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Identifying Best Practices in Pavement Design, Materials, Construction, and Maintenance in Wet-Freeze Climates Similar to Michigan

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ABSTRACT

The intent of this research is to identify best practices for pavements in wet-freeze climates. For the purposes of this report, a best practice is a procedure that has been shown by research or experience to produce improved results and that is established or proposed as a standard suitable for widespread implementation. This project identified the criteria used to determine locations around the country and the world with a similar wet-freeze climate as that of Michigan. This project documented the process of conducting the literature review, the method of analysis pertaining to the discovered information, and the organization of the report. This report also provided research findings. In the course of this research, it became clear that MDOT is a pioneer in developing and implementing best pavement practices in wet-freeze climates. The research team did not find many best practices that are not currently used by MDOT that merit immediate recommendation for adoption. The researchers had a few recommendations that merit consideration of further review once additional research and experience becomes available.

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LIST OF ABBREVIATIONS AND ACRONYMS

Acronym	Name
AASHTO	American Association of State Highway and Transportation Officials
AASHO	American Association of State Highway Officials
AAC	Alkali-activated cement
AC	Asphalt concrete
ARFC	Asphalt rubber friction course
ASCE	American Society of Civil Engineers
ASR	Alkali-silica reactivity
ASTM	American Society for Testing and Materials
ATB	Asphalt treated base
ATPB	Asphalt treated permeable base
AzDOT	Arizona Department of Transportation
BBR	Bending beam rheometer
BCOA	Bonded concrete overlay of asphalt
BST	Bituminous surface treatment
CDW	Construction demolition waste
CIR	Cold in-place recycling
CMA	Cold-mix asphalt
CRCP	Continuously reinforced concrete pavement
CRMA	Crumb rubber modified asphalt
CTB	Cement treated base
DIAMS	Drainage Information Analysis and Mapping System
DOT	Department of Transportation
DSC	Differential scanning calorimeter
DSR	Dynamic shear rheometer
EAM	Epoxy terminated ethylene
EAPA	European Asphalt Pavement Association
ECR	Epoxy-coated rebar
EPA	Environmental Protection Agency
ESAL	Equivalent single axle loads
FDR	Full-depth repair
FHWA	Federal Highway Administration
FRP	Fiber reinforced polymer
FTIR	Fourier transform infrared
GDOT	Georgia Department of Transportation
GFRP	Glass fiber-reinforced polymer
GPC	Gel permeation chromatography
HIR	Hot in-place recycling
HMA	Hot-mix asphalt
HPC	High performance concrete
HPMS	Highway Performance Monitoring System

Acronym	Name
HWMA	Half warm-mix asphalt
HWTT	Hamburg wheel-track testing
IC	Intelligent compaction
IRI	International Roughness Index
ISSA	International Slurry Seal Association
ISU	Iowa State University
JPC	Jointed plain concrete
JPCP	Jointed plain concrete pavement
LNDG	Low-noise diamond grinding
LTPP	Long-term pavement performance
MDOT	Michigan Department of Transportation
ME	Mechanistic-empirical
MEPDG	Mechanistic-Empirical Pavement Design Guide
MnDOT	Minnesota Department of Transportation
MnROAD	Minnesota Road Research Facility
MMFX	Martensitic Microcomposite Formable Steel
MTO	Ministry of Transportation of Ontario
NAPA	National Asphalt Pavement Association
NCHRP	National Cooperative Highway Research Program
NGCS	Next generation concrete surface
NYDOT	New York (State) Department of Transportation
ODOT	Ohio Department of Transportation
OGFC	Open graded-friction course
OPC	Ordinary Portland cement
PCA	Portland Cement Association
PCC	Portland cement concrete
PCM	Phase change material
PCP	Pre-cast concrete pavement
PG	Performance grade
PGED	Prefabricated geocomposite edge drains
PLC	Portland limestone cement
PPA	Polyphosphoric acid
PSI	Pavement serviceability indices
RAP	Reclaimed asphalt pavement
RAS	Recycled asphalt shingles
RCA	Recycled concrete aggregate
RCC	Roller-compacted concrete
SAMI	Stress absorbing membrane interlayers
SBR	Styrene-butadiene rubber
SBS	Styrene-butadiene-styrene
SEBS	Styrene-ethylene-butylene-styrene copolymer
SGC	Superpave Gyratory Compactor
SHRP/SHRP2	Strategic Highway Research Program

Acronym	Name
SIP	Stripping inflection point
SMA	Stone-matrix asphalt
SN	Structure numbers
TMA	Thermal mechanical analysis
TMY3	Typical meteorological year
TSR	Tensile strength ratio
UHPC	Ultra high-performance concrete
U.S.	United States
UTBWC	Ultra-thin bonded wearing course
VFA	Voids filled with asphalt
WMA	Warm-mix asphalt
WSDOT	Washington (State) Department of Transportation
WSU	Washington State University
Abbreviation	**Meaning**
C	Celsius
CO2	Carbon dioxide
cm	Centimeter
F	Fahrenheit
km	Kilometer
k	Kip(s)
mm	Millimeter
NaCl	Sodium chloride
pH	Potential of hydrogen
pp	page

EXECUTIVE SUMMARY

This final report for the project "Identify Best Practices in Pavement Design, Materials, Construction, and Maintenance in Wet Freeze Climates Similar to Michigan" serves as a synthesis of best practices in pavement design, materials, construction, and maintenance from around the United States and abroad.

The local wet-freeze climate makes the requirements for Michigan's pavement system different from many other regions. Since a wet-freeze climate can lead to pavement distresses like cracking, frost heaving, material degradation and thaw weakening, appropriate procedures for design, material selection, and maintenance need to be selected for withstanding high precipitation and cold winter temperatures. Failure to take into account the weather conditions may lead to inadequate or reduced pavement performance.

This research report examines current and emerging practices for pavement design, construction, preservation, and maintenance in wet-freeze climates. For the purposes of this report, a best practice is a procedure that has been shown by field-validated research or experience to produce optimal results and that is established or proposed as a standard suitable for widespread adaptation.

Because MDOT is a leader in developing and adopting technologies and practices for wet-freeze climates, many of the domestic and foreign practices in this report may have already been tested in Michigan and will not be identified as "foreign" to Michigan. Given the changing nature of technologies and, hence, the fluidity that necessarily occurs with adopting and then modifying or replacing of best practices, the researchers have identified practices as currently used by the Michigan Department of Transportation (MDOT) or practices that are not currently used but either merit consideration for adoption as a best practice or are not worth considering at this time. Some practices may be similar or modified by MDOT researchers and practitioners to meet local needs, and those will be described as they are applied in Michigan. Furthermore, if the research refers to a practice that is adopted or being investigated within the state of Michigan, a general reference of "Michigan" will be made; references to practices that are specific to the Michigan Department of Transportation will be explicitly addressed with "Michigan Department of Transportation" or "MDOT".

The first section of this report identifies the criteria used to determine locations around the country and the world with similar wet-freeze climate as that of Michigan. Literature referring to pavement practices in these locations provided a source for identifying potential or current practices in Michigan. Some references came from locations not typically identified as wet-freeze areas, however, localized regions within these areas may experience conditions similar to Michigan, and when the project team felt that a best practice from these areas may be worth further exploration, it was included in the report along with a brief explanation as to why.

Four pavement types were considered in this report; asphalt (or flexible), concrete (or rigid), composite, and aggregate-surfaced (aggregate-surfaced pavements are mentioned here for completeness, but not evaluated because they are rare in MDOT-owned road networks)). Four determinants affect a pavement's ability to withstand conditions in wet-freeze climates: pavement materials, design, construction, and preservation and maintenance. This research used the four determinants along with the four pavement types to carry out the overall project objectives of documenting the current practices in use by MDOT as well as other state and local agencies; recommending best practices that could be implemented in Michigan; and identifying barriers to implementing the best practices not presently used in Michigan.

Section 2 of this report explains the process of conducting the literature review, the method of analysis pertaining to the discovered information, and the organization of the report.

Section 3 of this report contains the research findings, which are then summarized in a table and expanded upon within the body of the report. Items are identified in the table as either MDOT best practices or not currently an MDOT best practice. Items are further identified according to whether they can be immediately implemented or require further study before deciding on implementation. Items in the table are discussed in the body of the report. Current MDOT best practices are included in the discussion for the sake of completion and items not currently best practices in Michigan are further discussed as to their use in other wet-freeze areas, barriers to implementation in Michigan, and why the technology is promising for wet-freeze locations.

Section 4 of this report summarizes the conclusions of this report and makes recommendations for specific practices and technologies. Some technologies and practices not currently in use in Michigan do merit consideration once they have been thoroughly evaluated through research and practice. The research team did not identify any current practices that should be abandoned.

The results of this report demonstrate how MDOT is a leader in the research, development, and application of best practices for pavement construction, preservation, and maintenance both nationally and internationally. This research should serve MDOT by helping to identify those best practices from other states or countries that can build on MDOT's leadership and expertise in climates like Michigan's. This could potentially lead to improvements in pavement systems by lowering construction and maintenance costs and/or extending pavement durability, both within Michigan and in all areas with climate conditions similar to Michigan.

1. INTRODUCTION

The Michigan Department of Transportation (MDOT) has requested this report, which summarizes best practices and engineering innovations for pavement materials, design methodologies, technologies of construction, and preservation/maintenance strategies usable in wet-freeze climates similar to Michigan's. This report provides a collection of this data.

1.1 BACKGROUND

1.1.1 Wet Freeze

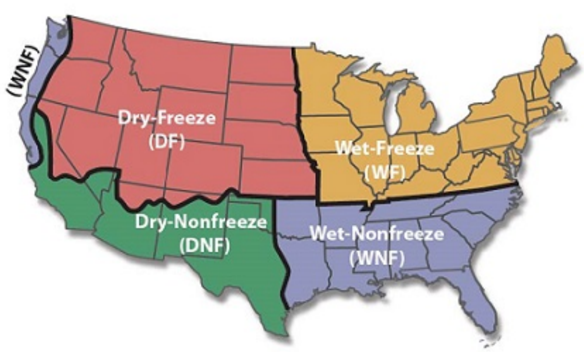
Weather conditions affect pavement material selection, design processes, construction procedures, and maintenance strategies, and Michigan's climate presents pavement researchers and practitioners with significant challenges. The 2000 edition of the *Highway Performance Monitoring System* (HPMS) Field Guide defined wet-freeze climates as those that "[experience] long winters with the temperatures below freezing for extended periods" (Federal Highway Administration, 2000, p. 267). Such climates leave pavements susceptible to damage due to frost or water retention in the subgrade. According to the 2016 HPMS, the states that, by default, are considered to have wet-freeze climates are Connecticut, Delaware, Illinois, Indiana, Iowa, Kentucky, Maine, Maryland, Massachusetts, Michigan, Minnesota, Missouri, New Hampshire, New Jersey, New York, Ohio, Pennsylvania, Rhode Island, Vermont, Virginia, West Virginia, and Wisconsin as well as the eastern portions of South Dakota, Nebraska, and Kansas (Federal Highway Administration, 2016a).

The American Association of State Highway and Transportation Officials (AASHTO) more specifically identifies the wet, hard-freeze, spring-thaw climate zone as covering Iowa, Maine, Massachusetts, Michigan, Minnesota, New Hampshire, New York, Vermont, and Wisconsin, as well as the northern parts of Connecticut, Illinois, Indiana, New Jersey, Ohio, Pennsylvania, Rhode Island, and West Virginia (American Association of State Highway and Transportation Officials, 1993). Two Canadian provinces—Ontario and Quebec—were considered to be wet-freeze climates by the research team because the predominate climate in these provinces is similar to the wet-freeze characteristics defined by the HPMS Field Guide and AASHTO.

Two of the most important climate parameters of a region are annual precipitation and freezing index. These climate parameters influence such factors as the pavement's surface temperature, frost penetration depth, and the number of freeze/thaw cycles experienced by the pavement, which are necessary considerations for designing, constructing, and maintaining pavements. The Freezing index (named "air-freezing index" in National Climatic Data Center) is "a common metric for determining the freezing severity of the winter season and estimating frost depth for midlatitude regions, which is useful for determining the depth of shallow foundation construction"(Bilotta, Bell, Shepherd, & Arguez, 2015). The freezing index is defined by the area under the temperature curve during the freezing period, represented by the following calculation:

$$Freeze\ Index = \sum_{i=1}^{N}(32 - T)$$

where T is the average daily temperature (°F) for a day *i* and N for the number of days during the freezing period. The freezing season begins when T becomes less than or equal to 32°F (0°C) for several days and ends when T in spring becomes greater than 29°F (-2°C) for several days. A freezing index that the pavement experiences is conservatively assumed to be equal to air's freezing temperature. The Federal Highway Administration (FHWA) uses annual precipitation and freezing index to divide the United States into four climate regions (see Figure 1) (Federal Highway Administration, 2014):



Climate Zone	Annual Rainfall	Freezing Index (°F-Days)
Wet Non-Freeze	> 28"	< 100
Wet Freeze	> 28"	> 100
Dry Non-Freeze	< 28"	< 100
Dry Freeze	< 28"	> 100

Figure 1: Four US Climate Regions based on FHWA (Federal Highway Administration, 2014)

The state of Michigan is located in the wet-freeze zone as defined by AASHTO and FHWA. The state of Michigan has an annual average precipitation of 32.8 in. (83.3 cm), and a freezing index of 1400 (°F-Days) to 2200 (°F-Days) ("Air Freezing Index- USA Method, National Climatic Data Center,"). For these two climate parameters, Michigan is higher than the FHWA baseline of a wet-freeze climate zone (28 in. [71 cm] and 100 °F [38 °C] -Days, respectively). Thus, the high levels of precipitation and the very low temperatures are parameters that drastically affect the design, construction, and preservation and maintenance practices of the roads in Michigan. Using these two parameters, it was possible to determine locations within the United States, Canada, Europe and Asia with conditions similar to Michigan's climate (see Table 1). The annual snowfall amounts shown in Table 1 are annual averages based on weather data collected from 1981 to 2010 for the NOAA National Climatic Data Center. Some other important parameters aided in making better comparisons between the Michigan's climate and locations with similar conditions.

