.5	9.5	9.5	9.5	9.5	9
17,500,000	11	10	10	10	10	10	11	10	10	10	10	10
20,000,000	11.5	10.5	10.5	10.5	10.5	10.5	11	10	10	10	10	10

Adapted from ISU (2019)

For aggregate gradation requirements, Table 11 presents the grain size distribution for crushed stone used as a granular subbase under concrete pavements. Note that Iowa limits the fines content passing No. 200 to a 6% maximum (IADOT 2012). For quality requirements, Table 12 lists the requirements for IADOT for virgin coarse aggregate subbase materials in terms of Los Angeles abrasion, alumina testing, and A freeze (IADOT 2012).

Table 11. Allowable IADOT Grain Size Distribution for Granular Subbase Crushed Stone

Gradation	Intended use	Sieve size and percent passing			
		1 1/2″	1/2″	No. 8	No. 200
4121 Crushed Stone	Granular subbase	100	40–80	5–25	0–6

IADOT (2012)

Table 12. IADOT's Coarse Aggregates Quality Requirements—Virgin Aggregates

Coarse Aggregate Quality	Maximum Percent Allowed	Test Method
Abrasion	50	AASHTO T 96
Alumina[a]	1.5	Office of Materials Test Method No. Iowa 222
A Freeze	25	Office of Materials Test Method No. Iowa 211, Method A

IADOT (2012). *Note (a): If the Alumina value fails, determine the A Freeze value for specification compliance. Office of Materials Test Method No. Iowa 222 does not apply to gravel.*

CONCEPT OF GRAVEL-TO-SAND RATIO

Xiao and Tutumluer (2012) introduced a ratio to assess the stability of granular bases/subbases. The gravel-to-sand ratio (G/S) is a measure for stability and packing of unbound aggregate layers.

Figure 6 presents the equation to calculate the G/S ratio. This equation was derived from the two parameters of the Talbot equation, i.e., D_{max} and n, fitted from the percent passing data, according to the "gravel" and "sand" definitions of the unified soil classification system (USCS). Note that USCS defines gravel sizes as materials smaller than 3 in. and retained on No. 4 sieve (4.75 mm), and sand-sized materials as materials passing No. 4 sieve but retained on No. 200 (0.075 mm).

$$\frac{G}{S}=\frac{p_{75mm}-p_{4.75mm}}{p_{4.75mm}-p_{0.075mm}}=\frac{1-\left(\frac{4.75}{D_{\max}}\right)^n}{\left(\frac{4.75}{D_{\max}}\right)^n-\left(\frac{0.075}{D_{\max}}\right)^n}=\frac{\left(D_{\max}\right)^n-4.75^n}{4.75^n-0.075^n}$$

Figure 6. Equation. Calculating gravel-to-sand (G/S) ratio.

where, P_{75mm}, $P_{4.75mm}$, $P_{0.075mm}$ are the percentages passing sieve sizes 3 in. (75 mm), No. 4, and No. 200, respectively; $D_{\max}$ is the maximum particle size for gravel (3 in. or 75 mm for USCS); and n is the Talbot equation power multiplier.

Xiao and Tutumluer (2012) and Tutumluer et al. (2015) analyzed several gradation bands for Minnesota Department of Transportation (MnDOT) and found that the optimum G/S ratio for most gradations is between 1.5 and 2, which ensures stability and high shear strength of a granular base/subbase. The shear strength was found to improve significantly when the G/S ratio approached 1.5 or higher. To illustrate the effect of G/S ratio on packing and stability, Figure 7 presents an illustration for the effect of the proportion of gravel and sand in the aggregate mix. A large G/S ratio indicates a mix with high gravel content and typically high porosity, while a low G/S ratio indicates an aggregate mix with high sand content, where the larger aggregates are floating in the finer mix and have a low number of contact points. Aggregate mixes with large G/S ratios develop shear or permanent deformation resistance through contact and friction resistance between the large particles, and the stability will be dependent on the grain size distribution of the gravel-sized particles. Aggregate mixes with low G/S ratios, in contrast, generally have lower shear strength and are more prone to rutting.

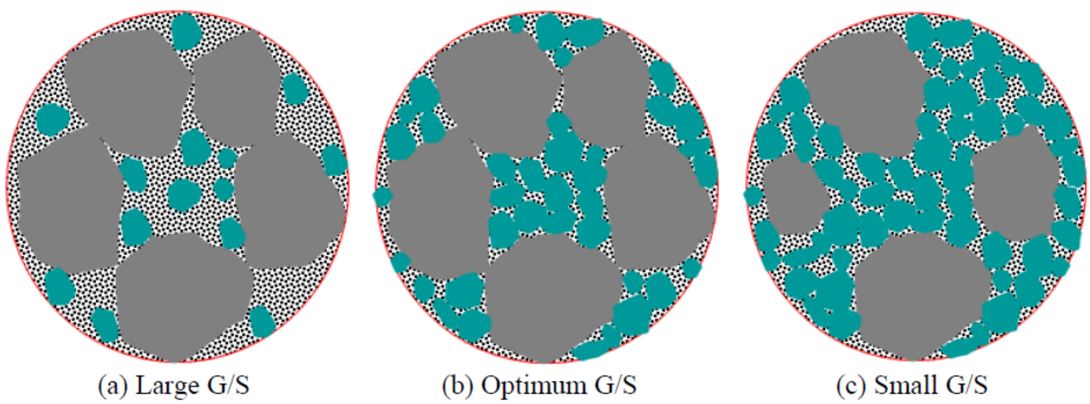


Figure 7. Illustration. Phase diagram illustrations for the effect of the G/S ratio on the packing state.

Xiao and Tutumluer (2012)

Tutumluer et al. (2015) proposed additions to the aggregate base specifications in Minnesota based on stability requirements dictated by the G/S ratio. The proposed modifications were concluded based on discrete element modeling analysis and evaluations of long-term pavement performance data and field data from test cells constructed at Minnesota (MnRoad experiment). Discrete element modeling simulations recommended tighter specification on gradation bands, particularly the percent passing the No. 4 sieve (4.75 mm) being the divider between gravel and sand sizes. Tutumluer et al. (2015) recommended gradation bands for two new aggregate base layer materials—Class 5-Qa and PAB-Qa—based on stability requirements. Further, the fines in the Class 5-Qa recommendation were decreased to allow for greater permeability and drainability. A maximum of 5% passing No. 200 sieve (0.075 mm) was allowed. Table 13 presents the recommended gradation bands for Class 5-Qa and PAB-Qa gradations.

Table 13. Recommended Gradations for MnDOT

	Sieve size and percent passing								
Gradation	1 1/2″	1″	3/4″	3/8″	# 4	#10	#40	#200	G/S
Class 5-Qa	100	80–100	65–90	50–70	30–50	20–40	10–30	0–5	1.0–2.3
PAB-Qa		100	65–90	50–70	30–50	15–35	5–25	0–5	1.0–2.3

Tutumluer et al. (2015)

The research also provided recommendations for the aggregate quality requirements for the two base layer materials compared to existing gradation bands. The maximum loss in the Los Angeles abrasion tests was decreased, and the minimum percent crushed faces was increased compared to the traditional aggregate materials. Table 14 presents a summary of the recommended aggregate quality requirements for Class 5-Qa and PAB-Qa proposed to MnDOT. The study mentioned that contractors and producers are able to meet the new requirements if proper incentives are given for their efforts in attempting new methods and processes to obtain them, while the state and the public will benefit from better performance and longer life for concrete pavements.

Table 14. Recommended Aggregate Quality Requirements

Coarse Aggregate Quality	Class 5-Qa	PAB-Qa
Minimum two-face crushing	30%	85%
Maximum Los Angeles rattler loss	35%	35%
Maximum shale	7%	–
Maximum spall materials	–	5%
Gravel / sand ratio (max/min)	1.85/1.22	1.85/1.22
Lab- or field-tested permeability	300 ft/day	300 ft/day

Tutumluer et al. (2015)

IMPORTANCE OF SEPARATION LAYERS

Several studies have proven the efficiency and need of using a separation layer to maintain a clean subbase/base layer throughout the design life and prevent the intrusion of fines, which contribute to drainability issues, pumping, and erosion. Common separation layers include dense-graded granular layers (e.g., IDOT CA 6 coarse aggregate materials) and geotextile fabrics.

Signore and Dempsey (2002) studied the effects of separation layer type on the pumping resistance of concrete pavement. A laboratory accelerated testing procedure with cyclic loading was applied. Both geotextile separator layers and dense-graded CA 6 aggregate layers were used and compared to a control case with no separation layer employed. Experiments were conducted with both unstabilized and lime-stabilized subgrades to also study the effect of subgrade stabilization on the migration of fines into the overlying layers. According to this study, the use of a geotextile separator reduced pumping by 80% from the non-separated case. A CA 6 separation layer offered significant separation benefits while at or below optimum moisture content. However, upon nearing saturation, the CA 6 layer allowed for significant intermixing of the open-graded subbase layer into the dense-graded separation layer. Figure 8 presents a summary of the results. Using a geotextile separator layer provides a more durable (and cheaper) separation option than a dense-graded aggregate layer for all field conditions, including a nearly saturated pavement structure.