Table 1. Locations with similar climate to Michigan

State[1]/Province[2] / City	Annual precipitation		Freezing Index (°F-Days)	Number of days with temperature of 32 °F (0 °C) or less	Average annual snowfall		Average annual temperature (°F)[3]		
	(in)	Days			(in)	Days	Low	Avg.	High
Michigan	32.8	~ 140	1400 - 2200	~ 140	51.1	44.7	27.0	44.4	60.0
Iowa	34.0	~ 105	1500 - 2200	~ 140	34.9	26.0	33.0	47.8	63.0
Wisconsin	32.6	~ 115	2000 - 2800	~ 150	50.9	39.0	29.0	43.1	59.0
Illinois	39.2	~ 120	1200 - 1800	~ 125	24.6	20.0	38.0	51.8	68.0
Ohio	39.0	~ 140	1100 - 1400	~ 120	27.5	30.0	39.0	50.7	69.0
Ontario	~ 35	~ 155	800 - 3000	~ 150	55.0	56.0	37.0	46.5	54.0
Quebec	~ 42	~ 170	1800 - 2500	~ 130	105.0	71.0	32.0	43.3	51.0
Shenyang City*, China[4]	~28	~ 87	undef	~150	undef	undef	36.8	43.9	51.9
Shulan City*, China[4]	~ 28	~ 123	undef	~170	undef	undef	30.7	38.6	46.8
Sapporo City*, Japan[5]	43.5	undef	undef	undef	~ 180	undef	41.5	48.0	55.2
Sendai City*, Japan[5]	49.4	undef	undef	undef	~ 30	undef	48.0	54.3	61.5
Niigata City*, Japan[5]	71.7	undef	undef	undef	~ 70	undef	51.1	57.0	63.7
Moscow City*, Russia[6]	~ 28	~ 170	undef	undef	undef	undef	~ 34	~ 40	~ 47
Aberdeen City*, the United Kingdom[7]	34.1	~ 140	undef	undef	45.4	34	41.0	47.0	53.0
Oslo City*, Norway[8]	30.0	113	undef	undef	undef	undef	36.3	42.8	49.3

1. ("Air Freezing Index- USA Method, National Climatic Data Center,")
2. ("Calculating insulation needs to fight frost heave by comparing freezing index and frost depth. In: Tech Solutions 605.0. DOW Chemical Canada-Building Solutions,")
3. ("Average Annual State Temperatures, Current Results, Weather and Science Fact," ; "Canada Cities Annual Temperature, Current Results, Weather and Science Facts,")
4. ("China Meteorological Data Service Center", http://data.cma.cn)
5. ("Tables of Climatological Normals (1981–2010), Japan Meteorological Agency", http://www.data.jma.go.jp/obd/stats/data/en/normal/normal.html)
6. (In one single year, "Climate: Average Monthly Weather in Moscow, Russia", "World Weather & Climate Information", https://weather-and-climate.com/)
7. ("Average Annual Precipitation for the United Kingdom", "Yearly Snowfall Averages for the United Kingdom", "Average Annual Temperatures in the United Kingdom", https://www.currentresults.com/)

8. (“Average Annual Precipitation for European Cities”, “Coldest Cities in Europe” , https://www.currentresults.com/)
9. Locations with “undef” (undefined) designations may use methods for caluculating degree-days, freezing index, and precipitation that differ from the US and Canadian methods.
10. Locations marked with an asterisk (*) are cities. Some of these cities share a name with a region, province, district, or other political region that represents a larger geographic area than the city with the same name.

The local wet-freeze climate makes the requirements for Michigan’s pavement system different from many other regions. Building and maintaining roads requires a particular consideration of design procedures and construction practices that are compatible with local climate conditions. These considerations need to result in a pavement structure that is designed and constructed to withstand wet-freeze conditions. Since a wet-freeze climate can lead to pavement distresses like cracking, frost heaving, material degradation and thaw weakening, appropriate procedures for design, material selection, and maintenance practices need to be employed to withstand high precipitation and cold winter temperatures. Failure to take into account the weather conditions when selecting the pavement’s materials, design, and construction techniques may lead to inadequate pavement performance and reduced service life.

1.1.2 Pavement Types

There are many ways in which pavement types can be classified. One of the most common ways is to categorize pavements by their structure. Using a structural approach, pavements can be grouped into the following broad categories—asphalt (or flexible), concrete (or rigid), composite, aggregate-surfaced, sealcoat, and interlocking concrete pavers (American Association of State Highway and Transportation Officials, 2015b, pp. 2-3).

Conventional asphalt pavements have an asphalt surface layer, composed of asphalt binder, aggregate, and at times other additives, which is usually supported by a stabilized and/or unstabilized base layer(s), and a sub-base layer. The load carrying capacity of the asphalt pavement is influenced by the strength and stiffness of all the pavement layers, including the underlying base, subbase, and subgrade layers. Its applications range from low-volume roads and streets with low/moderate traffic loads to high-volume roads, highways, and interstates with heavy traffic loads. As of 2017, about 82 percent of paved roads in the United States are asphalt pavements (Federal Highway Administration, 2017a).

Concrete pavement has a concrete surface layer that distributes the traffic loading. This concrete layer is composed of portland cement concrete (PCC), which most often consists of portland cement and a supplementary cementitious material (SCM) such as fly ash or slag cement, water, aggregates, and admixtures. Generally, concrete is used to pave high-volume roads, highways, and interstates with heavy traffic loads. As of 2017, about six percent of paved roads in the United States were concrete pavements (Federal Highway Administration, 2017a).

Composite pavement combines asphalt and concrete layers into one pavement type. Most composite pavements have an asphalt surface layer over an existing concrete; however, there are some composite pavements that use concrete as the surfacing over asphalt layers. Composite pavements may be used for low-volume to high-volume roads, streets, highways, and interstates. About 12 percent of paved roads in the United States are composite pavements (Federal Highway Administration, 2017a).

Aggregate-surface pavement (e.g., gravel roads) and sealcoat pavement (i.e., chip seal over gravel roads) are generally used for lower-volume roads. Interlocking concrete pavers see use in limited areas and are not widely used outside of attempting to achieve a particular aesthetic value in an urban setting. Since few state-owned roads consist of these pavements types, they will not be addressed in the scope of this research.

1.1.3 Determinants Affecting Pavements

Four determinants affect a pavement's ability to withstand conditions in wet-freeze climates: pavement materials, design, construction, and preservation and maintenance. These four determinants interconnect with each other and affect one another. For example, material selection and pavement design each affect the type of construction that can be used and the future preservation and maintenance that are required; likewise, construction concerns, anticipated preservation efforts, and maintenance needs can influence the choice of materials and pavement design. Therefore, the research contained in this report limits itself to these four determinants.

Selecting materials to construct well-performing and long-lasting pavement is mainly dependent upon in-service weather conditions as well as availability of material and financial resources: heavy traffic and severe weather conditions usually call for higher-quality materials. While the selection of higher-quality materials can result in a better pavement in terms of improved performance (e.g. reduced distress, improved ride quality over the service life), they may pose difficulties in the construction process due to handling requirements and possibly generate a higher overall project cost. Thus, material selection is a balance between cost, quality, and availability according to the requirements of a specific project. In general, materials selection refers to materials used in all the functional layers—including the surface layer, base, or subbase layers. Material selection, however, works in concert with the other three determinants when it comes either to achieving a desired service life for a pavement or to falling short of that goal.

Pavement design is significant in determining the selection of pavement type, materials, construction processes, and the preservation/maintenance strategies that will be required to ensure an optimal service life. The design decisions are largely influenced by traffic volume/loads, in-service weather conditions, the desired service life, availability of materials, soil characteristics, and expenses and costs. Recently, most state Departments of Transportation (DOTs) have performed local design calibrations of MEPDG required distresses, such as IRI, cracking, and asphalt rutting based on the observed long-term pavement performance (LTPP) database so that the design outcomes can be more reliable within their own states.

Pavement construction is also a determinant of the long-term performance of a pavement in wet-freeze climates. Construction processes are dependent upon construction methods and technologies as well as factors like the quality and availability of construction materials, equipment, the skill of workers, and the soil conditions. Using state-of-the-art construction techniques may lead to a faster, more affordable construction process and a higher-quality pavement.

Finally, preservation and maintenance is important for a pavement's longevity (extending pavement service life and ensuring the pavement remains in good condition). Pavement preservation is the practice of planning for and applying cost-effective treatments to existing roadways in order to delay further deterioration, maintain or improve the functional condition, and preserve the road network. In Michigan, preservation is also called preventive maintenance. On the other hand, maintenance is routine, scheduled, or reactive roadwork that addresses specific problems to restore a road network to an acceptable level of service. Appropriate preservation and maintenance strategies can significantly increase the service life of the pavement and determine the quality of its performance during its service life. Choosing appropriate preservation and maintenance strategies is even more important for locations with severe climate conditions, such as the prolonged low temperatures, the cyclic temperature changes, the high level of precipitation, and the significant depth of snowfall that are common in Michigan's wet-freeze climate.

The recommendations in this report for implementing best practices in pavement design, construction, preservation, and maintenance are selected based on their applicability in Michigan. The recommendations can be adopted by Michigan's state and local road-owning agencies as well as contractors. They also rely on materials and equipment that are either already available in Michigan or easily obtainable from other regions. Finally, they should address both the short- and long-term expectations of the quality of Michigan's road network.

1.1.4 Best Practices

This research report examines best practices for pavements in wet-freeze climates. For the purposes of this report, a best practice is a procedure that has been shown by field-validated research or experience to produce optimal results and that is established or proposed as a standard suitable for widespread adaptation. Given the changing nature of technologies and, hence, the fluidity that necessarily occurs with adopting and then modifying or replacing of best practices, the researchers will identify the best practices as either practices that are currently used by the MDOT or practices that are not currently used but either merit consideration for adoption as a best practice or are not worth considering at this time. Furthermore, if the research refers to a practice that is adopted or being investigated within the state of Michigan, a more general reference of

"Michigan" will be made; references to practices that are specific to the Michigan Department of Transportation will be explicitly addressed with "Michigan Department of Transportation" or "MDOT".

1.2 OBJECTIVES AND SCOPE

The objectives of the research comprising this report are the following:

- Document current practices in use by MDOT as well as other state and local agencies with regard to the type, materials, design, construction, and preservation and maintenance of pavements in wet-freeze climates.
- Recommend the best practices that could be implemented in Michigan.
- Identify barriers (including barriers such as cost, equipment or materials needed, construction technologies involved, pavement performance, required skill/technique, and workers' experience with the practice) to implementing the best practices not presently used in Michigan.

Due to project constraints, the research team will limit its discussion to asphalt pavement and concrete pavement, which are the predominant pavement types on Michigan's state-owned road network. However, composite pavements will also be briefly addressed.

1.3 ANTICIPATED APPLICATION OF THIS RESEARCH REPORT

This research report identifies current best practices in Michigan and other states with wet-freeze climates for pavement materials selection, design, construction, and preservation and maintenance. As such, this research will:

- Help MDOT to identify which best practices in other states or countries can be potentially implemented in Michigan.

- Provide MDOT with an opportunity to review current practices and determine if best practices in other states warrant testing and potential adoption for use in Michigan—this could potentially lead to improvements in pavement systems by lowering construction and maintenance costs and/or extending pavement durability.

- Examine potential resources that may be valuable if updates are desired for MDOT specifications, manuals, and/or guidelines for pavement design, pavement materials, construction and maintenance.