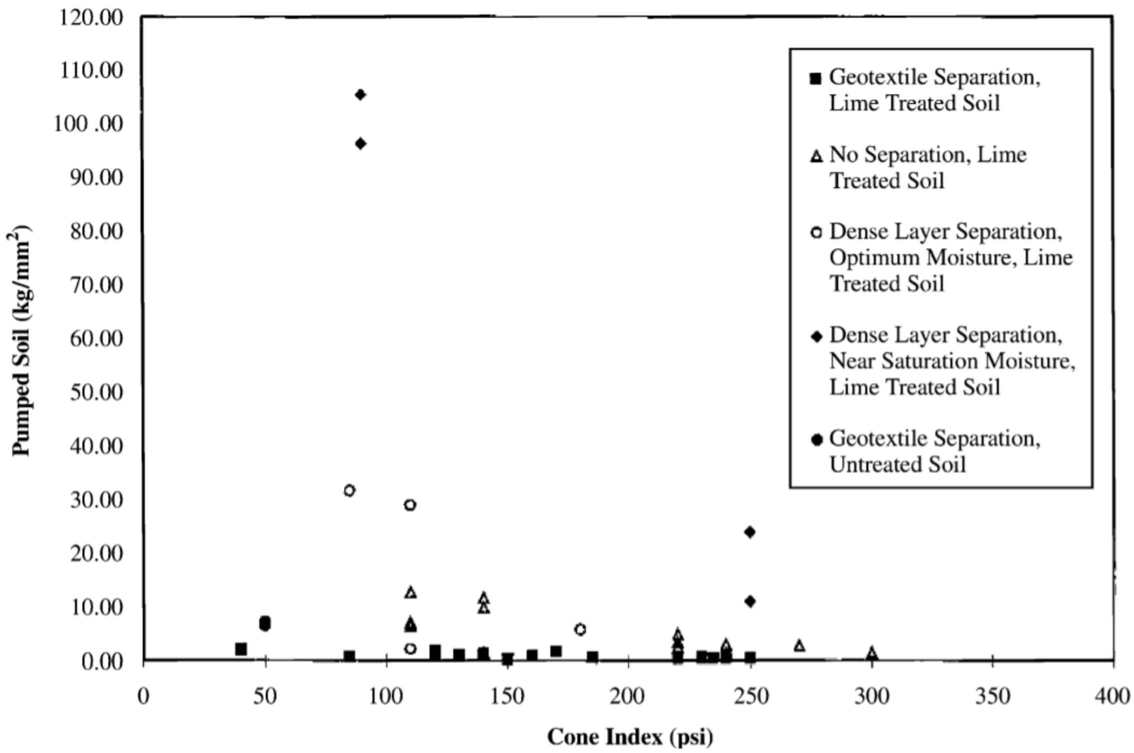


Figure 8. Plot. Pumped material versus cone index for setups of Mexico clay subgrade, a separation layer (CA 6 dense-gradded layer or geotextile), and an open-graded aggregate subbase.

Signore and Dempsey (2002)

Another study by Kermani et al. (2020) assessed the capability of geotextile as a separation / filtration layer in reducing subgrade fines migration. A one-third scale model mobile-load simulator (a lab-sized APT device) was used. A control section versus sections with a geotextile placed at the interface of subgrade and subbase were evaluated. Sieve analysis was used to quantify the magnitude and rate of the migration of subgrade particles into the subbase at 200,000 and 1,000,000 loading cycles. The study concluded that the geotextile reduced subgrade migration and faulting by 71% and 52%, respectively. More fines accumulated in the subbase beneath the approach slab than the leave slab, which resulted in faulting of the slabs. As expected, more fines migrated to the bottom half of the subbase closest to the subgrade. Figure 9 presents the percentage of fines migrating into the subbase from the subgrade for the tests with and without a geotextile separator. This study thus proved the effectiveness of a geotextile separator in reducing fines migration, which maintains the drainability of the subbase and reduces pumping and erosion potentials.

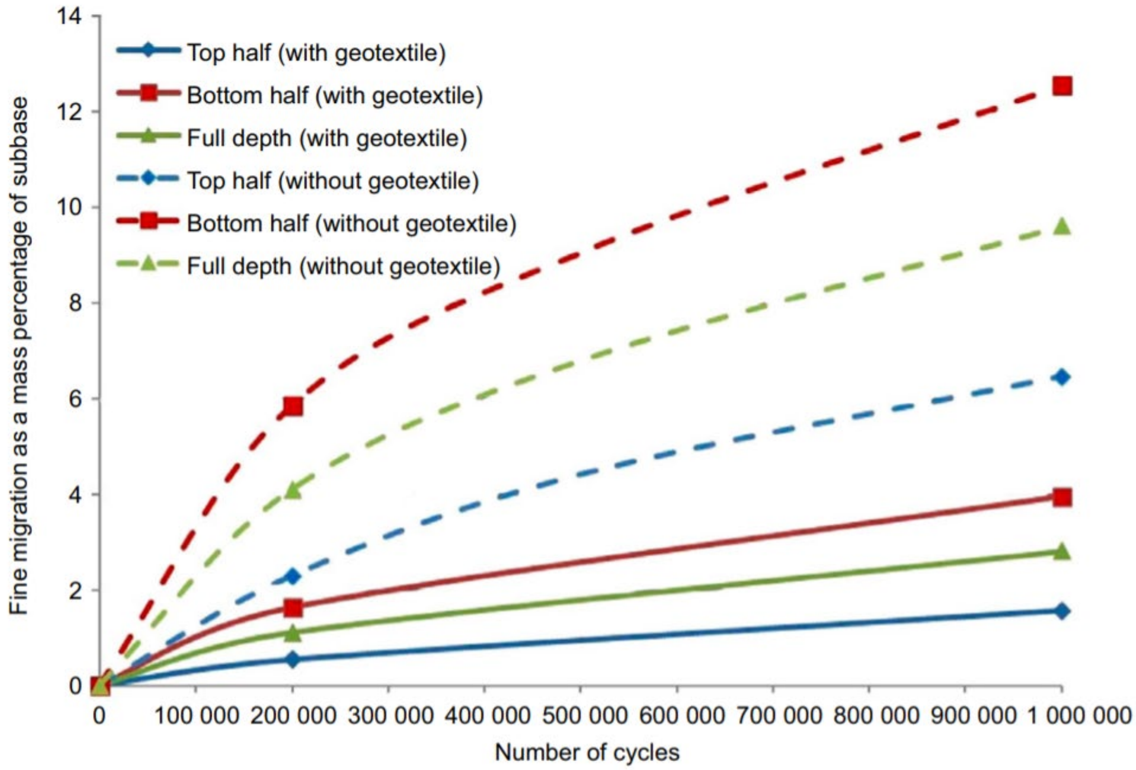


Figure 9. Graph. Percentage of subgrade pumping into the subbase based on the mass of contaminated subbase.

Kermani et al. (2020)

Table 15 presents the applications of geotextile fabrics related to drainage and seperation in pavements. This table was adapted from short course materials taught by Jorge Zornberg and Erol Tutumluer at the GeoAmericas Geosynthetics Specialty Conference in October 2020.

Table 15. Geotextile Usage in Pavement Applications for Drainage and Separation

Application	Objective(s)	Mechanism(s)	Geotextile Function		Benefits in Roadway Performance
			Primary	Secondary	
Reduction of layer intermixing	Avoid contamination of unbound aggregate layers with fine-grained subgrade soil particles	Minimize (a) loss of aggregate particles into underlying soft subgrade, and (b) migration of fine-grained soil particles into overlying unbound aggregate layers	Separation	Filtration	Maintain the as-designed structural capacity by minimizing/eliminating (a) time and serviceability related decrease in base/ballast or subbase/subballast layer thickness, and (b) reduction in the quality of aggregate materials

Application	Objective(s)	Mechanism(s)	Geotextile Function		Benefits in Roadway Performance
			Primary	Secondary	
Reduction of moisture in structural layers	Provide in-plane drainage to minimize access and accumulation of moisture within structural layers	Provide (a) gravity-driven drainage (for saturated soil conditions), and (b) enhanced drainage due to capillarity (for unsaturated soil conditions)	Drainage	Filtration Separation	Avoid or minimize (a) generation of positive pore water pressures (due to traffic loading in near-saturated layers), and (b) moisture content increase in unsaturated layers (to maintain adequate modulus and shear strength over time)
Mitigation of distress induced by shrink/swell subgrades	Retard or eliminate environmental longitudinal cracks along roadways due to the presence of expansive or frost-susceptible subgrade soils	Maintain integrity and uniformity of unbound aggregate layer to minimize stress concentration that triggers longitudinal cracks	Stiffening (and/or drainage) (or barrier)		Maintain integrity of asphalt surface course and, in turn, reduce/eliminate degradation mechanisms, such as environmental longitudinal cracks along roadways, which are triggered by water content fluctuations and frost action in the subgrade

RECOMMENDATIONS OF AMERICAN CONCRETE PAVEMENT ASSOCIATION

The American Concrete Pavement Association (ACPA) published a series of documents in 2008 to tackle issues related to the proper design of concrete pavements. Most of the documents were primarily related to the proper design of subbase layers under concrete pavement to ensure drainability, stability, and durability. This section discusses the findings and recommendations of the documents related to the use of granular subbases under concrete pavements.

ACPA TS204.01P, "Uniform Support in Concrete Pavements," (ACPA 2008a) states that of all subgrade and subbase design characteristics, uniform support is of utmost importance for building a long-lasting roadbed. Strength is not the most important characteristic, because the rigidity of concrete helps to distribute any wheel load into a large surface area, thus transmitting very low-pressure levels to the underlying subbase and subgrade layers. This technology brief stated that the uniformity of the subbase is more important than the strength and/or the thickness for ensuring durability and good performance, mainly because the high strength and rigidity of a concrete pavement is coming from the concrete slab and not the foundation layers. In fact, field testing and inspection showed that concrete pavements constructed on low-strength, uniform soils performed better than those constructed on stronger, nonuniform ones.