2. LITERATURE REVIEW METHODS AND APPROACH

2.1 METHODS OF RESEARCH

To determine current pavement material selection, design, construction, preservation, and maintenance practices and innovative technologies and techniques for pavements in wet-freeze climates, the research team investigated the following sources:

- FHWA website
- MDOT website
- MnDOT website
- Other DOT websites
- Transport Research International Documentation
- The National Academies Press
- ASCE Civil Engineering database
- Google and Google Scholar
- Elsevier Press
- Springer Press
- Taylor & Francis Press
- Science Direct Press
- YouTube.com
- Typical Meteorological Year (TMY3) dataset
- Weather.com

The research team used the following key terms, shown in Table 2, in their search:

Table 2: Literature review key search terms

advanced materials and technology	frost heaves	perpetual pavement award
annual	full-depth reclamation	polymer concrete pavement
Temperature/Precipitation/Snowfall	geosynthetic materials	polyphosphoric acid
asphalt mixture	ground penetrating radar	porous asphalt Michigan
asphalt pavement	highway construction	porous asphalt pavement
asphalt pavement with stabilized	hot mix asphalt	precast concrete pavements
base	intelligent compaction	rejuvenators
asphalt surface type	load restrictions	road construction
best practice(s)	long-life pavement	semi-rigid asphalt pavement
best practice pavement	materials	semi-rigid flexible pavement
bituminous	mechanistic empirical	SHRP2
bituminous materials	Michigan composite pavement	specifications for construction

climate condition	mixture design	string-less paving
composite pavement	pavement best practices	sub-surface/sub-grade
concrete pavement	pavement construction	Superpave mixtures
concrete pavement materials	pavement design	sustainable roads/infrastructure
CRCP	pavement drainage	tack coat
damage detection	pavement maintenance	thaw weakening
deicing materials	pavement materials	two lift concrete
design	pavement rehabilitation	warm mix asphalt
drainage	Pavement repair techniques	weather condition
drainage systems for	pavement safety	wet freeze
concrete/asphalt pavements	pavement service life	wet freeze practice
embankment	pavement systems	wet freeze zone
freezing Index	pavement technology	wet-freeze climates
frost depth	pavement type(s)	winter maintenance
		winter maintenance pavement

2.2 METHODS OF ANALYSIS

First, the research team identified best practices and state-of-the-art technologies in pavement design, materials, construction, and preservation and maintenance in wet-freeze climates similar to Michigan. For each practice and technology, the team noted both specific problems associated with those practices as well as strategies used by Michigan and other agencies to tackle those problems.

Second, to narrow the scope of potential practices and technologies for evaluation, the research team used weather data to focus on agencies whose pavements face climate conditions similar to those in Michigan. The reports included in the review were identified from the United States' departments of transportation (DOTs) as well as from the Federal Highway Administration's repository; in addition to these reports, the research team investigated technical reports from governmental and non-governmental agencies in Canada, the European countries, and China to extract useful information about current pavement practices in their wet-freeze climate regions.

Finally, to add to the set of knowledge used in this report, the researchers also examined practical studies from various technical reports and journal publications that might support agency practices or that discuss practices and technologies not yet adopted as standards by public agencies.

2.3 HOW TO READ THIS REPORT

This report has been organized for the benefit of both those who are familiar with current MDOT best practices and those who are not. Section 3 contains a summary table which lists topics and identifies whether or not each topic is considered a current best practice in Michigan. A report section number is provided for each of the items listed in the table. A description of the topic can be found at the identified section within the body of the report following the table. For those topics not considered current best practices in Michigan there is additional information provided, following the summary/overview; locations where the practice is currently used and outcomes, barriers to implementation, and why the practice is promising for wet-freeze climates. The organization of this report is intended to provide the user quick access to information on best practices in pavement materials, design, construction, and maintenance for asphalt (flexible), concrete (rigid), composite, and aggregate-surfaced roadways.

3. RESEARCH FINDINGS

Table 3 categorizes and summarizes the technologies and practices listed in this report. Technologies and practices are identified in Table 3 according to MDOT standards with indicators as to the status as an MDOT practice, the technology's potential for implementation, and researcher recommendations regarding whether a technology should be implemented. The far-right column points the reader to the document's section where the practice or technology is described. If both MDOT and another state currently apply the listed best practice, then it will only be marked in the MDOT Current Best Practice column.

Table 3: Table of research findings

MDOT Standard Specification	Topic	MDOT Practice		Status of Technology (Is it implementable?)				Recommendations		Section
		Current Best Practice	Not MDOT Current Practice	Best Practice Outside of MDOT	Field Trials & Monitoring	Not Viable or Practical	Emerging Technology	Consider Implementing	Consider Reviewing Again as More Research Becomes Available	
Design Method – Thickness										
500	**Asphalt Concrete**									
	AASHTOWare Pavement ME	X								3.1.1
	China's Pavement Design		X	X					X	3.1.2
600	**Concrete Pavement**									
	AASHTOWare Pavement ME	X								3.1.3
	Modified European Method		X			X				3.1.4
Design Method – Mix										
500	**Asphalt Concrete**									
	Superpave™	X								3.2.1
902	**Aggregate**									
	Dense-graded Asphalt Mixtures	X								3.2.2
	Gap-graded Asphalt Mixtures	X								3.2.3
	Open-graded Asphalt Mixtures		X			X				3.2.4
600	**Portland Cement Concrete**									
	Optimized Aggregate Grading	X								3.2.5
Pavement Type										
500	**Asphalt Concrete Pavement**									
	Conventional Asphalt Pavement	X								3.3.1
	Full-depth HMA Pavement	X								3.3.2
	Porous Asphalt Pavement		X			X				3.3.3
	Perpetual Asphalt Pavement		X		X				X	3.3.4

		MDOT Practice		Status of Technology (Is it implementable?)				Recommendations		
MDOT Standard Specification	Topic	Current Best Practice	Not MDOT Current Practice	Best Practice Outside of MDOT	Field Trials & Monitoring	Not Viable or Practical	Emerging Technology	Consider Implementing	Consider Reviewing Again as More Research Becomes Available	Section
600	**Concrete Pavement**									
	Jointed Plain Concrete Pavement	X								3.3.5
	Continuously Reinforced Concrete Pavement		X		X			X		3.3.6
	Bonded Concrete Overlay		X		X					3.3.7
	Pervious Concrete Pavement		X			X				3.3.8
	Precast Concrete Pavement		X		X			X		3.3.9
	Two-lift Concrete Pavement		X		X				X	3.3.10
	Roller-compacted Concrete Pavement		X		X				X	3.3.11
	Self-consolidating Concrete Pavement		X		X				X	3.3.12
	High-performance PCC	X			X					3.3.13
500 & 600	**Composite Pavement**									
	Bonded Concrete Overlay of Asphalt (BCOA)		X		X			X		3.3.14
	Unbonded Concrete Overlay of Asphalt Pavement (UBCOA)		X		X					3.3.15
	Unbonded Concrete Overlay of Concrete (UBCOC)	X								3.3.16
	Asphalt over New Concrete Pavement		X		X					3.3.17
Material										
200	**Subgrade**									
	Subgrade Stabilizer		X		X			X		3.4.1
300	**Base**									
	HMA Base Crushing and Shaping	X								3.4.2
	Permeable Base	X								3.4.3
	Semi-Rigid Base		X	X					X	3.4.4
	Geotextile Separators	X								3.4.5
501	**Plant-produced Hot-mix Asphalt**									
	Conventional Hot-mix Asphalt	X								3.4.6
	Warm-mix Asphalt	X							X	3.4.7
	Anti-stripping Agents	X								3.4.8
	PPA Extenders		X		X				X	3.4.9
	Half Warm-mix Asphalt		X				X		X	3.4.10
	Cold-mix Asphalt		X			X				3.4.11
	Reclaimed Asphalt Pavement	X								3.4.12
	Recycled Asphalt Shingles	X								3.4.13
	Recycled Tire Rubber Modified Asphalt	X								3.4.14
	Fiber-modified Asphalt		X		X				X	3.4.15
901	**Cement and Lime**									
	Portland Cement (ASTM C150)	X								3.4.16

MDOT Standard Specification	Topic	MDOT Practice: Current Best Practice	MDOT Practice: Not MDOT Current Practice	Status of Technology (Is it implementable?): Best Practice Outside of MDOT	Status of Technology (Is it implementable?): Field Trials & Monitoring	Status of Technology (Is it implementable?): Not Viable or Practical	Status of Technology (Is it implementable?): Emerging Technology	Recommendations: Consider Implementing	Recommendations: Consider Reviewing Again as More Research Becomes Available	Section
	Blended Cement (ASTM C595)	X								3.4.17
	Supplementary Cementitious Materials (Slag Cement and Fly Ash)	X								3.4.18
	Portland Limestone Cement					X				3.4.19
	Geopolymer and Alkali-activated Cement		X				X		X	3.4.20
902	**Aggregate - Non-conventional (Non-Mined Sources)**									
	Construction Demolition Waste (Building rubble)	X								3.4.21
	Slag Aggregates	X								3.4.22
	Reclaimed Asphalt Pavement	X								3.4.23
	Recycled Concrete Aggregate	X								3.4.24
903	**Admixtures and Curing Materials for Concrete**									
	Water Reducers Admixtures	X								3.4.25
	Non-Chloride Accelerators	X								3.4.26
	Liquid Membrane-Forming Curing Compound	X								3.4.27
904	**Asphaltic Materials**									
	Cut-back Asphalt		X							3.4.28
	Emulsified Asphalt	X								3.4.29
	Neat Asphalt Binder	X								3.4.30
	Polymer-modified Binder	X								3.4.31
	Tack Coat	X								3.4.32
	Low-tracking Bond Coat Emulsified Asphalt	X								3.4.33
	Bio-derived Binder		X				X		X	3.4.34
914	**Dowel and Tie Bars**									
	Epoxy-coated	X								3.4.35
	Stainless Steel and Stainless Steel Clad Dowels and Tie Bars		X				X	X		3.4.36
	Basalt		X				X	X		3.4.37
	Galvanized and Zinc-clad		X				X	X		3.4.38
	Glass-fiber-reinforced Polymer		X				X	X		3.4.39
	Corrosion-resistant Steel (MMFX™)		X				X	X		3.4.40
914	**Joint and Waterproofing Materials (Concrete)**									
	Hot-poured Joint Sealant	X								3.4.41
	Pre-formed Joint Sealant		X		X					3.4.42
n/a	**Other Materials**									
	Nanomaterials		X				X		X	3.4.43
	Phase Change Materials		X				X		X	3.4.44

MDOT Standard Specification	Topic	MDOT Practice: Current Best Practice	MDOT Practice: Not MDOT Current Practice	Status of Technology (Is it implementable?): Best Practice Outside of MDOT	Status of Technology (Is it implementable?): Field Trials & Monitoring	Status of Technology (Is it implementable?): Not Viable or Practical	Status of Technology (Is it implementable?): Emerging Technology	Recommendations: Consider Implementing	Recommendations: Consider Reviewing Again as More Research Becomes Available	Section
Construction										
200	**Earthwork**									
	Machine-guided Excavation (Total Station)	X								3.5.1
	Automated Grade Control	X					X			3.5.2
400	**Drainage**									
	Pipe Culvert	X								3.5.3
	Drainage Structures	X								3.5.4
500	**Hot-mix Asphalt Pavement & Surface Treatments**									
	Percent Within Limits Acceptance	X								3.5.5
	Use of Warranties	X								3.5.6
	HMA Material Transfer Device	X								3.5.7
	HMA Longitudinal Joint Specification	X								3.5.8
	Echelon Paving	X								3.5.9
	Regression of Air Void	X								3.5.10
	Ride Quality Requirement	X								3.5.11
	HMA Production Manual	X								3.5.12
	Intelligent Compaction		X		X				X	3.5.13
600	**Concrete Pavement**									
	Percent Within Limits Acceptance	X								3.5.14
	Slip-form and Fixed-form Paving	X								3.5.15
	Stringless Paving	X			X				X	3.5.16
	Real-time Smoothness		X		X		X	X		3.5.17
	Two-lift Concrete Paving		X		X				X	3.5.18
Maintenance/Preservation										
400	**Drainage**									
	Open-graded Underdrain Outlet Cleaning and Repair	X								3.6.1
	Drainage Retrofit	X								3.6.2
	Drainage Information Analysis and Mapping System		X		X				X	3.6.3
500	**Hot-mix Asphalt Pavement & Surface Treatments**									
	HMA Patching	X							X	3.6.4
	Crack Filling and Crack Sealing	X								3.6.5
	HMA Longitudinal Joint Sealer		X		X			X		3.6.6
	Chip Seal (Seal Coat)	X								3.6.7
	Slurry Seal	X								3.6.8
	Fog Seal	X								3.6.9
	Cape Seal	X								3.6.10
	Rejuvenators	X								3.6.11
	Microsurfacing	X								3.6.12

		MDOT Practice		Status of Technology (Is it implementable?)				Recommendations		
MDOT Standard Specification	Topic	Current Best Practice	Not MDOT Current Practice	Best Practice Outside of MDOT	Field Trials & Monitoring	Not Viable or Practical	Emerging Technology	Consider Implementing	Consider Reviewing Again as More Research Becomes Available	Section
	Stress-absorbing Membrane Interlayers and Texas Underseal	X								3.6.13
	Conventional Overlay	X								3.6.14
	Ultra-thin Overlay	X								3.6.15
	Hot In-place Recycling		X		X				X	3.6.16
	Cold In-place Recycling		X	X				X		3.6.17
	Full-depth Reclamation	X								3.6.18
600	**Concrete Pavement**									
	Cross Stitching		X							3.6.19
	Dowel Bar Retrofit	X								3.6.20
	Diamond Grinding and Grooving	X								3.6.21
	Slab Stabilization or Slab Undersealing	X								3.6.22
	Partial-Depth Repair	X								3.6.23
	Full-depth Repair	X								3.6.24
	Silane/Siloxane Seal		X							3.6.25

3.1 DESIGN METHOD – THICKNESS

Asphalt Concrete

Pavement design in the United States has been well developed over the last several decades, but the United States has also significantly differed in its approach to pavement design from other regions. For instance, France's method accounts for "subgrade bearing capacity, pavement materials, and the traffic as main input parameters" (Njock & Yueguang, 2015, pp. 923, 925). China's asphalt pavement design method is using multi-layered elastic continuous system theory. While these other regions are mainly using tensile stress or strain of pavement layers as the control index, the United States is using pavement distresses as its control index. These control criteria result in different designed pavement thickness, which affect pavement design, material selection, and overall cost of construction.

3.1.1 AASHTOWare Pavement ME

This is an MDOT current practice.

Empirical pavement design has been the traditional method of pavement design in the United States; in fact, it was the predominant method used from 1960 to 2007. An empirical pavement design method uses experience, experimentation, or a combination of both (Washington Asphalt Pavement Association, 2010) when making pavement design decisions. The American Association of State Highway and Transportation Officials (AASHTO) developed an empirical method as the basis for design decisions used on AASHO Road Test sections in Illinois in the late 1950s [editorial note: the AASHO Road Test was conducted prior to 1973, at which time the American Association of State Highway Officials—or AASHO—was renamed to AASHTO] (Highway Research Board, 1962). In 1993, AASHTO released a guide for the empirical pavement design method, which took into account the results of the AASHO Road Test as well as equivalent single axle loads (ESAL), structure numbers (SN), and pavement serviceability indices (PSI) (American Association of State Highway and Transportation Officials, 1993). Consequently, while some agencies still use AASHTO 72 and AASHTO 86, the most common empirical approach is known as AASHTO 93 and has been widely used by many agencies. However, the empirical design method is based on results of the AASHO Road Test in Illinois, which is problematic because it addresses "limited pavement types, loads and load applications, age, and environment" (American Association of State Highway and Transportation Officials, 1993, p. I.12).

At present, pavement design in Michigan integrates AASHTO 93 and mechanistic-empirical design methods (Michigan Department of Transportation, 2016c).

Mechanistic-Empirical Pavement Design Guide

Pavement design can play a pivotal role in enhancing resistance to thermal cracking, which is a common distress in cold regions.

In 2008, AASHTO released a new pavement design guide that combined both the empirical and the mechanistic approaches to help "provide an equitable design basis for all pavement types" (ARA Inc. ERES Consultants Division, 2004): the *Mechanistic-Empirical Pavement Design Guide* (MEPDG) (American Association of State Highway and Transportation Officials, 2008). The MEPDG is the first articulation of mechanistic-empirical pavement design procedures. Whereas an empirical model uses experience and/or experimentation for making pavement design decisions, a mechanistic model analyzes pavement properties to determine how the pavement will react to traffic loads (Newcomb, Willis, & Timm, 2010, pp. 8, 19). Integrating these methods into the mechanistic-empirical (ME) design approach relates phenomena (e.g. stresses, strains, and deflections in the pavement structure such as total rutting, asphalt concrete rutting, thermal cracking, top-down fatigue cracking, bottom-up fatigue cracking, and international roughness index) with physical cases (e.g. loads, material properties) using a mathematical model (American Association of State Highway and Transportation Officials, 2008, p. 15; Washington Asphalt Pavement Association, 2010). The MEPDG distress prediction models, which relied on the Long-term Pavement Performance database, have calibration data sets that are "many times larger and much more diverse" than data used for other mechanistic-empirical models (American Association of State Highway and Transportation Officials, 2008, p. 33). Associated software for the MEPDG—the AASHTOWare® Pavement ME Design™ software—was released in April 2011 (L. Pierce & Smith, 2015, p. 1).

During the first few years after the release of the MEPDG, some state DOTs have continued to use AASHTO 93 for pavement design and then the MEPDG to verify a pavement's design. Recently, most state DOTs perform local calibrations based on the observed LTPP database to ensure the design outcomes can be more reliable within their own states. Some state DOTs have also adopted the new MEPDG to design pavement after they finished their local calibrations.

MDOT has been assessing the ME design method and supporting ME-related projects since 2004. In an MDOT evaluation of the sensitivity analysis and validation of the performance models for jointed plain concrete (JPC) and hot-mix asphalt (HMA) by (Buch, Chatti, Haider, & Manik, 2008), HMA pavement performance was significantly affected by eleven design and material variables, including asphalt concrete (AC) layer thickness; AC mix characteristics; base, subbase, and subgrade moduli; and base and subbase thickness. Binder grade played the most important role in affecting transverse cracking (Buch et al., 2008). NCHRP project 1-47 concluded that the bound surface layers (HMA, PCC) are sensitive to MEPDG-predicted pavement performance for all pavement types and distresses (Schwartz, 2011, p. 52).

Because traffic inputs in the ME method dramatically change from ESAL to axle load spectra and different truck configuration inputs, an MDOT project by Buch, Haider, Brown, and Chatti (2009) characterized traffic inputs. To implement MEPDG in Michigan, a series of projects were conducted, including characterization of HMA properties (RC-1593), sensitivity and evaluation of rehabilitation designs (RC-1594), local calibration and validation of the pavement ME performance models (RC-1595), and improvement on climatic inputs (RC-1626) (Buch et al., 2013; Haider, Buch, Brink, Chatti, & Baladi, 2014; Kutay & Jamrah, 2013; You, Yang, Hiller, Watkins, & Dong, 2015).

In Michigan, MDOT published its own user design guide for applying ME pavement design in 2015 (Michigan Department of Transportation, 2015). This guide provides information on ME software operation, design types, inputs, and evaluation of the design results.

States with wet-freeze climates have responded differently to the adoption of pavement design methods. For example, the wet-freeze states of Missouri, Indiana, and Maryland implemented the MEPDG. Indiana DOT fully implemented MEPDG in 2009; they have defined input parameters, reviewed DOT data and LTPP databases, obtained necessary equipment with a testing plan, conducted material and traffic analysis, finished local calibration of MEPDG performance prediction models, compared the results between existing design procedures and the MEPDG, provided training in ME principles, and revised the Indiana DOT Design Manual (L. C. Pierce & McGovern, 2014, p. 43). Missouri DOT fully implemented MEPDG as of 2009; they have obtained Missouri-specific traffic data, characterized material properties, evaluated field test sections, and conducted local calibration (L. C. Pierce & McGovern, 2014, p. 43). Maryland State Highway Administration has added an MEPDG-specific chapter to their *Pavement & Geotechnical Design Guide* for new construction and uses the AASHTO 93 method in cross-checking designs. Pennsylvania DOT is currently designing a MEPDG user guide for Pennsylvania condition. New Hampshire DOT is evaluating the MEPDG and is currently using AASHTO 1972 design method. Vermont Agency of Transportation is currently calibrating the MEPDG model and is currently using AASHTO 1993 for pavement design. New Jersey DOT has developed an MEPDG material database. Virginia DOT is developing a material database, conducting traffic analysis and classifying subgrade. New York State DOT has a number of studies related to the MEPDG and is currently using AASHTO 1993 method. Connecticut DOT, in conjunction with the University of Connecticut, conducted a study of MEPDG design inputs. Wisconsin is actively evaluating the MEPDG (L. Pierce & Smith, 2015). Massachusetts DOT attempted to calibrate the MEPDG pavement performance model, but has not finish due to limited numbers of construction projects.

Illinois DOT and Minnesota DOT (MnDOT) currently use a state-specific ME method. Illinois DOT applied ME design procedure on flexible pavements, rigid pavement, and asphalt overlay or rubberized pavement (L. C. Pierce & McGovern, 2014, p. 15). MnDOT, developed their own modelling system—the MnPAVE Flexible computer program—that outputs a pavement's anticipated service life based upon a damage factor (Minnesota Department of Transportation, 2014).

3.1.2 China's Pavement Design

This is not an MDOT current practice. It has been widely used in China; therefore, the research team recommends conducting research to compare United States' pavement design with China's pavement design.

By the end of 2016, the total length of China's expressway network was 81,400 miles (131,000 kilometers), which is the world's largest expressway system by length (Ministry of Transport of the People's Republic of China, 2017b). Most of the expressways are asphalt concrete pavements designed with China's asphalt pavement design method.

China's asphalt pavement design method is based on "Specifications for Design of Highway Asphalt Pavement" (Ministry of Transport of the People's Republic of China, 2017a) using multi-layered elastic continuous system theory. According to the Ministry of Transport of the People's Republic of China standard JTG D50, the mixed traffic is converted into equivalent 22.5 kip (100 kN) single-axle load applied to two pairs of dual tires, while 18.0 kip (80 kN) of equivalent load in the United States (Ministry of Transport of the People's Republic of China, 2017a). The pavement design is controlled by five indicators: fatigue life of asphalt layer, fatigue life of stabilized base, permanent deformation of asphalt layer, vertical compressive strain at the upper of subgrade, and low temperature cracking index, while the United States is using pavement distresses as its control index. These equivalent single-axle loads and control criteria result in different designed pavement thickness, which affect pavement design, material selection, and overall cost of construction.

Portland Cement Concrete

3.1.3 AASHTOWare Pavement ME

This is an MDOT current practice.

Concrete pavement design has shifted from an empirical pavement design approach to a mechanistic-empirical pavement design approach in the United States.

Prior to 2007, road agencies both nationally and internationally (such as the Quebec Ministry of Transportation) followed AASHTO's 1986 and 1993 editions of the *Guide for Design of Pavement Structures*, which detailed an empirical approach to concrete pavement design (Kathleen T Hall, n.d., p. 1). The guide determined axle load applications based on JPCP and jointed reinforced concrete pavement (JRCP) sections of the AASHTO Road Test (Kathleen T

Hall, n.d.). However, since the basis of the empirical design method is the Illinois road sections used in the AASHO Road Test, the method can only address “limited pavement types, loads and load applications, age, and environment” (American Association of State Highway and Transportation Officials, 1993, pp. I-12).

In 2008, AASHTO released the *Mechanistic-Empirical Pavement Design Guide* (MEPDG), providing guidance on applying mechanistic-empirical design principles to a variety of concrete pavements including JPCP, CRCP, JPCP overlays (greater than 6 inches [15.25 cm]), CRCP overlays (greater than 7 inches [17.75 cm]) and JPCP restoration (American Association of State Highway and Transportation Officials, 2008, pp. 20-21). Its performance prediction models consist of JPCP transverse cracking, JPCP mean joint faulting, CRCP punchouts, and JPCP and CRCP IRI (American Association of State Highway and Transportation Officials, 2008, pp. 20-21). For implementation of the mechanistic-empirical design in Michigan and other wet-freeze climates, agencies can refer to AASHTO’s *Mechanistic-Empirical Pavement Design Guide*.

3.1.4 Modified European Method

This is *not* an MDOT current practice, and the research team does not recommend it for further consideration in Michigan’s wet-freeze climate.

In 1993 and 1994, MDOT began an evaluation of European pavement design by placing a test section of European and Michigan pavements along northbound I-75 in Detroit. A typical European pavement relies upon high quality—and, thus, higher cost materials, design, and construction; consequently, these pavement designs have achieved 40- to 50-year service lives despite sustaining heavier axle loads and higher volumes of commercial traffic as well (Weinfurter, Smiley, & Till, 1994, p. 5). Therefore, MDOT constructed a European pavement design project to evaluate the design and assess “the applicability of certain European concepts to the United States highway system” (Weinfurter et al., 1994, p. 1). Michigan selected the structural layer thicknesses and respective materials in accordance with the German design procedures. Although the I-75 European pavement design test sections have been demonstrating delamination originating at the transverse joints and longitudinal cracking since 2011 and have required an HMA overlay in 2017, the evaluation project showed that MDOT was willing to consider innovative pavement designs and implement changes to their current practices based on insights from the evaluation project (D. L. Smiley, 2010, p. 22; Staton, 2013).

3.2 DESIGN METHOD – MIX

Asphalt Concrete

3.2.1 Superpave™

This is an MDOT current practice.

Superpave™ (superior performing asphalt pavement) mixture design method is the result of a Strategic Highway Research Program (SHRP) initiative and is widely used and accepted by many state agencies, including MDOT. This promising technique is not, however, limited to wet-freeze climates. As a design method with applications for all 50 states, Superpave™ considers hot and cold temperatures, binder specifications for all climates, aggregate specifications, traffic volumes, and aggregate and binder criteria for varying volumetric properties.

In 2007, the special provision for Superpave™ hot-mix asphalt (HMA) was proposed by MDOT in 2007 (Michigan Department of Transportation, 2007). In 2009, development of specification of the Superpave™ simple performance tests (SPT) was conducted in RC-1532 (You, Goh, & Williams, 2009).

3.2.2 Dense-graded Asphalt Mixtures

This is an MDOT current practice.

Dense-graded aggregate is the most widely used type of asphalt mixture for surfacing and overlays. Dense-graded aggregate can be used to produce a smooth, quiet riding asphalt concrete surface when used as a surfacing layer; however, of itself, it provides no specific wet-freeze climate benefit except for surface condition improvements.

Dense-graded asphalt mixture is composed of dense-graded aggregate and neat or modified asphalt binder; this mix produces an asphalt concrete that has a low air-void content and a maximum density after compaction (T. J. Van Dam et al., 2015, pp. 3.34, 34.12, 37.19, A.35). When compacted, the dense-graded asphalt concrete forms a nearly impermeable layer that inhibits water infiltration due to the low porosity of the dense-graded aggregates that it contains (American Association of State Highway and Transportation Officials, 2015b, pp. 3.28 - 23.29). Mixing and compacting of dense-graded asphalt mixture are generally done at temperatures ranging from 275°F to 350°F (135°C to 177°C), but warm-mix asphalt additives can reduce those required temperatures by to 30°F to 50°F (17°C to 28°C).

3.2.3 Gap-graded Mix Asphalt Mixtures

This is an MDOT current practice.