The four major causes of nonuniformity under concrete pavements are: 1) expansive soils, 2) frost-susceptible soils causing frost heave, 3) pumping from erodible layers underneath, and 4) wet soils. A subbase layer thus helps provide a more uniform support, but primarily prevents pumping and erosion from the subgrade. Open-graded drainage layers used as subbases with a reduced fines content to increase permeability to 350 ft/day or higher in laboratory tests were found to be ineffective for long-term uniformity. They can cause premature failure because of the infiltration of fines or the penetration of mortar into the subbase, causing slab cracking.

ACPA TS204.06P, "Unstabilized (Granular) Subbases," (ACPA 2008b) provides key information for the ICT project R27-193-5 in terms of recommendations for granular subbase material selection, compaction and consolidation requirements, and thickness and permeability requirements. The main highlights provided in this publication are as follows.

- To help unbound subbases serve their primary function of preventing pumping and erosion, limiting the percentage of fines passing the No. 200 (75 µm) is of utmost importance. According to AASHTO M 147 (AASHTO 2017a) and AASHTO M 155 (AASHTO 2004) requirements, the maximum percent of fines passing No. 200 shall not exceed 15%. For areas where frost action can be an issue, the fines should be limited to a much lower value, and a near minimum fines content (as per the specification in that area) shall be used.
- Additional subbase material properties that shall be met (as per AASHTO M 147 specifications) are:
    - Maximum particle size of no more than one-third the subbase thickness.
    - Plasticity index of 6 or less.
    - Liquid limit of 25 or less.
    - LA abrasion resistance (AASHTO T 96 [AASHTO 2019a]) of 50% or less. Use of soft materials is discouraged because they will generate fines under compaction and traffic loading.
    - Target permeability of ~150 ft/day, but no more than 350 ft/day.
- Sufficient compaction of the subbase layer is of utmost importance to minimize consolidation. Densities higher than 95% of standard compactive effort (AASHTO T 99 [AASHTO 2019b] density) is deemed sufficient to minimize consolidation of a dense-graded granular subbase layers, while achieving low subbase densities can lead to premature failures.
- A minimum subbase thickness of 4 in. is required. This minimum requirement comes for constructability purposes, because research has found that unbound subbase thicknesses as low as 2 in. can be sufficient to prevent pumping for long periods and under heavy traffic. This technology series also discourages the use of thick subbase layers because of high secondary consolidation levels in the subbase layer. A 4 in. to 6 in. subbase thickness is recommended.

- The use of unbound subbase layers is discouraged for CRCP or JPCP with undowelled joints, which are not commonly constructed. For doweled JPCP, the use of unbound subbases is a low-cost and well-performing option when constructed properly.

ACPA TS204.08P, "Free-Draining Daylighted Subbases," (ACPA 2008c) concludes that free-draining daylighted subbases with a permeability up to 350 ft/day in laboratory tests are preferred over highly permeable subbases because of their more durable and stable nature. A target permeability of 50 to 150 ft/day is desirable for the daylighted subbases. Though free-draining subbases drain slower than permeable subbases (because of increased fines), they are more stable, and stability can be further enhanced using high-quality angular aggregates. The use of recycled concrete aggregates in lieu of virgin aggregates also shows good performance for free-draining subbases. The technology brief indicates that daylighted subbases under flexible and rigid pavements can outperform and may yield better long-term performance than piped edge drains if the pipes are not maintained regularly. Finally, the study recommends using a separation layer to maintain the drainability of the daylighted base and prevent the migration of fines. The use of geotextile fabrics is preferred (and strongly suggested) over a dense-aggregate separation/filter layer and shall be placed directly below the daylighted free-draining subbase.

ACPA TS204.10P, "Permeable Subbases: Reasons to Avoid Their Use," (ACPA 2008d) presents broad categories for reasons to avoid using permeable subbases, i.e., subbases having a permeability coefficient higher than 350 ft/day under concrete pavements. These reasons are 1) loss of support due to breakdown of the aggregate, 2) loss of support due to infiltration of the subgrade into the subbase, 3) early-age cracking due to penetration of mortar from the concrete pavement into the subbase, and 4) instability as a construction platform. Further, this technology brief mentions that the most comprehensive study conducted on the performance of permeable bases under concrete pavements showed that for properly designed doweled JPCP, the impact of using permeable subbases is a slight improvement to faulting resistance (because the dowels already prevent most of the joint movements resulting in pumping and erosion). More importantly, unstabilized permeable subbases add ~15% to the total cost of concrete pavement compared to a standard dense-graded unstabilized subbase, but the cost is not justified in terms of performance or added pavement life.

In conclusion, the learning outcomes of the ACPA publications are that unbound subbase materials need to be properly constructed to achieve sufficient density and must be constructed from high-quality angular aggregates to prevent further buildup of fines due to particle breakage. They must be both stable and drainable by controlling the grain size distribution and the percent of fines passing sieve No. 200 and should be kept clean throughout the design life by using a separation layer (most commonly a geotextile) to prevent the intrusion of fines from the subgrade and underlying layers.

EFFECTS OF JOINTED PLAIN CONCRETE PAVEMENT DESIGN INPUTS

Schwartz et al. (2013) performed global sensitivity analyses to determine the sensitivity of pavement performance as predicted by the *Mechanistic-Empirical Pavement Design Guide* (MEPDG) to variability of design inputs. Flexible and rigid pavements were evaluated for five climate conditions (hot-wet, hot-dry, cold-wet, cold-dry, and temperate), and three traffic levels (low, medium, and high). Artificial neural network (ANN) response surface models (RSMs) were fitted to the *MEPDG* results.

A normalized sensitivity index (NSI) was adopted as the quantitative metric. The NSI is defined as the percentage change of predicted distress (e.g., total rutting) relative to its design limit. The study adopted the "mean ± two standard deviations" value of NSI ($NSI_{\mu \pm 2\sigma}$) as the most robust ranking measure to incorporate mean sensitivity and variability of sensitivity. The following four sensitivity categories were defined: (1) hypersensitive, $NSI_{\mu \pm 2\sigma}$> 5; (2) very sensitive, 1 < $NSI_{\mu \pm 2\sigma}$ < 5; (3) sensitive, 0.1 < $NSI_{\mu \pm 2\sigma}$ < 1; and (4) non-sensitive, $NSI_{\mu \pm 2\sigma}$ < 0.1.

Table 16 presents the ranking of all design parameters of JPCP pavements design inputs in terms of their effect on distresses (faulting and transverse cracking) and International Roughness Index (IRI). Design inputs related to subgrade and subbase input parameters such as subgrade and subbase modulus, subbase thickness, and erodibility index contribute to overall pavement distresses, but other design inputs related to the concrete layer design can be more significant and contributing to overall distresses and performance.

Table 16. Ranking of New JPCP Design Inputs by Maximum $NSI_{\mu \pm 2\sigma}$ Values

Design Input	Maximum $NSI_{\mu \pm 2\sigma}$ Values (ANN RSMs)				
	Faulting	Transverse Cracking	IRI	Maximum	Pavement Foundation
Slab Width	−17.97	−5.04	−8.81	−17.97	
PCC 28-Day Modulus of Rupture	0.92	−4.21	−0.63	−4.21	
PCC Thickness	0.51	−3.88	−0.50	−3.88	
Design Lane Width	1.58	−3.78	0.65	−3.78	
PCC Unit Weight	−2.33	3.13	−1.19	3.13	
PCC Coef. of Thermal Expansion	2.16	2.81	1.25	2.81	
PCC Ratio of 20-yr to 28-day MOR	0.50	−2.69	−0.26	−2.69	
PCC 28-Day Elastic Modulus	0.21	2.57	0.37	2.57	
Surface Shortwave Absorptivity	0.68	2.27	0.55	2.27	
Joint Spacing	0.66	1.79	0.36	1.79	
PCC Water-to-Cement Ratio	0.62	1.62	0.82	1.62	
PCC Thermal Conductivity	−0.21	−1.12	−0.21	−1.12	
Subgrade Resilient Modulus	−0.20	−0.34	−0.99	−0.99	√
Dowel Diameter	−0.69	0.98	−0.37	0.98	
PCC Poisson's Ratio	0.26	−0.75	0.19	−0.75	
Traffic Volume (AADTT)	0.63	0.56	0.37	0.63	
PCC Cement Content	0.30	0.55	0.18	0.55	
Base Resilient Modulus	0.33	0.40	0.22	0.40	√
Groundwater Depth	0.08	−0.37	−0.06	−0.37	
Base Thickness	−0.12	0.35	−0.08	0.35	√
Edge Support—Load Transfer Efficiency	−0.13	−0.26	−0.07	−0.26	
Erodibility Index	0.25	−0.19	0.16	0.25	√
Construction Month	0.11	0.22	0.07	0.22	

Adapted from Schwartz et al. (2013)

Further, Brand et al. (2013) demonstrated an insensitivity of the soil type and resilient modulus on fatigue cracking by running 28 simulations under different factorial combinations of subgrade soil type, subgrade resilient modulus, traffic level, and climatic zones. They observed that the required slab thicknesses to limit transverse cracking to less than 20% varied less than 0.25 in. over a range of soil types and resilient modulus values. Haider et al. (2009) showed that the base type has a moderate effect on the cracking and faulting models, by comparing a granular base to an asphalt-stabilized base for slab-base interface friction.