Gap-graded aggregate can be used to produce stone-matrix asphalt, which offers such benefits as extended service life, skid resistance, and enhanced visibility—all of which are important qualities for pavements in wet-freeze climates (National Asphalt Pavement Association & Federal Highway Administration, 2002, p. 4). Gap-graded aggregate has larger sizes and smaller sizes but has an absence of certain intermediate sizes (T. J. Van Dam et al., 2015, p. A.6).

Stone-matrix asphalt (SMA) demonstrates several benefits, some of which can be significant for improving pavement performance in wet-freeze climates. A SMA surfacing layer is composed of a particular type of gap-graded aggregate so that "certain intermediate sizes are substantially absent," which provides a stable aggregate-to-aggregate skeleton, a rich asphalt content, filler, and stabilizing agents to obtain a maximum rutting resistance and durability (National Asphalt Pavement Association & Federal Highway Administration, 2001, p. 12; T. J. Van Dam et al., 2015, p. A.6).

An SMA surfacing layer requires high-quality aggregates in order to form the skeleton; such aggregates include cubical aggregate, low-abrasion aggregate, crushed stone, and manufactured sands. The matrix created by fine aggregate, mineral filler, and additives plays a critical role in pavement performance.

The cost of SMA cement is reported to be 20 to 25 percent higher than the cost of dense-grade cement (National Asphalt Pavement Association & Federal Highway Administration, 2002, p. 5). Even with the increased cost, SMA is considered to be a cost-effective mixture by Maryland DOT and Georgia DOT due to the pavement's improved overall performance (National Asphalt Pavement Association & Federal Highway Administration, 2002, p. 5).

SMA has been used in Europe for more than 30 years. The first use of SMA in a U.S. project was in 1991 in Wisconsin; that same year also saw SMA used in Michigan, Georgia, and Missouri (National Asphalt Pavement Association & Federal Highway Administration, 2002, p. 3). The SMA sections in Michigan were paved on M-52 south of I-96 in Ingham County (Michigan Department of Transportation, 1992). Michigan has used gap-graded Superpave™ since 2002 (Jackson, Vargas, & Pucinelli, 2008, p. 28); MDOT's special provision includes specifications for mix design, materials, construction, and measurement and payment (Michigan Department of Transportation, 2016d).

3.2.4 Open-graded Asphalt Mixtures

This is not an MDOT current practice.

Open-graded aggregate can be used to produce permeable courses with improved friction, which enhance drainage but are susceptible to clogging (Cooley et al., 2009, p. 3). Open-graded aggregate is composed of a high percentage of coarse aggregate and a low percentage of fine aggregate in order to obtain 18 to 22 percent air voids (Jackson et al., 2008, p. 4). Open-graded asphalt is most commonly used in a mix with asphalt cement as a paving layer, known as an open graded-friction course (OGFC).

Open-graded friction course (OGFC) is a surfacing layer which uses a gradation of aggregate that produces a permeable course with improved friction; however, using this type of surfacing in wet-freeze climates poses such problems as increased winter-maintenance (Cooley et al., 2009, p. 3). The benefits of using an OGFC are predominantly related to improving safety, decreasing environmental concerns such as noise levels, and providing rutting resistance (Cooley et al., 2009, pp. 1-2). MDOT currently has a moratorium on OGFC due to durability issues that they encountered in the early 1980s (Michigan Department of Transportation, 2017c, p. 6.03.17).

Portland Cement Concrete

3.2.5 Optimized Aggregate Grading

This is an MDOT current practice.

Optimizing aggregate gradations have long been known to contribute to concrete strength and performance while reducing the required amount of cement. Many means of measuring the aggregate gradations exist, including the Shilstone curve, the 0.45 power chart, the 8-18 chart, the 5-15 chart, and, most recently, the Tarantula curve. The 8-18 chart provides a plot of sieve size against percent retained with the intention that this value should retain between 8% and 18% (Iowa Department of Transportation, 2017). The Tarantula curve, developed by Ley, Cook, and Fick (2012), is based on a modification to the typical 8-18 chart. Wet-freeze states including Minnesota, and Iowa have been able to obtain aggregate gradations that fall within the Tarantula curve. Texas has demonstrated that mixtures with an aggregate gradation falling within the Tarantula curve had excellent response to vibration with very low cementitious materials content (approximately 450 lbs/yd^3, or 267 kg/m^3) (P. Taylor & Fick, 2015, p. 3).

The implementation of the Tarantula curve can be costly as it may require using four or more aggregate bins to achieve the appropriate gradation depending on aggregate sources. Additionally, many states already implement some level of aggregate optimization (such as through the use of the Shilstone chart, the 0.45 power chart, or the 8-18 chart). Additionally, there can sometimes be an economic limitation such that it is impossible to meet the requirements of the Tarantula curve with the selected or available aggregates.

Optimized aggregate grading is currently recommended as a best practice by the Federal Highway Administration; however, initial adoption of optimized aggregate grading often results in increased costs due to lack of local familiarity and requirements for additional aggregate bins and control systems at the batch plant. But a number of agencies, including MDOT, have experienced no net increase in cost over time due to savings incurred through the reduction in cementitious materials and improved uniformity during placement. Additionally, the aggregate grading is only one attribute of the aggregate (shape, texture, mineralogy are others), and thus an aggregate grading that works in one location might not necessarily would not be inherently limited to the mixtures based on location. In all cases, regardless of grading, aggregates to be used in wet-freeze climates must be freeze-thaw durable in accordance with the respective state DOT's requirements.

3.3 PAVEMENT TYPE

Asphalt Concrete Pavement

3.3.1 Conventional Asphalt Pavement

This is an MDOT current practice.

Composed of HMA, conventional asphalt pavement makes up approximately 82% of America's paved roads (Asphalt Pavement Alliance, 2017a). Consequently, conventional asphalt pavement is used almost universally across the U.S., regardless of climate zone, and comprises one of the predominant pavement types in Michigan along with concrete and aggregate (although MDOT does not utilize aggregate roads) (Michigan Department of Transportation, 2017c, p. 168). Conventional asphalt pavement is effectively used on moderate- to low-volume roadways (American Association of State Highway and Transportation Officials, 2015b, pp. 2-8).

Conventional asphalt pavement—commonly composed of sand, aggregate, and a petroleum-based asphalt cement (asphalt/bitumen binder)—typically has an impermeable dense-graded surface layer ranging from 3 to 5 inches (8 to 13 cm) thick and a compacted, higher-quality dense-graded, 6- to 12-inch-thick (15 to 30 cm) aggregate base and/or a lower-quality, 8- to 16-inch-thick (20 to 41 cm) aggregate subbase that help to support the traffic load (see Figure 2) (American Association of State Highway and Transportation Officials, 2015b, pp. 2-8). It typically has a service life ranging from 10 to 20 years (American Association of State Highway and Transportation Officials, 2015b, pp. 2-8). An important consideration for constructing conventional asphalt pavement is achieving good compaction of the surface, base, and subbase layers in order to provide stable and durable pavement structure to support the traffic loading. Most preservation and maintenance strategies for asphalt pavements have been developed with conventional asphalt in mind.

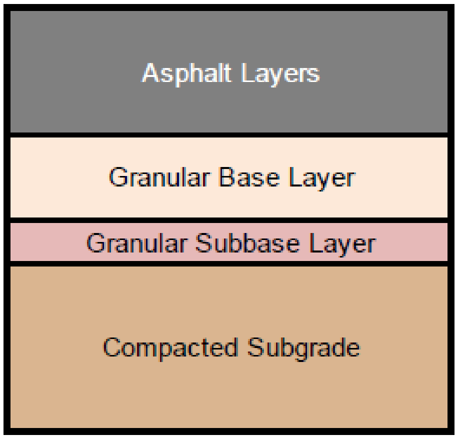


Figure 2: Conventional asphalt pavement (Not to scale) (T. J. Van Dam et al., 2015, Figure 4.3)

In comparison to concrete (rigid) pavement, asphalt pavement usually has a similar service life before needing rehabilitation and tends to be more prone to moisture problems. However, asphalt pavement can provide a quieter and smoother surface and can be more easily repaired in comparison with concrete pavement (McDaniel, 2010). Conventional asphalt pavements can be used for most applications where other pavement types can be used.

3.3.2 Full-depth Hot-mix Asphalt Pavement

Full-depth hot-mix asphalt (HMA) pavement has been used on Michigan county roads with low-volume traffic, but not on MDOT roads with high-volume traffic. There are concerns about frost protection since it is directly built on subgrade. In addition, MDOT uses the term full-depth HMA to describe its reconstruction design of three courses of HMA over aggregate base and sand subbase.

Full-depth HMA pavement is “a flexible pavement structure that uses HMA throughout the entire thickness (binder course and surface course layers)” (see Figure 3) (Illinois Department of Transportation, 2016, p. 54-1.3).

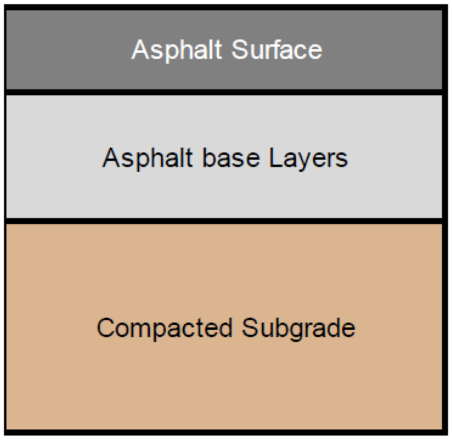


Figure 3: Cross section of full-depth HMA pavement (Not to scale) (T. J. Van Dam et al., 2015, p. 4.10)

Full-depth HMA pavement can be implemented on low-volume local roads as well as high-volume interstates. The design service life can vary from 10 to 25 years. A surface treatment for the wearing surface may be integrated into the system if needed due to the traffic loads (American Association of State Highway and Transportation Officials, 2015a, pp. 2-11). Full-depth hot-mix asphalt pavement (HMA) is included in the Illinois DOT specifications. The Illinois DOT has been monitoring the performance of 55 full-depth HMA pavement projects for several decades. Among these projects, two demonstration projects built in 1986. Some sections were overlaid with an HMA surface, both of the two projects have sound pavement after 25 years. Based on the monitor data, Illinois DOT has not found any problems that would indicate the need for revisions to their current design procedures for full-depth HMA pavement.

3.3.3 Porous Asphalt Pavement

This is *not* an MDOT current practice, and the research team considers this technology not viable or practical in Michigan's wet-freeze climate at this time (it is included in this report for completeness).

Porous asphalt pavement—composed of open-graded aggregate, polymer-modified asphalt binder, and often fibers—can enhance the ability of pavements in wet climates to disperse water from the surface; however, when these pavements are used in freeze climates, they do require additional consideration with regard to winter maintenance procedures. In contrast to conventional asphalt pavement, a porous structure is created in the pavement by modifying the asphalt binder and amount of compaction to maximize water infiltration (see Figure 4 and see Dylla and Hansen (2015, pp. 2-6) for more detail on this pavement design). Porous asphalt pavements have been typically used for parking lots and low-volume roadways (Dylla & Hansen, 2015, p. 4).

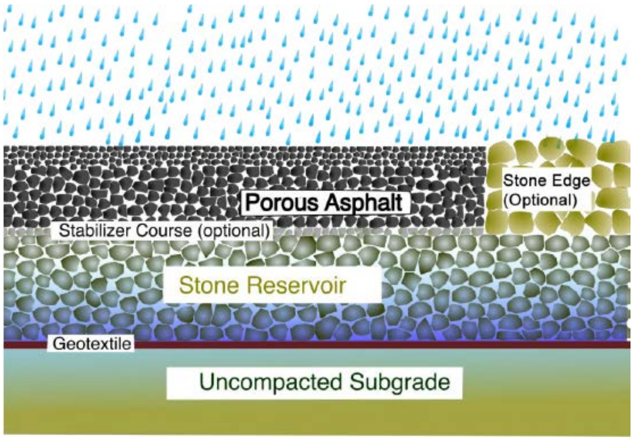


Figure 4: Typical porous pavement with stone reservoir cross-section (Not to scale) (Dylla & Hansen, 2015)

Porous asphalt has been considered a best practice in regards to water quality by the United States Environmental Protection Agency, and several state agencies, such as New Jersey and Pennsylvania, have adopted this practice. This technology has potential in wet climates due to its improved drainage capabilities although its application is still limited by the costs involved in keeping the pavement free of clogging debris. Its application is also facing limiting factors in freeze climates. The Minnesota Department of Transportation (MnDOT) has been conducting research from the Local Road Research Board to identify the performance of full-depth porous asphalt pavement in cold climates and, subsequently, to provide guidance for Minnesota's local road network. After monitoring two porous pavement intersections for three winter seasons, an MnDOT report by Weiss, Kayhanian, Khazanovich, and Gulliver (2015) concluded that porous asphalt pavement can facilitate management of road surface icing through its ability to allow water infiltration but that its best application may be limited to subgrade drainage (pp. 85, 94). However, a case study of porous asphalt in Colorado revealed substandard drainage. And, while a New Hampshire study comparing the performance of porous asphalt to dense-graded asphalt found that porous pavement significantly reduced pollutant mass load due to the management of stormwater runoff, its infiltration rates decreased substantially with time and its surface required frequent regenerative air sweeping to maintain infiltration and to prevent clogging (Dylla & Hansen, 2015).