Overall, the findings in the literature are somewhat inconsistent and inconclusive, and there is a need to examine previous studies' findings in more detail. Despite the inconsistency in the literature regarding the effect of base/subbase properties on the performance of concrete pavements, the need for a non-erodible subbase is well recognized to maintain uniform support under concrete pavements and ensure satisfactory service performance, including the minimization of distresses like pumping and joint faulting, which can initiate and/or accelerate pavement deterioration. In fact, faulting models adopted by pavement M-E and new research findings define an "erodibility factor" for base/subbase as one of the factors contributing to faulting at the joints of JPCP (ARA 2003). Figure 10 presents the pavement M-E faulting model.

$$Fault_m = \sum_{i=1}^{m} \Delta Fault_i$$

$$\Delta Fault_i = C_{34} \times \left(FAULTMAX_{i-1} - Fault_{i-1}\right)^2 \times DE_i$$

$$FAULTMAX_i = FAULTMAX_0 + C_7 \times \sum_{j=1}^{m} DE_j \times Log\left(1 + C_5 \times 5.0^{EROD}\right)^{C_6}$$

$$FAULTMAX_0 = C_{12} \times \delta_{curling} \times \left[Log\left(1 + C_5 \times 5.0^{EROD}\right) \times Log\left(\frac{P_{200} \times WetDays}{p_s}\right)\right]^{C_6}$$

$$C_{12} = C_1 + C_2 \times FR^{0.25}$$

$$C_{34} = C_3 + C_4 \times FR^{0.25}$$

Figure 10. Equation. Pavement M-E faulting model.

ARA (2003)

where,

$Fault_m$	=	Mean joint faulting at the end of month *m* (inch)
$\Delta Fault_i$	=	Incremental monthly change in mean transverse joint faulting during month *i* (in.)
$FAULTMAX_i$	=	Maximum mean transverse joint faulting for month *i* (in.)
$FAULTMAX_0$	=	Initial maximum mean transverse joint faulting (in.)

EROD	=	Base/subbase erodibility factor
DE_i	=	Differential deformation energy accumulated during month i
$\delta_{curling}$	=	Maximum mean monthly PCC slab corner upward deflection due to temperature curling and moisture warping
P_S	=	Overburden on subgrade (pounds)
P_{200}	=	Percent subgrade material passing #200 sieve
WetDays	=	Average annual number of wet days (greater than 0.1 in. rainfall)
FR	=	Base freezing index defined as the percentage of time the top base temperature is below freezing temperature (32°F)
C_1 to C_8	=	Calibration constants

Note that more recently, Lytton et al. (2019) proposed modified faulting models for JPCP and then validated and calibrated the model parameters with long-term pavement performance (LTPP) data. An inflection point was observed in the field faulting data that differentiates two stages of faulting, and the proposed models captured this inflection point, which indicates the critical faulting depth and the beginning of erosion. Faulting before the critical depth results in the accumulated deformation of the underlying layers, while faulting after the inflection point is due to the infiltration of water through joints and scouring the surface of the subbase. At the critical faulting depth, the second derivative of the faulting equation is equal to zero. Figure 11 illustrates the trends for field faulting data, while Figure 12 presents the general equation proposed by Lytton et al. (2019) to describe the faulting depth curve. Subbase erodibility is thus a significant factor that needs to be controlled and minimized to mitigate the adverse effects of faulting.

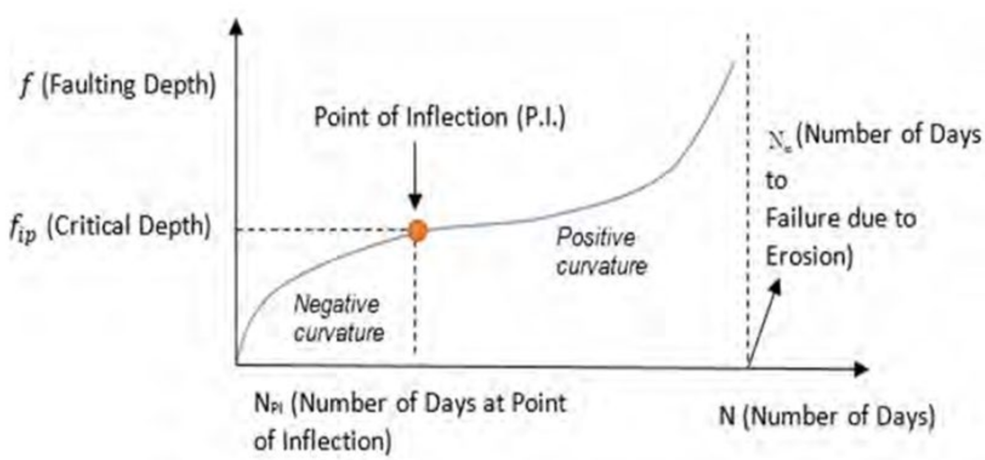


Figure 11. Illustration. Field faulting curve.

Lytton et al. (2019)

$$f = \rho_e[ln\,(\frac{N_\infty}{N - N_o})]^{-1/\beta_e}$$

Figure 12. Equation. Mathmatical model that describes field faulting trends.

Lytton et al. (2019)

where:

f is the faulting depth.

N is the number of days after pavement construction date.

N_o is the number of days when faulting initiates.

N_∞ is the number of days to failure due to erosion.

ρ_e and β_e are model coefficients.

CHAPTER 3: PROPOSED SUBBASE DESIGN

This chapter presents steps for designing a durable and well-performing aggregate subbase for concrete pavements in the state of Illinois. Chapter 2 reviewed the performance of granular subbases in the state, the practices of surrounding states, case studies for well-designed and well-performing granular bases under concrete pavements, and recent research and current practice related to the use of granular subbases and separation layers. This chapter presents the design steps for a grain size distribution to ensure drainability and stability. Further, the subbase is underlain by a geotextile to prevent the intrusion of fines from the subgrade and to maintain a drainable subbase throughout the design period.

The methodology used to design the granular subbase is presented in Figure 13, which shows the main factors to be taken into consideration in the subbase design for a well-performing and long-life concrete pavement. These factors are uniformity, non-erodibility, drainability, stability, and constructability. For stability and uniformity, the grain size distribution will be controlled to ensure the subbase is well graded, has enough sand-sized particles to fill the voids and minimize movements, and has enough gravel-sized particles as a primary structure for maximizing shear strength. Drainability and non-erodibility will be obtained by limiting the fines content passing the No. 200 sieve (0.075 mm) to minimize pumping. Constructability will be ensured by limiting the maximum nominal aggregate size and assigning minimum density requirements, which will also ensure stability. Further, to ensure the subbase is stable and drainable throughout the design life, it will be underlain by a geotextile fabric to keep it clean from the intrusion of subgrade fines, drainable due to minimized fines content, and to minimize pumping potential and loss of support. Overall, three broad criteria will be considered in the final design that cover all the requirements listed above: stability, drainability, and durability.

Figure 13. Illustration. Requirements for well-performing and long-lasting subbases for concrete pavements.

STABILITY REQUIREMENTS

As a starting point, the current commonly used IDOT subbase gradations were evaluated against the final design proposed for Minnesota DOT (Class 5-Qa) proposed by Tutumluer et al. (2015). The gravel-to-sand (G/S) ratio was evaluated for four common IDOT gradations (CA 6, CA 10, CA 12, and CA 19) for upper bound, lower bound, and mid-gradation. Table 17 presents the G/S ratio of the MnDOT Class 5-QA gradation band. The results for IDOT subbase gradation bands are summarized in Table 18 to Table 21. Further, Figure 14 presents plots of the four IDOT common subbase gradation bands relative to the MnDOT Class 5-Qa gradation.

For Class 5-Qa, the calculated G/S ratios range between 1.4–1.9, with a G/S ratio of 1.6 for the mid-gradation. These values indicate a stable base for the uniformly graded gradation band, as recommended by Xiao and Tutumluer (2012) and Tutumluer et al. (2015). Note that the fines passing the No. 200 sieve (0.075 mm) are limited to 5% to ensure drainability requirements are met. The top size of the aggregates (1.5 in.) was selected for a subbase layer thickness of 5 in. Note that other states have a minimum subbase thickness of 4 in. for constructability requirements and findings in the state of Illinois showed 2 in. of subbase can be sufficient to minimize/eliminate pumping; however, 4 in. is required for constructability requirements. Therefore, this top size may need to be further refined for IDOT's purposes to allow construction of a 4 in. subbase layer without exceeding top size requirements for construction purposes. For IDOT's CA 6 gradation band, the mid-gradation has an optimum G/S ratio for stability. However, the upper bound and lower bound G/S ratios are lower and higher than the recommended range, respectively, indicating that these are not ideal for a stable base under concrete pavements. Further, fines content passing No. 200 are higher than ideally required to ensure a drainable subbase and prevent pumping and erosion under concrete pavements. The top aggregate size is also higher than the preferred size for a 4 in. subbase thickness. While some grain size distributions within the CA 6 gradation band can be suitable for stability and non-erodibility requirements, the gradation band shall be further optimized to ensure stability and drainability under concrete pavements. For IDOT's CA 10 gradation band, the lower bound falls within the Class 5-Qa gradation band and poses fines content and size requirements for thin subbases under concrete bands; however, other gradations (e.g., the upper bound or mid-gradation) are not recommended for stability and drainability requirements due to higher sand contents reducing the shear strength and higher fines content lowering the quality of drainage and the flow of water.

For the other two gradation bands, i.e., IDOT CA 12 and CA 19, the use in thin subbase layers under concrete pavements is not recommended. CA 12 has a finer gradation for the top sizes and relatively higher sand content, reducing its stability and shear strength. CA 19, in contrast, has a 3 in. top size and is not recommended for constructability purposes of 4 in. to 6 in. subbase thicknesses. The overall size distribution of the CA 19 aggregate also makes the matrix unsuitable from a stability point of view due to lack of proper proportions of sand and gravel in the matrix. Note that both CA 12 and CA 19 gradation bands also have high fines content passing the No. 200 sieve (0.075 mm), indicating poor performance for drainage purposes and adversely affecting the quality of drainage under concrete pavements. In conclusion, it is recommended that a new gradation band is proposed for use in thin granular subbase layers under concrete pavements to ensure stability and to limit fines content for drainability. The MnDOT Class 5-Qa will be used as a starting point because it passes stability requirements for the proportion of sand and gravel in the mix and limits on fines content.