Porous asphalt pavements have been in use in Michigan for more than 10 years. Streets utilizing porous pavement have included Sylvan Avenue in Ann Arbor and Willard Street in Ann Arbor (Mills, 2016). Its applications have also included parking lots at the University of Michigan, 2002; the Ford Rouge Center, 2002; the City of Farmington Hills, 2007; Washtenaw Community College, 2007; Michigan State University, 2009; and the Manistee Meijer's store, 2014 (Mills, 2016; Office of the Washtenaw County Drain Commissioner - Janis Bobrin, p. 2).

Even though there have been successful demonstration pavement sections for parking lots in wet-freeze climates, the maintenance challenges and high initial cost posed by porous pavements make it impractical for the research team to recommend that MDOT adopt porous asphalt pavement as best practice at this time. Additionally, porous asphalt pavement's large amount of voids results in a weaker pavement than conventional asphalt which has, thus far, limited its application to low-volume roads and parking lots.

On the other hand, porous asphalt pavement has been demonstrating to be effective at reducing stormwater runoff, enhance runoff quality, and restore groundwater reserves (Dylla & Hansen, 2015, p. 3). It can also expedite snow and ice melting in the winter, thereby reducing the amount of chemical deicing/anti-icing needed (Dylla & Hansen, 2015, p. 3).

3.3.4 Perpetual Asphalt Pavement

This is *not* an MDOT current practice. It is still in field trials and monitoring; therefore, the research team recommends reviewing this practice again as more research becomes available.

Perpetual asphalt pavement offers a variety of benefits ranging from reduced overall life-cycle costs to reduced environmental impact; however, perpetual asphalt pavement does not promise particular benefits for wet-freeze climates. The Asphalt Pavement Alliance (APA) defines perpetual (or life-long) asphalt pavement as "an asphalt pavement designed and built to last longer than 50 years without requiring major structural rehabilitation or reconstruction, and needing only periodic surface renewal in response to distresses confined to the top of the pavement" (Asphalt Pavement Alliance, n.d.; Newcomb et al., 2010, pp. 3, 7). Perpetual pavement consists of multiple layers of asphalt of differing design, a stabilized or unstabilized granular subbase, and a compacted or lightly compacted subgrade; furthermore, each layer has varying mechanical and structural properties that account for stresses, strains, or deflections (see Figure 5) (Asphalt Pavement Alliance, n.d.; Newcomb et al., 2010, pp. 8, 24-25, 27, 37). These layers work together to provide such benefits as a smooth riding surface, resistance to rutting and surface cracking, good surface friction, reduced splash, stability, good load distribution, and resistance to fatigue and reflective cracking (Asphalt Pavement Alliance, n.d.; Newcomb et al., 2010, pp. 24-25, 27, 37).

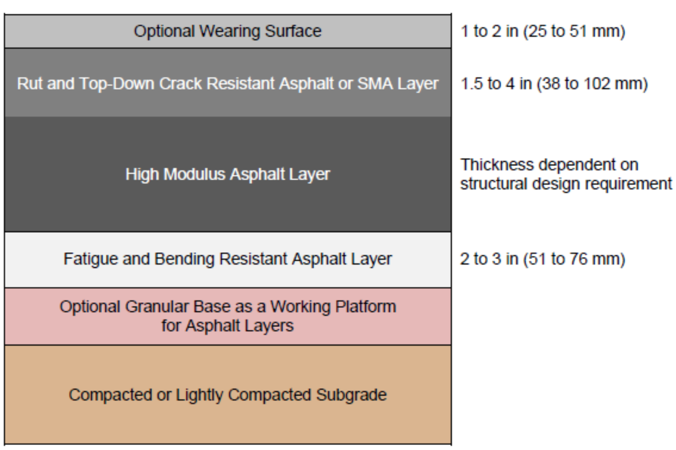


Figure 5: Perpetual pavement cross-section (Not to scale) (T. J. Van Dam et al., 2015, p. 4.11)

Some examples of such long-lasting pavements include: a 2-mile (3.2-kilometer) section of Minnesota State Highway 36 near Stillwater and Oakdale; a 7.7-mile (12.4-kilometer), two-lane stretch of Minnesota State Highway 371 in Cass County, between Pine River and Backus; a 3-mile (4.8-kilometer), two-lane section of US Highway 62 in Arkansas, near Berryville; a 3-mile (4.8-kilometer), four-lane section of divided Interstate 180 in Pennsylvania, in Northumberland County; and a 3-mile (4.8-kilometer) section of BinZhou test road in Shandong, China (Asphalt Pavement Alliance, 2008, 2017b, 2017d; G. Wang, Wang, Thompson, & Ahn, 2012, pp. 1, 19).

In Michigan, MDOT has a demonstrated project of perpetual asphalt pavement, a 1.2-mile (1.9-kilometer) section of northbound US-24 in Detroit (Asphalt Pavement Alliance, 2007, 2017c; Construction Equipment Staff, 2008; Eaker & Bancroft, 2004)[1].

The upfront costs associated with perpetual asphalt pavement can be higher due to the necessity for more oversight as well as thicker asphalt layers in the design and construction processes (Newcomb et al., 2010, pp. 3, 11).

However, by design, a properly constructed perpetual asphalt pavement should not require major structural rehabilitation or reconstruction during its designed-for service life (which is longer than the typical pavement design); only corrective surface maintenance procedures should be necessary (European Asphalt Pavement Association, 2007, p. 5; Newcomb et al., 2010, p. 7). Maintenance requirements are generally limited to wear course resurfacing and crack sealing. In comparison to conventional asphalt pavement, perpetual asphalt pavement has a reduced life-cycle cost of repairs and/or reconstruction, lower rehabilitation-induced user delays, and a lower environmental impact due to its reduced use of non-renewable resources and energy over the service life of the pavement (Newcomb et al., 2010, pp. 3, 11). These benefits result from the optimized design of the layers comprising a perpetual pavement.

Concrete Pavement

3.3.5 Jointed Plain Concrete Pavement

This is an MDOT current practice.

Jointed plain concrete pavement (JPCP) is the most widely used type of concrete pavements due to its relatively low construction costs compared to CRCP and widespread applicability (N. J. Delatte, 2008, p. 27). JPCP is an "unreinforced cast-in-place concrete pavement designed with or without doweled transverse joints and tied longitudinal joints" (see Figure 6) (California

[1] Editor's note: The cited document incorrectly spells the author's name, Michael Eacker, as "Michael Eaker" - to facilitate the correct reference to the cited document, this report uses the author's name as spelled in publicly available sources of the cited document. Elsewhere, the author's name is spelled correctly

Department of Transportation, 2015, pp. 210-211). JPCP has relatively short joint spacing and is designed to transfer load across joints using dowels, and to a lesser degree (but still relevant), aggregate interlock. Dowels are most commonly solid smooth steel bars, typically epoxy-coated, that accommodate the horizontal movement at the joint that occurs due to moisture, and/or temperature induced volumetric change, facilitating the transfer of load from one slab to the next (California Department of Transportation, 2008b, p. 7; N. J. Delatte, 2008, p. 27). JPCP also uses tie bars, which are typically sections of epoxy-coated deformed reinforcing steel, to tie adjacent concrete lanes, shoulders, or curbs together. Tied joints act as a hinge which does not permit the joint to open or close, but does relieve stress. Because the joint cannot open, load is transferred from one slab to the next by aggregate interlock. There is a limit on how many lateral feet of concrete that can be tied together, with a common value being four 12-foot (3.7 m) lanes (48 feet [14.6 m] total), although some states like Colorado allow greater distances.

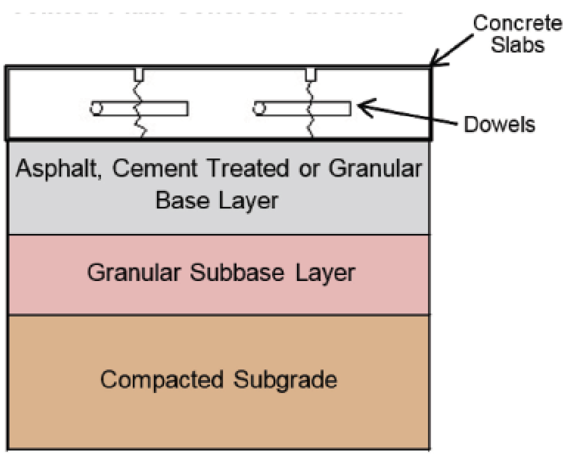


Figure 6: Jointed plain concrete pavement (Not to scale) (T. J. Van Dam et al., 2015, p. 4.13)

JPCP requires a subgrade with good soil compaction, a treated or untreated subbase and/or base, and a concrete surface arranged in slabs that are connected in the same lane via load-transferring transverse joints and adjacent lanes through longitudinal joints often connected with tie bars that hold the joint tightly closed maintaining aggregate interlock (N. J. Delatte, 2008, pp. 25-27, 249, 255). For highway pavements, JPCP is often constructed using slipform paving, which takes low-slump concrete and consolidates it, forms it into the proper geometric shape, and applies to initial surface by 'slipping' or pulling the forms continuously through and surrounding the plastic concrete mass" to produce a smooth-finish concrete (American Concrete Pavement Association, 1996, pp. vi-6; N. J. Delatte, 2008). Alternatively, for small placements or placements in constricted areas, it is common to use fixed form paving that retains concrete in molds "staked to the subgrade or base" during the paving process (N. J. Delatte, 2008, pp. 271-273, 274). In slipform paving, dowel and tie bars can be inserted into the pavement by the paving machine, although it is common to use dowel basket assemblies to hold the dowel bars in position and, in the case of side form paving, holes in the forms can be used to position tie bars along the longitudinal construction joint. JPCP requires finishing, texturing, curing, and joint sawing and sealing (N. J. Delatte, 2008, p. 279).

Michigan's state and local agencies have extensively used JPCP. While its application in Michigan is extensive and has had good results, some reported problems were associated with early mid-slab cracking of JPCP. In three of the four projects, the cracking was related to poor construction practices including non-uniform base/subbase on a section of I-75, the frozen sub-base encountered (in violation of specifications and good practice) when paving a ramp on I-275, and the lack of isolation joints on a section of US-12 (D. Smiley & Hansen, 2007, p. 45). To ensure long-life of JPCP, it is recommended that the moisture content of the concrete aggregates be controlled during batching, that the concrete mixture be appropriately cured, that aggregate segregation is avoided during placement of the open-graded base (note that MDOT has changed the base gradation to provide better stability during construction), reduce concrete temperatures during placement, and expand the use of the P1-modified high-performance concrete paving mixtures utilizing optimized tough, durable coarse aggregates and 25 to 40 percent replacement of portland cement with SCM (D. Smiley & Hansen, 2007, pp. 46-47).

The steel dowels in JPCP can be susceptible to corrosion (N. J. Delatte, 2008, p. 27) and this is why the dowels are commonly coated with a protective layer of epoxy, although other more durable coatings, including galvanization, stainless steel and fiber-reinforced polymers have been investigated.

MDOT documented a case of JPCP experiencing top-down, mid-panel transverse cracking due to multi-axle trucks applying loads at each end of the slab simultaneously in combination with stress generated by slab temperature curling and moisture warping. Under these specific conditions, once the cracking initiated, it rapidly increased in severity necessitating costly repairs or reconstruction (D. Smiley & Hansen, 2007, p. 45). This experience was considered an isolated case. Spalling is also a concern for JPCP, as it can rapidly appear if the joints were poorly constructed or do not remain properly sealed. Over time, faulting can also become an issue.

Nonetheless, overall performance of JPCP is quite good and it is the standard concrete pavement type through much of the country. JPCP is considered a low-maintenance pavement that can experience an extended service life with the use of timely maintenance procedures, such as joint and crack resealing, cross-stitching, dowel bar retrofitting, and diamond grinding (N. J. Delatte, 2008; Leemann & Hoffmann, 2005); guidance for managing JPCP distresses can be found in "Concrete Pavement Preservation" by Smith et al (2014). Because JPCP does not require steel reinforcement, its construction process is simpler with a reduced need for skilled workers and it has a low initial cost of construction. This lack of steel reinforcement also means corrosion-related pavement problems are significantly reduced (N. J. Delatte, 2008, p. 27)—a benefit that could have positive implications for wet-freeze climates.

3.3.6 Continuously Reinforced Concrete Pavement

This is not an MDOT current practice. Michigan has used CRCP in the past but does not currently use it. The research team recommends reviewing this practice and consider implementing.

As the name implies, continuously reinforced concrete pavement (CRCP) uses continuous longitudinal reinforcement (typically 0.6 to 0.7 percent cross-sectional area) to eliminate transverse contraction joints, instead allowing the pavement to randomly crack transversely, with typical crack spacing of 1.5 to 6 feet (46 to 183 cm). The steel reinforcement holds the cracks tight, allowing aggregate interlock to transfer load across the crack interface. The transverse steel is on chairs and is designed to support the longitudinal steel as well as restrain any longitudinal cracks that may form (see Figure 7). The main attractions of CRCP, if constructed properly, is its excellent ride quality (no joint faulting), ability to be overlaid with asphalt without the risk of reflection cracking, and long life.

Major drawbacks of CRCP is its high initial construction cost, it is difficult to construct (especially by an inexperienced contractor), and it is more costly to repair than other pavement types. MDOT stopped using CRCP in 1978 and Louisiana stopped using CRCP in 1975 due to premature failures experienced in CRCP projects due to "insufficient thickness of the concrete slab, poor base, rounded aggregate, and/or poor construction technique, in addition to poor subgrade conditions" (Concrete Reinforcing Steel Institute, 2004, p. 2; Michigan Department of Transportation, 2017c, p. 6.04.06; Roesler, Hiller, & Brand, 2016, p. 71). Louisiana has since resumed using CRCP in 2003 after assessing the successes from other states that are successfully using CRCP including Illinois and Texas (Concrete Reinforcing Steel Institute, 2004; Roesler et al., 2016, p. 2). Michigan is considering the use of CRCP for a short section of pavement in Jackson to bridge over subsidence caused by collapse of abandoned underground coal mines. CRCP is also now routinely used in California by Caltrans for their most highly trafficked routes.

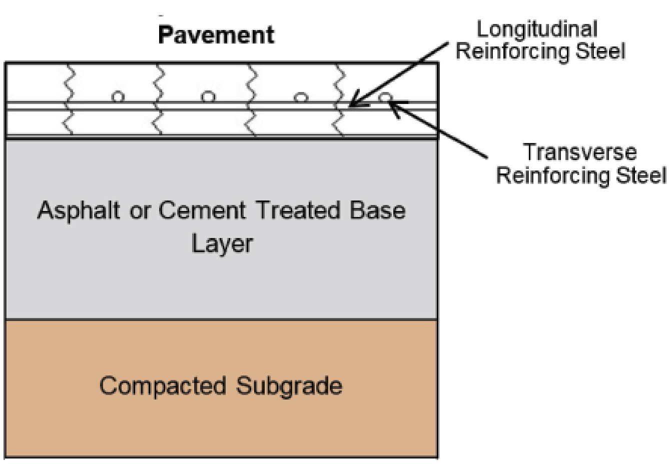


Figure 7: Continuously reinforced concrete pavement (Not to scale) (T. J. Van Dam et al., 2015)

CRCP has been used for decades in the United States, in such states as California, Georgia, Illinois, Louisiana, North Dakota, Oklahoma, Oregon, South Dakota, Texas, and Virginia—some of which are not classified as wet-freeze climates. California, Illinois, and Texas are considered lead states in terms of usage, where CRCP is the design type of choice for heavily trafficked routes. The Long-Term Pavement Performance (LTPP) GPS-5 experiment demonstrated the longevity and overall good performance of CRCP (Federal Highway Administration, 2007, pp. 14-15). While Texas and California are not considered wet-freeze states, they both have a wealth of research, knowledge, and experience related to CRCP design and performance. California's mountainous regions, which experience freeze-thaw and considerable snowfall, have CRCP roads, most notably on I-5 in Northern California near the Oregon border (Plei & Tayabji, 2012, p. 6). Overall, CRCP has shown very good performance and longevity.

The Illinois Department of Transportation has constructed CRCP on their freeway systems for nearly 65 years in a wet-freeze environment. The majority of the Chicago area urban interstates were originally constructed using CRCP and were reconstructed in the last decade using CRCP. Gharaibeh, Darter, and Heckel (1999) provide a review of design and performance of CRCP pavements in Illinois. The majority of the sections constructed between 1955 and 1994 were 7 to 10 inches (18 to 25.5 cm) thick (Gharaibeh et al., 1999). Just over half of these sections experienced D-cracking, a distress caused by freeze-thaw deterioration of coarse aggregate particles; other types of failures observed in the evaluation included punchouts, localized failures (potholes), existing repairs, and transverse cracks in which the steel had ruptured (Gharaibeh et al., 1999). Most failures were observed in 7-inch (18 cm) thick sections whereas the best performance was found in the 10-inch (25.5 cm) thick sections.

Recently, CRCP has been considered for use on the Illinois Tollway (Tayabji, Tyson, Roesler, & Gillen, 2016). The Illinois Tollway is located in the Chicago area, a wet-freeze area. The AASHTOWare Pavement ME Design software was used for the design, and the application included the use of a 3-inch (8-cm) thick flexible HMA base on granular subbase.

Due to the presence of the reinforcement (commonly 0.06 to 0.07 percent in the longitudinal direction), CRCP comes with a higher initial cost than traditional jointed plain concrete pavement (JPCP). The construction of CRCP also requires greater care than JPCP and, thus, DOTs and local agencies may be reluctant to accept the technology due to the learning curve related to CRCP design and construction practices. Finally, even though CRCP typically requires less overall maintenance than JPCP, its maintenance techniques are more costly and require more specialization (Michigan Department of Transportation, 2017c, p. 6.04.06). Yet overall, CRCP is a considered a cost-effective pavement type due to improved performance, longevity, and reduced life-cycle costs.

Both the Illinois DOT and the Illinois Tollway continue to make extensive use of CRCP in a wet-freeze region. Texas and California have both elected to use CRCP as their first choice for concrete pavement on heavily trafficked highways, including routes in California that would be considered wet-freeze. One of the main reasons includes an expected service life in excess of 50 years for CRCP.

3.3.7 Bonded Concrete Overlay

This is not an MDOT current practice.

Bonded concrete overlays can be placed on an existing concrete or asphalt pavement. Bonded concrete overlays of asphalt specifically refers to a concrete overlay bonded to an asphalt pavement, and are thus considered a composite pavement and therefore discussed under Section 3.3.14. A bonded concrete overlay of concrete requires full bonding between the overlay and substrate concrete so that the two behave in a monolithic fashion. It is a rarely used technique, programmed specifically to add structural capacity to a concrete pavement that is otherwise in good condition. Typically 2 to 4 inches (5 to 10 cm) thick, it is essential to the performance of the system that the overlay remains bonded to the existing concrete pavement, requiring excellent surface preparation and cleaning and exact matching of existing joints in the overlay (Harrington & Fick, 2014, pp. 6-7). Further, the existing concrete pavement must be relatively distress free. The use of this type of overlay is considered risky and should only be done under rare circumstances where an existing concrete pavement in excellent condition in known to not have adequate structural capacity for anticipated future traffic.

3.3.8 Pervious Concrete Pavement

This is *not* an MDOT current practice; the research team considers this technology not viable or practical in Michigan's wet-freeze climate at this time.

Pervious concrete, also known as porous concrete pavement, allows stormwater to flow through the pavement surface and natural soils (see Figure 8) (Eller, 2010, Executive Summary). The goal of this permeable pavement structure is to reduce water runoff and management while improving runoff water quality through soil filtration.

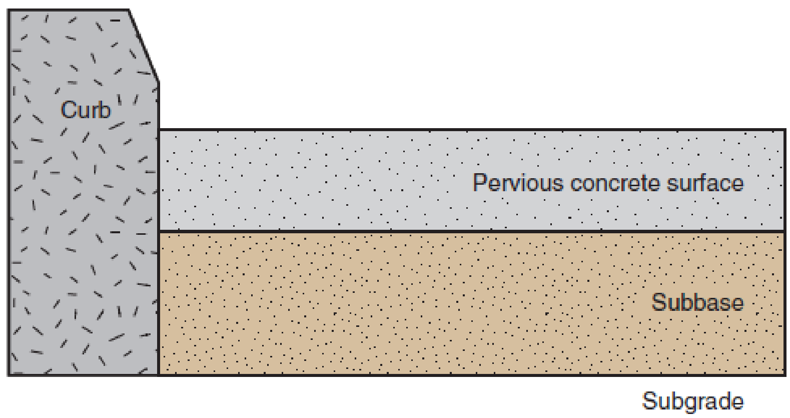


Figure 8: Pervious concrete pavement structure (Not to scale) (American Concrete Pavement Association, 2006, p. 1)

Pervious concrete pavements and slabs-on-grade have been constructed in several wet-freeze states including California (alpine areas), Indiana, Kentucky, Minnesota, Nevada (alpine locations), Ohio and Pennsylvania. Pervious concrete is most often used in low traffic areas to support surface infiltration to enhance stormwater management, and is considered a best management practice for sidewalks, shoulders, parking lots and driveways of various sizes. Although most of these applications did not require maintenance within the first few years, it is well documented that pervious surfaces require routine maintenance, including simple vacuuming or pressure washing activities, to maintain their infiltration properties. In one study, N. Delatte, Miller, and Mrkajic (2007) found that many pervious concrete field sites had moderate to severe clogging, though only a handful had either raveling or cracking (pp. 47-49).

Michigan's first pervious concrete pavement is an intersection on Lafayette Street built by the City of Ionia (Prein & Newhof, 2012). However, a concern associated with pervious concrete in Michigan, according to Bailey and DeGraaf (2015), is water retention during a freeze cycle. In addition to the American Concrete Pavement Association's (ACPA) PerviousPave structural design method for pervious concrete pavement, the Michigan Concrete Association provides specifications for using pervious concrete (American Concrete Pavement Association, 2016; Michigan Concrete Association, 2017, n.d.).

It has not been demonstrated that pervious concrete has a high resistance to cyclic freezing and thawing. Long-term freeze-thaw performance has not been determined. Specific problems posed by pervious concrete pavement have included water retention in the pavement structure especially during freezing cycles; additional costs for materials, construction, and maintenance; moisture damage; and potential ground water contamination (Bailey & DeGraaf, 2015; Weiss, Kayhanian, Gulliver, & Khazanovich, 2017, p. 1). Furthermore, construction of pervious concrete pavement requires additional care to avoid over-compaction (Tennis, Leming, & Akers, 2004, p. 18); if the pavement becomes over-compacted, the permeability cannot be restored. Finally, pervious concrete is known to be prone to clogging if the site layout is not well planned and if the surface is not properly maintained; clogging accelerates if abrasives (e.g., sand) are used to enhance winter traction, a common practice in many freeze-thaw areas. Therefore, pervious concrete pavement requires regular maintenance, like pressure washing and vacuuming, to remove particles that lead to clogging (Weiss et al., 2015, pp. 46, 76). This technology has potential in wet climates due to its improved drainage capabilities although its application is still limited by the costs involved in keeping the pavement free of clogging debris.

Nonetheless, pervious concrete presents a number of benefits. Laboratory studies have been conducted to evaluate techniques to increase pervious concrete's freeze-thaw resistance; Schaefer, Wang, Suleiman, and Kevern (2006) found that that changes made to the pervious concrete's composition can increase its freeze-thaw durability without a significant increase in material cost (p. 39). Pervious concrete pavement has also been found to offer improved skid resistance as well as a reduction in hydroplaning, water spray, run-off volume, and noise levels in comparison to traditional PCC mixtures (Schaefer et al., 2006, p. 1; Weiss et al., 2017, p. 1). Its high porosity allows stormwater to "seep into the ground [thereby] recharging ground water, reducing storm water runoff, and meeting U.S. Environmental Protection Agency (EPA) storm water regulations"; therefore, pervious concrete pavement minimizes land-use requirements for drainage systems (National Ready Mixed Concrete Association, 2011). Pervious concrete can also be considered a cool pavement, reducing the urban heat island effect as long as subsurface water is available for evaporation (Schaefer et al., 2006, p. 1; Weiss et al., 2017, p. 1).

Pervious concrete pavements allow for precipitation to drain through the pavement instead of accumulating on the surface and having to be addressed as run-off (Eller, 2010, p. vi; National Ready Mixed Concrete Association, 2011). The use of pervious concrete can also improve the friction characteristics of a parking lot or sidewalk while also reducing the amount of snow removal that must take place during winter storms.

3.3.9 Precast Concrete Pavement

This is *not* an MDOT current practice. The research team recommends reviewing this practice and consider implementing.

Pre-cast concrete pavement (PCP) is a repair method that allows rapid replacement of damaged concrete pavement while taking advantage of the ability to extend a construction season (Tayabji, Ye, & Buch, 2012). PCP is a pavement design that relies upon concrete panels cast in a plant and subsequently installed on-site (Federal Highway Administration, 2017b). This method reduces the on-site time needed for construction and curing, making well-designed and well-constructed PCP can be a rapidly-deployable solution for either new construction or rehabilitation on high-volume sections of the road network (Federal Highway Administration, 2017b). PCP falls into the general categories of jointed precast concrete pavement and precast prestressed concrete pavement (Tayabji et al., 2012, p. xv).

PCP has been used by a number of states located in wet-freeze regions including New York, Iowa, and Illinois, along with the Canadian Provinces of Quebec and Ontario. Currently, the state of California, where high traffic volumes in urban areas justifies the higher cost, has made significant use of PCP. The Illinois Tollway Authority also uses PCP: PCP was first used on the Illinois Tollway in 2007 for slab replacements, prompting the Tollway to develop specifications and plans for PCP in 2009; since then, the Tollway has used PCP for all types of repairs (Tayabji et al., 2012, pp. 19, 24, 86, 175). The Illinois DOT also uses PCP for the rehabilitation of concrete pavements (Tayabji et al., 2012). In New York, PCP has been used to repair both concrete pavements and asphalt pavements throughout the state (Tayabji et al., 2012, pp. 19, 24, 86, 175).

States including Michigan, Indiana, Virginia, and Pennsylvania have also investigated the use of PCP. In Michigan, for example Michigan State University began an evaluation in 2003 of the PCP system as an alternative repair method to full-depth repairs by monitoring test sections of I-675 and M-21; in 2010, test results of the panels on I-675 that five of the nine panels that were installed still had good performance (Tayabji & Brink, 2015, p. 4; Tayabji et al., 2012, p. 41). Additional sections have been constructed by MDOT on US-131 and on I-94 near Kalamazoo. Minnesota performed an installation of PCP in 2005 with the conclusions showing that costs due to user delay, including additional vehicle operating costs and lost productivity, need to be taken into account when determining whether to use PCP, which has a higher initial cost (T. R. Burnham, 2007).