Table 17. MnDOT Class 5-Qa Gradation Band, Showing G/S Ratios

Sieve Size (in.)	1.5	1	0.75	0.375	No. 4	No. 10	No. 40	No. 200	
Sieve Size (mm)	**37.5**	**25**	**19**	**9.5**	**4.75**	**2.0**	**0.42**	**0.075**	**G/S ratio**
Upper Bound	100	100	90	70	45	40	30	5	1.38
Lower Bound	100	80	65	50	35	20	10	0	1.86
Mid-Gradation	100	90	77.5	60	40	30	20	2.5	1.6

Table 18. IDOT CA 6 Gradation Band, Showing G/S Ratios

Sieve Size (in.)	1.5	1	0.5	No. 4	No. 16	No. 200	
Sieve Size (mm)	**37.5**	**25**	**12.5**	**4.75**	**1.18**	**0.075**	**G/S ratio**
Upper Bound	100	100	90	56	40	12	1.0
Lower Bound	100	90	60	30	10	4	2.7
Mid-Gradation	100	95	75	43	25	8	1.6

Table 19. IDOT CA 10 Gradation Band, Showing G/S Ratios

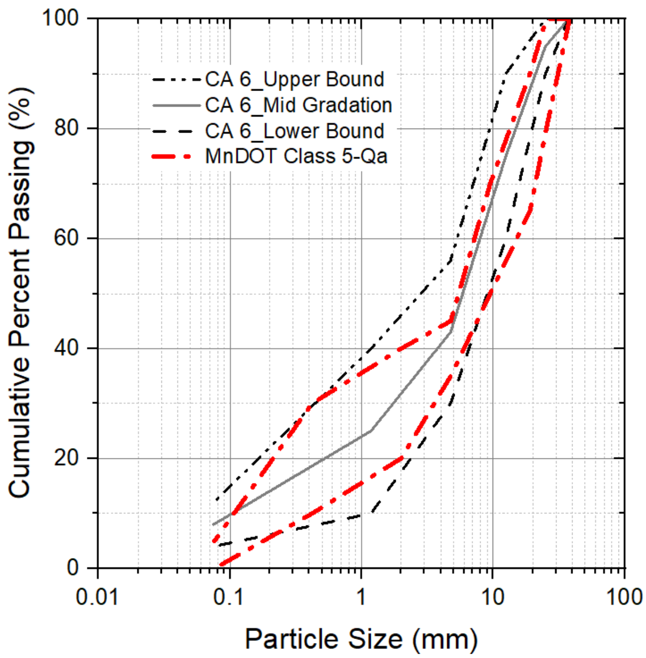
Sieve Size (in.)	1	0.75	0.5	No. 4	No. 16	No. 200	
Sieve Size (mm)	**25**	**19**	**12.5**	**4.75**	**1.18**	**0.075**	**G/S ratio**
Upper Bound	100	100	95	60	45	13	0.9
Lower Bound	100	90	65	40	15	5	1.7
Mid-Gradation	100	95	80	50	30	9	1.2

Table 20. IDOT CA 12 Gradation Band, Showing G/S Ratios

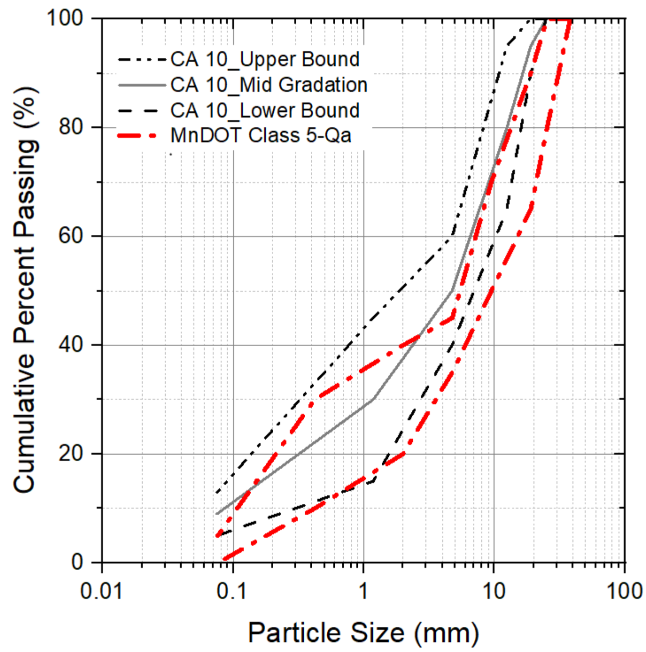
Sieve Size (in.)	0.75	0.5	0.375	No. 4	No. 16	No. 200	
Sieve Size (mm)	**19**	**12.5**	**9.5**	**4.75**	**1.18**	**0.075**	**G/S ratio**
Upper Bound	100	100	95	70	45	13	0.5
Lower Bound	100	90	75	50	25	5	1.1
Mid-Gradation	100	95	85	60	35	9	0.8

Table 21. IDOT CA 19 Gradation Band, Showing G/S Ratios

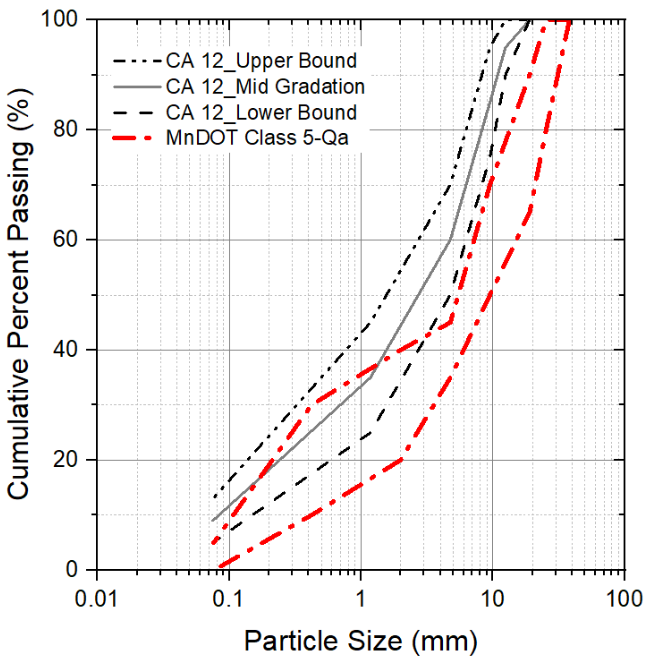
Sieve Size (in.)	3	1	No. 4	No. 16	No. 50	No. 200	
Sieve Size (mm)	**75**	**25**	**4.75**	**1.18**	**0.3**	**0.075**	**G/S ratio**
Upper Bound	100	100	75	55	30	15	0.4
Lower Bound	100	90	45	25	10	5	1.4
Mid-Gradation	100	95	60	40	20	10	0.8



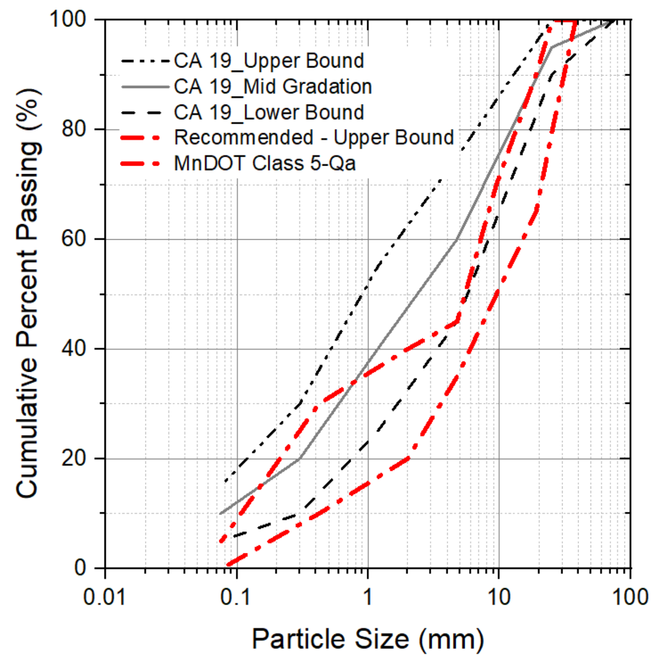
CA 6 gradation band



CA 10 gradation band



CA 12 gradation band



CA 19 gradation band

Figure 14. Graphs. Common IDOT gradation bands for use in subbase layer, plotted against MnDOT Class 5-Qa gradation band.

DRAINABILITY REQUIREMENTS

According to Tutumluer et al. (2015), the G/S ratio may provide an indication of the hydraulic conductivity and suction potential of unbound materials, because it provides a reflection of the relative quantities of large coarse aggregates and smaller sand-sized particles; the latter being more controlling of the hydraulic conductivity and suction potential. Gupta et al. (2004) also confirmed that coarse aggregates and fine aggregates control hydraulic conductivity and water retention characteristics, respectively.

In order to check the drainability requirements of the proposed grain size distribution that passes stability requirements, DRIP software is utilized to model scenarios of concrete pavements with granular subbases. DRIP (Drainage Requirements in Pavements) is a software developed by the Federal Highway Association and Applied Research Associates through a National Cooperative Highway Research Program (NCHRP) project. Version 1.0 of the software was released in 1995, while the current and most recent software (Version 2.0) was released in 2004. DRIP can perform hydraulic design computations for subsurface drainage in rigid and flexible pavements including inflow calculations, permeable base/subbase design, separator layer design (both aggregates and geotextile separator layers), as well as edge drain design (ARA 2004). Drainage requirements for subbases are defined as: 1) sufficient stiffness to support traffic without significant permanent deformation under dynamic loading, 2) sufficient transmissivity to rapidly drain pavement section and prevent saturation of unbound base layer, and 3) sufficient air void to provide a capillary break. To calculate drainage quality, DRIP defines five categories (excellent to very poor) for drainage quality based on the time to drain 50% of the drainable water. Table 22 presents the five drainage quality categories (ARA 2004).

Table 22. Quality of Drainage Measured by Time to Drain

Quality of Drainage	Time to Drain
Excellent	2 hours
Good	1 day
Fair	7 days (168 hrs.)
Poor	1 month
Very Poor	Does not drain

ARA (2004)

The quality of drainage is computed based on subbase properties (gradation, porosity, relative porosity, and thickness) and the time taken to drain water. DRIP adopts the Moulton equation for calculating hydraulic conductivity (see Figure 15). This equation is highly sensitive to the fines content passing the No. 200 sieve (0.075 mm) and is generally considered conservative. The methodology is thus to check the Class 5-Qa upper and lower bounds for quality of drainage and propose further refinements to this gradation band to ensure the quality of drainage is fair, good, or excellent. Note that the proposed gradations are considered conservative in terms of fines content (both sand-sized materials and materials passing No. 200), and more sand/fines can be allowed for a fair or higher drainage quality if the permeability can be verified by determining the hydraulic conductivity more accurately using a laboratory constant head permeameter setup or by other field measures. For any gradation, stability requirements must be met by checking the G/S ratio.

$$K_{sat}\left(\text{ft/d}\right)=\frac{6.214\times10^{5}\,D_{10}^{1.478}n^{6.654}}{2834.6\times p_{200}^{0.597}}$$

Figure 15. Equation. Calculating permeability using Moulton equation.

where D_{10} is the sieve size (in.) for a 10% material passing, P_{200} is the percent of material passing the No. 200 sieve (less than 0.075 mm), and n is the porosity (decimal).

The procedure used for calculating quality of drainage using DRIP software was iterative. First, the quality of drainage for the lower and upper bounds of the Class 5-Qa were determined. In order to do so, the following design assumptions were made and input to the software:

- Subbase thickness was assumed 4 in.
- Width of pavement draining in one direction was assumed 18 ft. This is composed of one lane with a 12 ft width and a 6 ft shoulder.
- A pavement cross slope of 2% was assumed. A 0.5% slope was assumed along the pavement length.
- The subbase was assumed to be compacted to a dry density of 121 pcf, and a 2.7 specific gravity was assumed for the subbase aggregates.
- Crack infiltration method was used to calculate flow into the pavement. For this approach, an infiltration rate (I_c) of 2.4 ft^3/ft/day per crack (i.e., joint) was assumed. This is a typical value used for pavements. A 15 ft joint spacing was assumed.
- Meltwater (due to melting of ice in thawing seasons) was included as part of the inflow calculations.
- Casagrande and Shannon method was used to calculate the time to drain.

Based on the conducted drainage analysis using DRIP software and the assumptions listed above, the lower bound of the Class 5-Qa gradation band with the coarser gradation was found to have a permeability of ~130 ft/day, resulting in a “good” drainage quality rating. In contrast, the upper bound (finer gradation) of the Class 5-Qa was found to have a significantly lower permeability that resulted in a poor drainage quality and was thus further refined to increase the permeability and result in a better drainage quality. In order to do so, more stringent requirements on the allowed range of percentage of materials passing the No. 10, No. 40, and No. 200 sieves were proposed. Further, percent passing requirements for the No. 50 sieve in lieu of the No. 40 sieve were proposed because the No. 50 sieve is more commonly specified for aggregate gradation bands in IDOT standards.

Table 23 presents the subbase gradation band proposed by this research to achieve both stability and fair to good drainage quality. Note that the process to fine-tune this gradation band using DRIP software was iterative, and multiple sample runs were conducted and analyzed before this final gradation was proposed. The gradation band is termed "CA 21" because IDOT has coarse aggregate gradations up to CA 20. In terms of fines content, the finalized proposed gradation is conservative because the Moulton equation is known to calculate conservative permeability. It is noted in the drafted specification (a standalone document) that this gradation band is not unique and other gradations with slightly higher fines content may be used if they are checked for stability (G/S ratio) and drainability (experimentally with a laboratory permeability test or a field permeability setup). However, a fines content passing the No. 200 sieve exceeding 6% is not recommended under concrete pavements, which is in line with the practices and research findings of surrounding states (Iowa and Minnesota).

Table 23. Proposed Stable and Drainable Subbase Gradation under Concrete Pavements (CA 21)

Sieve Size (in.)	Sieve Size (mm)	CA 21 Upper Bound	CA 21 Lower Bound	CA 21—Range of percent passing (%)
1.5	37.5	100	100	**100**
1	25	100	80	**90 ± 10**
0.75	19	90	66	**78 ± 12**
0.375	9.5	70	50	**60 ±10**
No. 4	4.75	45	35	**40 ±5**
No. 10	2	32	20	**26 ± 6**
No. 50	0.42	17	9	**13 ± 4**
No. 200	0.075	4	0	**2 ± 2**
	G/S ratio	1.3	1.9	1.3–1.9
	Drains in	162 hrs.	7.9 hrs.	7.9–162 hrs.
	Drainage Quality	Fair	Good	Fair–Good
	permeability	3.9 ft/d	131 ft/d	3.9–131 ft/d

Figure 17 presents a plot for the CA 21 gradation band proposed for use in subbase layers under concrete pavements in Illinois and how it compares to the Class 5-Qa gradation band proposed by Tutumluer et al. (2015) for MnDOT. In order to check middle gradations, four examples of grain size distribution curves within the proposed CA 21 gradation band were analyzed for stability (G/S ratio) and drainability using DRIP software. Figure 18 presents the four examples (a–d), while Table 24 presents the analyzed results. In addition to Moulton equation, the hydraulic conductivity was also calculated using the Mechnistic-Empirical Pavement Design Guide (MEPDG) Enhanced Integrated Climatic Model (EICM) equation (presented in Figure 16) for comparison. As shown in Table 24, all four example gradations pass the stability and drainability requirements proposed in this research and are expected to provide a uniform and drainable support under concrete pavements for good performance throughout the design life.

$$K_{sat}\left(\text{cm/s}\right) = 10^{-6} \times 10^{\left(5.3D_{10} + 0.049D_{60} + 0.0092\frac{D_{60}}{D_{10}} - 0.1P_{200} + 1.5\right)}$$

Figure 16. Equation. Calculating permeability using MEPDG EICM equation.

where D_{10} is the sieve size (mm) for a 10% material passing, D_{60} is the sieve size (mm) for a 60% material passing , and P_{200} is the percent of material passing the No. 200 sieve (less than 0.075 mm).

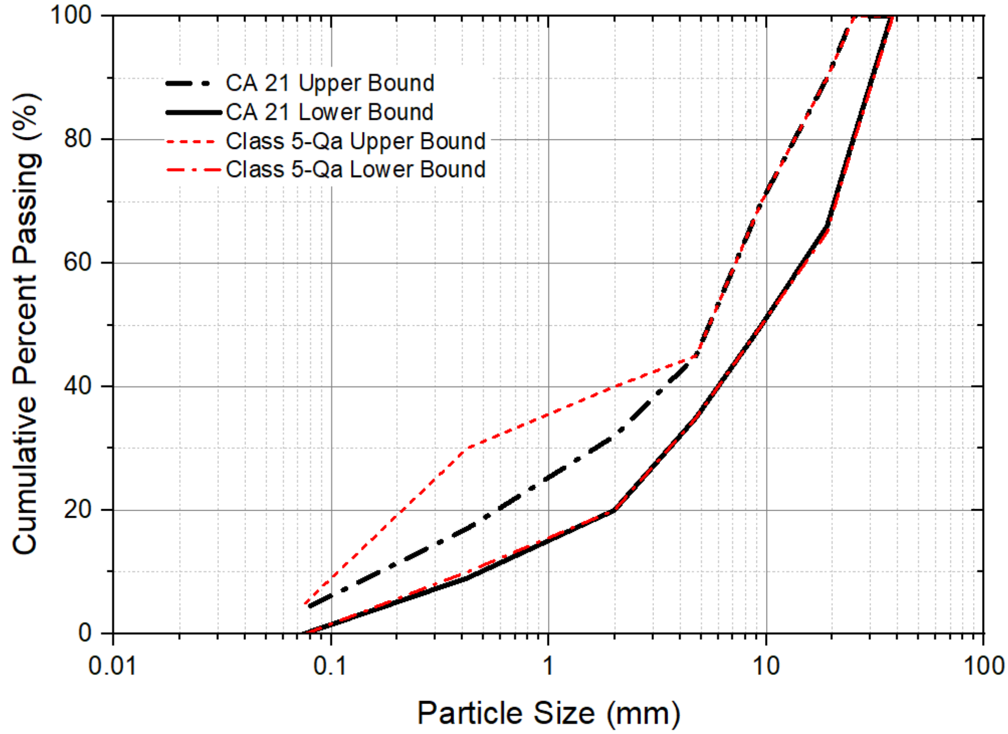


Figure 17. Graph. CA 21 proposed gradation band for subbases under concrete pavements.

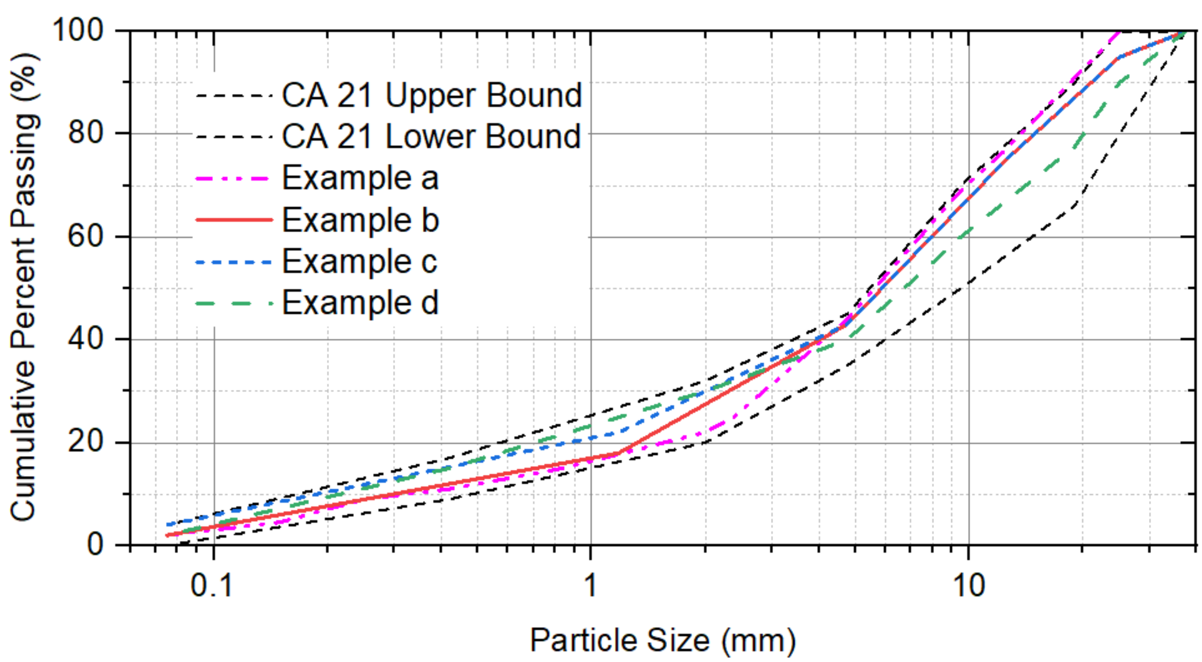


Figure 18. Graph. Example gradations checked for stability and drainability.

Table 24. Example Gradations Checked for Stability and Permeability/Drainability

Gradation	G/S Ratio	D10 (mm)	D60 (mm)	P200 (%)	Hydraulic Conductivity, k (ft / day)	
					Moulton Equation	MEPDG EICM
CA 21 Lower	1.9	0.384	15.016	0.1	130.4	117.8
CA 21 Upper	1.3	0.158	7.384	4	3.9	1.5
Example a	1.33	0.330	7.582	2	17.5	12.2
Example b	1.39	0.445	8.362	2	27.1	49.1
Example c	1.46	0.285	8.362	4	9.3	5.5
Example d	1.58	0.193	9.500	2	7.9	4.9

DURABILITY REQUIREMENTS

The research efforts detailed above presented an approach to ensure a stable and drainable daylighted subbase design is used under concrete pavements in Illinois. One last issue to tackle to ensure that this subbase remains clean and drainable throughout the design life is to provide a separation layer underneath the subbase to minimize the intrusion of fines as well as pumping and erosion.

For geotextile strength requirements, the AASHTO M 288 (AASHTO 2017) requirements for a Class 2 separator geotextile shall be closely followed. For apparent opening size (AOS) and permittivity, the values of these physical properties recently proposed by Hoppe et al. (2019) are met by a multitude of readily available commercial products and provide a relatively simple and efficient separation and drainage criteria to adopt by IDOT, particularly that the proposed values are appropriate for Illinois subgrades and material gradations. As proposed by Hoppe et al. (2019), a maximum AOS of No. 70 sieve size (0.212 mm), and a minimum permittivity of 0.1/sec are proposed for the geotextile fabric used under the daylighted subbase. The use of a nonwoven geotextile is recommended unless a woven geotextile is specially designed to provide the advantage of enhanced lateral drainage and additional suction flow capacity in addition to gravity flow. Nonwoven geotextiles tend to have higher flow rate and drainability by means of gravity.

AGGREGATE QUALITY REQUIREMENTS

IDOT’s *Standard Specifications for Road and Bridge Construction* manual (2016b) specifies that coarse aggregates for subbases shall be Class D quality or better. The quality requirements are presented in Table 25. Further, for plasticity index (PI) requirements, a PI of 0% to 9% is allowed for gravel materials. The PI quality requirement is waived for crushed gravel, stone, and slag materials.

Based on the current IDOT quality requirements for subbase materials, there is not much control on the cleanliness and deleterious materials content for Class D aggregates. Given the functions served by aggregate subbases under concrete pavements, control of deleterious materials and having more stringent requirements on abrasion and soundness is required to ensure performance. Thus, this research is recommending limiting materials that are allowed for use under concrete pavements to Classes A to C. Another proposed modification is to limit the use to nonplastic materials only when possible. Preferably, crushed virgin aggregates or recycled concrete aggregates, or a mix of both, shall be used to ensure high modulus (shear strength) and low permanent deformation potential, because these two materials have been widely studied and their performance is more established.

Table 25. IDOT Quality Requirements for Subbase Aggregates

Quality Test	Class A	Class B	Class C	Class D
Na_2SO_4 Soundness 5 Cycle, ITP 104, % Loss max.	15	15	20	25
Los Angeles Abrasion, ITP 96, % Loss max.	40	40	40	45
Minus No. 200 (75 µm) Sieve Material, ITP 11	1.0	–	2.5	–
Deleterious Materials				
Shale, % max.	1.0	2.0	4.0	–
Clay Lumps, % max.	0.25	0.5	0.5	–
Coal & Lignite, % max.	0.25	–	–	–
Soft & Unsound Fragments, % max.	4.0	6.0	8.0	–
Other Deleterious, % max.	4.0	2.0	2.0	–
Total Deleterious, % max.	5.0	6.0	10.0	–

Adapted from IDOT (2016b)

CONSTRUCTABILITY REQUIREMENTS

The review of literature presented in Chapter 2 concluded that sufficient compaction of the subbase layer is of utmost importance to minimize consolidation and that densities higher than 95% of standard compactive effort (AASHTO T 99 [AASHTO 2019b] density) is deemed sufficient to minimize consolidation of a dense-graded granular subbase layer, while achieving low subbase densities can lead to premature failures. Based on these findings, it is recommended to allow Type A materials only under concrete pavements. As per IDOT definitions, Type A material have compaction requirements and need to be compacted to 95% of the Proctor density. This quality check and construction requirement, accompanied with the use of aggregate sources with good quality, can further ensure stability is met and consolidation is minimized.

Another constructability requirement is to specify a minimum subbase thickness of 4 in. The review of literature in Chapter 2 concluded that subbase thickness is not critical under concrete pavements because of the high stiffness of the PCC slabs. Studies also showed that subbases with lower thicknesses up to 2 in. can still be efficient and sufficient to prevent pumping under concrete pavements. Thus, a 4 in. subbase thickness is mostly a constructability requirement to ensure proper uniformity and density can be achieved.

TRAFFIC FACTOR LIMITS FOR USING GRANULAR BASES

Based on the discussion presented in Chapter 2 for the practices of surrounding states as well as the performance monitoring of concrete pavements with granular subbases in Illinois, the designs and subbase requirements for concrete pavements presented in Figure 54-4.D of the *BDE Manual* (IDOT 2021) and presented earlier in Table 2 are indeed conservative and overly designed. A modification is proposed to allow the use of a daylighted granular subbase with a geotextile separator under concrete pavements for all classes and facility types with a traffic factor ranging between 2.0 and

10.0. These changes can be safely proposed given the findings from the literature. The CA 21 grain size distribution proposed above shall be used to ensure drainability and stability. For areas with a curb and gutter setup, the proposed grain size distribution (CA 21) for the subbase and underlying geotextile are still recommended. Table 26 presents the proposed changes to Figure 54-4.D of the *BDE Manual* highlighted in red and bold font. An aggregate subgrade improvement (ASI) or a Type A granular improvement on top of modified soil (GM) shall be used as subgrade remediation methods under the 4 in. daylighted subbase with geotextile separation to provide enough thickness for drainability and to ensure the functions of the subbase are properly served. For a modified soil (MS) improved subgrade, a 6 in. subbase thickness is recommended to ensure a fair to good drainability is met (as per DRIP analysis).

Table 26. Proposed Changes to Figure 54-4.D of the IDOT *BDE Manual*

Facility Type	Subbase (1)		Improved Subgrade Type (2) (3)
	Type	Minimum Thickness (in.)	
Class I			
Interstate / Freeway	HMA or PCC Stabilized	4	ASI, GM, or MS
Other Marked Routes	HMA or PCC Stabilized	4	ASI, GM, or MS
Unmarked Routes (**TF ≥ 10.0**)	HMA or PCC Stabilized	4	ASI, GM, or MS
Unmarked/ Marked Routes (2.0 ≤ TF < 10.0)	**Granular w/ Geotextile**	**4**	**ASI or GM**
Unmarked/ Marked Routes (2.0 ≤ TF < 10.0)	**Granular w/ Geotextile**	**6**	**MS**
Unmarked Routes (0.7 < TF < 2.0)	Not required	n/a	ASI, GM (4)
Unmarked Routes (TF ≤ 0.7)	Not required	n/a	ASI, GM, or MS
Class II			
Marked Routes	HMA or PCC Stabilized	4	ASI, GM, or MS
Unmarked Routes (**TF ≥ 10.0**)	HMA or PCC Stabilized	4	ASI, GM, or MS
Unmarked/ Marked Routes (2.0 ≤ TF < 10.0)	**Granular w/ Geotextile**	**4**	**ASI or GM**
Unmarked/ Marked Routes (2.0 ≤ TF < 10.0)	**Granular w/ Geotextile**	**6**	**MS**
Unmarked Routes (0.7 < TF < 2.0)	Not required	n/a	ASI, GM (4)
Unmarked Routes (TF ≤ 0.7)	Not required	n/a	ASI, GM, or MS
Class III			
Marked Routes	HMA or PCC Stabilized	4	ASI, GM, or MS
Unmarked Routes (**TF ≥ 10.0**)	HMA or PCC Stabilized	4	ASI, GM, or MS
Unmarked/ Marked Routes (2.0 ≤ TF < 10.0)	**Granular w/ Geotextile**	**4**	**ASI or GM**
Unmarked/ Marked Routes (2.0 ≤ TF < 10.0)	**Granular w/ Geotextile**	**6**	**MS**
Unmarked Routes (0.7 < TF < 2.0)	Not required	n/a	ASI, GM (4)
Unmarked Routes (TF ≤ 0.7)	Not required	n/a	ASI, GM, or MS

Facility Type	Subbase (1)		Improved Subgrade Type (2) (3)
	Type	Minimum Thickness (in.)	
Class IV			
Marked Routes	HMA or PCC Stabilized	4	ASI, GM, or MS
Unmarked Routes (**TF ≥ 10.0**)	HMA or PCC Stabilized	4	ASI, GM, or MS
Unmarked/ Marked Routes (2.0 ≤ TF < 10.0)	**Granular w/ Geotextile**	**4**	**ASI or GM**
Unmarked/ Marked Routes (2.0 ≤ TF < 10.0)	**Granular w/ Geotextile**	**6**	**MS**
Unmarked Routes (0.7 < TF < 2.0)	Not required	n/a	ASI, GM (4)
Unmarked Routes (TF ≤ 0.7)	Not required	n/a	ASI, GM, or MS

Adapted from Figure 54-4.D, *BDE Manual*.

Notes:

(1) For urban sections containing curb and gutter and a storm sewer system, the designer may omit the ***granular /*** *stabilized subbase when an ASI or GM improved subgrade is used, regardless of the traffic factor.*

(2) Improved Subgrade Types include: ASI—Aggregate Subgrade Improvement (minimum of 12 in.); GM—Granular over Modified Soil (4 in. CA 6 or CA 10 over 12 in. Modified Soil); MS—Modified Soil (minimum of 12 in.)

(3) The minimum thickness of improved subgrade shall be according to Section 54-2.01(f).

(4) Modified Soil may be used for the improved subgrade if a minimum 4 in. stabilized subbase is used.

CHAPTER 4: SUMMARY AND CONCLUSIONS

SUMMARY AND CONCLUSIONS

This report presented findings from a study that evaluated foundation layers (subgrade and subbase) under concrete pavements in the state of Illinois. It provided recommendations and scenarios where unbound granular layers could be safely and economically used under concrete pavements. The aim of this research effort is to provide a more economical and well-performing subbase design for concrete pavements. In the current IDOT concrete pavement design, a stabilized subbase layer with a 4 in. minimum thickness is required under concrete pavements for all road classes when the design traffic factors (TF) is higher than 2.0, except for urban sections with curb and gutter and a storm sewer system. These pavements are likely overdesigned. Stabilized subbases tend to be relatively expensive and can add a significant portion to the cost. Using granular subbases instead for appropriate traffic levels can save on cost while ensuring good performance.

The current practice and mechanistic design methods for constructing concrete pavements in Illinois were evaluated, including historical studies and research findings that led to the current design procedures and policies. Policies on the use of stabilized subbase dated back to findings from the American Association of State Highway Officials (AASHO) Road Test and to studies conducted by IDOT in the 1960s and 1970s related to the use of stabilized and granular subbases under concrete pavements. Some of the designs that the policies are based on are now obsolete and seldom used in Illinois.

The performance of concrete pavements constructed in Illinois on interstates and state highways as well as roadways with unbound granular subbases and subgrade remediation involving aggregate subgrade improvement were evaluated. Most evaluated cases showed very low distress levels, mostly of low to medium severity. On a few projects, cases with traffic levels exceeding 20 million ESALs and showing good performance/low distresses were also experienced in the state, indicating the suitability of using granular subbases for higher traffic factor than the current 2.0 limit. The use of open-graded drainage layers (OGDL) in the state was also evaluated. Studies either showed that OGDL did not improve performance or resulted in issues because of the loss of cement paste (mortar) into the large voids or migration of subgrade soil into the OGDL. The results were in line with studies from other states discouraging the use of OGDLs because of lack of stability.

The practices of surrounding states were also evaluated, and several Midwestern states were found to use unbound granular layers under concrete pavements as the normal practice, even for relatively high traffic levels (e.g. 9 million ESALs in Kansas and 20 million ESALs in Iowa). These states, however, were found to request relatively stringent aggregate quality requirements for subbases under concrete pavements.

A literature review on the most recent requirements for designing granular subbases under concrete pavements were also evaluated. From the literature, it was concluded that subbase layers under concrete pavements are mainly used to provide uniform support and prevent pumping. For uniformity, the subbase needs to be stable and non-erodable to prevent loss of support. For pumping preventions, the subbase needs to be drainable to prevent the accumulation of water that facilitates pumping action as well as needs to remain clean from the intrusion of subgrade fines. Because of the high stiffness of concrete slabs, which is orders of magnitude higher than that of a granular subbase, the thickness and strength of granular subbases are generally not an issue for concrete pavement designs. Thus, the stability and drainability of the subbase are two key properties. Both properties can be controlled through engineering the grain size distribution to provide a compromise between stability and drainability, i.e., control of gravel content, sand content, and fines content passing the No. 200 sieve (0.075 mm).

Based on the case study evaluations and the study of literature, a stable, drainable, and durable daylighted granular subbase design (CA 21) was proposed for use under concrete pavements in Illinois. From surrounding states' practices and the evaluation of concrete pavements with granular subbases in Illinois, the proposed daylighted subbase with a minimum thickness of 4 in. can be used for traffic factors between 2.0 and 10.0. The daylighted subbase shall be underlain by a geotextile fabric for separation and drainage. An aggregate subgrade improvement (ASI) or a Type A granular improvement on top of modified soil (GM) will be used as subgrade remediation methods under the daylighted subbase with geotextile separation, to provide enough thickness for drainability and to ensure the functions of the subbase are properly served.

The stability of the daylighted subbase was ensured by controlling the gravel-to-sand (G/S) ratio and limiting its value to 1.3–1.9. Limiting the G/S ratio ensures a proper quantity of large gravel aggregates are in contact for maximizing shear strength and proper sand content to fill the voids and reduce settlement and permanent deformation. Drainability requirements were met by limiting the percentage of fines passing the No. 200 sieve to 4%, and by checking that the quality of drainage is good or fair based on the time required to drain 50% of the water. The hydraulic conductivity and quality of drainage were calculated using DRIP software developed for the Federal Highway Administration. A recommendation was made to check drainage requirements more reliably for a specific material and grain size distribution using laboratory constant head permeameters or field-testing methods.

Lastly, the use of a geotextile fabric underneath the granular subbase was recommended as a separation layer to ensure the daylighted subbase remains clean and drainable throughout the design life. The use of a nonwoven geotextile was recommended unless a woven geotextile is required for enhanced lateral drainage and additional suction flow capacity (in addition to gravity flow). Geotextile strength properties following the requirements of AASHTO M 288 Class 2 geotextile separator were recommended. A maximum apparent opening size of No. 70 sieve (0.212 mm) and a permittivity of 0.1 sec^{-1} or higher were specified. Manufacturers' specification sheets were reviewed to ensure a wide variety of manufacturers have multiple products meeting these requirements.

RECOMMENDATIONS FOR FUTURE WORK

Based on the results and recommendations obtained from this report, the following recommendations for future work are proposed:

- Because permeability is a major factor contributing to the performance of the unbound granular subbase, a test procedure for accurately measuring the permeability of the material in the laboratory, at the target gradation and proper compaction level, shall be developed for IDOT. Aggregate gradations showing satisfactory permeability levels (ideally 50–150 ft/day for good and excellent drainability, but not exceeding 350 ft/day as per the recommendation of several research studies) shall be recommended for use as subbase materials given good quality aggregates are being used. Having a standard test method for measuring permeability while ensuring realistic field conditions are met can provide a means to allow more aggregate gradations to be utilized under concrete pavements, in addition to the proposed CA 21 gradation band, and can provide flexibility to increase the fines content passing No. 200 a little higher than 4% if field permeability and quality of drainage are not adversely affected by this increase.

- To put the proposed design in service under jointed plain concrete pavements with a design traffic factor between 2.0 and 10.0, it is recommended to implement short- and long-term performance monitoring of the proposed subbase design with a daylighted, stable, and drainable subbase underlined with a geotextile fabric. Field test sections can be constructed and monitored during construction (e.g., field permeability, compaction, lightweight and/or falling weight deflectometer testing for assessing uniformity and stiffness), and during the traffic use stage (distress types and severity, international roughness index, crack propagation, etc.). Based on long-term field monitoring, the proposed subbase design can be refined, and the design can be recommended for a higher (or lower) traffic factor based on actual field performance.

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