PCP uses similar materials to cast-in-place concrete pavements although it has specific guidelines for aggregate size, water-to-cementitious-materials ratio, air entrainment, and steel (if applicable) (Tayabji et al., 2012, pp. 61-62, 65). Proprietary components are also used in many PCP systems; these components include the joint load transfer systems of the PCP, the prestressing hardware, and the expansion joint components (Tayabji et al., 2012, p. 61). PCP is typically used on high-traffic-volume, heavy-traffic-load roadways; consequently, PCP should be designed to withstand these usage conditions (Tayabji et al., 2012, p. 115). Its design should account for such factors as stress and deflection, 28-day compressive strength, flexural strength, aggregate interlock, load expectancies for dowel bars at load transfer at joints, and slab curling due to temperature gradients (Tayabji et al., 2012, pp. 61-63, 115). PCP are pre-cast in a plant before being stored (typically for 14 days to allow for drying shrinkage) and then lifted onto a truck and shipped to the work site; thus handling of panels, which generally relies on a four-point lifting method, is a significant consideration (Tayabji et al., 2012, pp. 144, 156, 306). According to example specifications provided by the National Precast Concrete Association (2009), installation generally involves removal and preparation of the new/renewed subbase, placement of the pre-cast slab, bedding and leveling of the slabs to ensure the slabs are properly supported, backfilling load transfer joints, and joint sealing (p. 2). Since the slabs are constructed and cured in a plant under ideal conditions, precast concrete may offer a better service life than cast-in-place concrete pavements (Federal Highway Administration, 2017b). One downside that has been noted by many is that it is common to use high cementitious materials contents and accelerators in PCP manufacturing as the increase in early-age strength allows for the beds to be turned more quickly facilitating a 24-hour production cycle.

The initial cost of precast panels can be substantially higher than typical DOT repair strategies and, thus, its use is only cost effective where the user delay costs due to extended lane closure is high, e.g. in high-volume traffic areas that magnify high fuel costs and lost productivity (T. R. Burnham, 2007). Additionally, performance of PCP is influenced by construction techniques; an inexperienced contractor can improperly install slabs, which can damage the surrounding concrete pavement and lead to a lower-than-expected service life of the precast slabs (T. R. Burnham, 2007).

PCP slabs are cast at a production plant, where the manufacturer has good control over the materials, construction, and curing of the precast slabs. This provides several advantages. Since panels are cast and cured in a plant and are allowed to reach their design strength under ideal conditions, PCP can be placed in weather conditions that could be considered prohibitive for cast-in-place techniques, providing an advantage for paving operations in wet-freeze climates (Tayabji et al., 2012, p. 6). Furthermore, PCP techniques reduce or eliminate the need for formwork, and PCP slabs can be placed during night shifts and opened to traffic in time to support the morning commute thereby mitigating the impact of paving operations on the traveling public (Tayabji et al., 2012, p. 6). Finally, in some studies, PCP has demonstrated effectiveness in eliminating early age failures related to construction (Tayabji et al., 2012, p. 6).

3.3.10 Two-lift Concrete Pavement

This is *not* an MDOT current practice.

Two-lift concrete—also known as dual-layer concrete, wet-on-wet concrete, or portland cement concrete/portland cement concrete (PCC/PCC) composite pavement—is a pavement type that aims to “provide superior resistance to freeze-thaw damage as well as noise reduction and improved skid resistance”, which are all features of interest in wet-freeze climates (Federal Highway Administration, 2007; Rao et al., 2013b, p. 14). Two-lift concrete paving is a process that involves placing two layers of concrete using a wet-on-wet technique. The thicker bottom layer of concrete typically contains less expensive “locally available or recycled aggregates” and reduced cementitious materials content while the thinner top layer often consists of “dense, wear-resistant aggregates that provide enhanced durability” (National Concrete Pavement Technology Center, 2010). Due to the composite nature of PCC/PCC, the mix design of each layer of concrete can be optimized to provide different characteristics to the pavement: for example, PCC in the top layer can focus on traffic-related noise reduction and high wear resistance whereas the bottom layer can incorporate high amounts of recycle materials. This technique can be a cost-effective method of paving with lower cost (readily available) materials in the lower layer (National Concrete Pavement Technology Center, 2010).

Two-lift concrete pavements have been used in the United States and in several European countries—including Switzerland, Belgium, the Netherlands, France, and Germany—since the early 1900s (Rao et al., 2013b, p. 15). Austria uses two-lift concrete pavement as the standard concrete construction method. Demonstration projects using two-lift concrete pavements have been constructed in Iowa, North Dakota, Michigan, Illinois, and Pennsylvania (Hu, Fowler, Siddiqui, & Whitney, 2014, pp. 9, 12). The Illinois Tollway commissioned a study to evaluate the applicability of two-lift concrete pavement as part of a multi-billion-dollar improvement program, specifically intended to investigate the use of recycled materials in concrete pavements. The study found that up to 50% of the aggregate volume in the bottom concrete lift could be replaced with high-quality recycled material (both recycled concrete aggregate and reclaimed asphalt pavement) without resulting in decreased strengths (Gillen, Brand, Roesler, & Vavrik, 2012, p. 1). The pavement thickness was determined using the AASHTOWare Pavement ME Design software to optimize the thickness of the bottom layer of concrete. The final design used either 9- or 11-inch (23- or 28-cm) thick bottom layer with a 3-inch (8-cm) thick top layer, which the Tollway was set to construct several test sections utilizing two-lift concrete pavement construction (Gillen et al., 2012, p. 1). A recent application of two-lift paving was the 2008 paving of I-70 in Kansas that made use of a lower lift of 11.8-inch-thick (30-cm-thick) standard Kansas DOT paving mix followed by an upper lift of 1.6-inch-thick (4.0-cm-thick) rhyolite (imported from Oklahoma and used as a "coarse aggregate") (National Concrete Pavement Technology Center, 2010). In another recent application, MnROAD constructed two sections of PCC/PCC pavement in 2010 on I-94, which sees heavy truck traffic and faces severe climatic conditions; nonetheless, after its first year of use and one million heavy trucks traveling over the surface, the two-lift pavement showed no signs of distress (Rao et al., 2013b, p. 21).

A two-lift pavement was constructed in Michigan in 1992, where different mixtures in the bottom lift and the top lift were used based on the European concrete pavement design (utilizing the same material and construction specifications); there were problems encountered during the construction of this particular demonstration project, and the latest field investigation showed that the pavement was experiencing delamination of the top concrete lift and spalling (Staton, 2013, p. 29).

To date, there is not a uniform consensus on the material requirements for either the top or bottom lifts of two-lift concrete pavement, and there is a lack of long-term performance data. Construction of two-lift concrete pavement requires the use of two pavers, two concrete plants (or a single plant with two drums operating independently to produce two different concrete mixtures), and two sets of delivery trucks (Rao et al., 2013b, p. 96). Two-lift concrete pavement can have significantly higher costs in comparison to traditional concrete pavement although cost savings may be possible due to the incorporation of high volumes of recycled materials (Rao et al., 2013b, p. 104).

However, two-lift concrete pavements produce a very functional and economical pavement structure. They are particularly desirable when less expensive alternatives are needed, a low-maintenance pavement with greater resistance to surface distresses is required, a quieter riding surface is important, and recycling is an option (Rao et al., 2013b, p. 19). After the deleterious effects of traffic and weather have taken their toll on a concrete pavement, a two-lift concrete pavement's high-quality surface layer can be more quickly renewed (such as via diamond grinding) in comparison to having to perform full-depth repairs or a total reconstruction, which may be necessary for other pavement types (Rao et al., 2013b, p. 104). The lower concrete layer is designed to be structurally long lasting and, because of this, the pavement can resist distresses common with conventional concrete pavements, like top-down cracking, longitudinal cracking, fatigue cracking, and corner breaks (Rao et al., 2013b, p. 104). According to key findings in SHRP 2 R21, a two-lift concrete pavement, can be considered a low-maintenance pavement due to its high-quality and, thus, more durable PCC surface and fatigue-damage-resistant PCC slab (Rao et al., 2013b, p. 104)

3.3.11 Roller-compacted Concrete Pavement

This is *not* an MDOT practice.

Roller-compacted concrete (RCC) for non-industrial pavement applications is still in field trials in a number of states. RCC is a "very dry mixture" that relies on multiple passes with a heavy vibratory steel drums and rubber-tired rollers to compact it into its final form (N. J. Delatte, 2008, p. 43; Harrington, Abdo, Adaska, & Hazarnee, 2010, p. 1). RCC paving achieves a pavement with low permeability, which helps to prevent moisture or water from entering the pavement structure. Harrington et al. (2010) provide detail about specific aggregate gradations that are needed in order to achieve proper compaction (pp. 26-27). Specific details about the cementitious materials, the water, and other additives can be found in ACI 225R, ASTM C1602, and ASTM C94, respectively (Harrington et al., 2010, pp. 29-30). RCC follows the basic design principles of conventional concrete in terms of thickness; however, its lower layers must be able to accommodate the compaction process. RCC can have sawed joints, or allowed to naturally crack, with the desire that the latter creates a tight aggregate interlock (Harrington et al., 2010, pp. 43, 56). RCC is a versatile pavement with a wide range of urban road network applications (Portland Cement Association, 2010, pp. 1-2; Zollinger, 2016, p. 1).

RCC was first used in the U.S. and Canada in the 1970s, primarily for dams and industrial pavement (such as port facilities and intermodal yards) applications, and has since been used throughout the U.S. at an increasing rate. RCC's applications have included highway, arterial, and local pavements as well as industrial access roads, turn lanes, shoulders, and rest areas; sea ports and airports; and logging facilities (Harrington et al., 2010). In Virginia, approximately 2 lane-miles (3.2 lane-kilometers) were placed on several high-traffic roads and highways; these RCC pavements were reopened to traffic within 48 hours (Hossain & Ozyildirim, 2015). This result suggests that an RCC pavement constructed on Saturday morning can be open for traffic on Monday morning, as was the case in the study. A visual survey conducted 18 months after construction showed a few cracks had developed in the RCC pavement, which were attributed to poor construction techniques (Hossain & Ozyildirim, 2015). In Texas, approximately 190 lane-miles (305.8 lane-kilometers) of RCC pavement has been placed since 2003 (Zollinger & Hossain, 2017). Texas cites fast construction, fast opening to traffic, high durability, and competitive cost as the reasons for using RCC in pavement applications, with similar results in Virginia (Hossain & Ozyildirim, 2016). Texas' RCC pavements are performing well and have been withstanding high levels of traffic while requiring minimal maintenance activities (Zollinger & Hossain, 2017) (Zollinger, 2017). Discussion on other RCC projects can be found in A. Johnson (2014, p. 8) and in Mueller (1990, pp. 8, 21-23). RCC has not been used by MDOT.

Limitations of RCC for paving applications include its low water content, which makes RCC highly susceptible to evaporation of mix water during hot-weather construction (Harrington et al., 2010, p. 43). Because of the dryness of the RCC mixture, RCC is mixed at a production rate much lower than traditional PCC (Harrington et al., 2010, p. 10) slowing construction. Adjacent slabs/lanes must be constructed within an hour of each other to ensure proper bonding between the two (Harrington et al., 2010, p. 10). Thicker (greater than 8 inches [20 cm]) RCC must be placed in two or more lifts, with each successive lift being placed before the underlying lift has set, otherwise debonding between the lifts can occur. This requires well managed construction. Furthermore, specialized mixing equipment is needed in order to produce RCC consistently and at a high rate. RCC also requires the use of a high-density asphalt paver, which might not be available everywhere. RCC pavements cannot easily be constructed to a high degree of smoothness, making them inappropriate for use on high-speed facilities unless they are either diamond ground or overlaid with asphalt to improve the functional characteristics of the surface.

RCC mixtures have lower cement contents than traditional PCC mixes, which can reduce shrinkage-related cracking and permeability. Harrington et al. (2010) note that RCC has "excellent durability and resistance to chemical attack, even under freeze-thaw conditions" (p. 9), and CEMEX (2017) states that RCC can have improved "resistance [to] freeze-thaw damage". RCC pavements do not require the use of any air entrainment admixtures; it also does not require forms, reinforcing steel, or surface finishing (Zollinger, 2016, p. 4). Construction of RCC pavements is similar to that of asphalt pavements as both utilize the same equipment and follow similar steps.

According to the Portland Cement Association (2010), RCC-paved roads can be opened to light vehicular traffic "in as little as 4 hours after placement". This "ease and speed of construction" as well as the production methods and its lack of joints, dowels, and reinforcing steel can help RCC pavement projects realize cost savings, suggests the Portland Cement Association (2006). RCC pavement has demonstrated rut resistant and the ability withstand concentrated-load-related deformation (Portland Cement Association, 2010).

Although RCC is not currently considered a feasible alternative for high-speed pavement applications, it may fill a niche for rapid, economical concrete pavement construction for some applications including local roads and streets, access roads, frontage roads, shoulders, parking areas, and maintenance yards.

3.3.12 Self-consolidating Concrete Pavement

This is not an MDOT current practice.

The use of self-consolidating concrete (SCC) in pavement applications is an emerging technology and therefore, the research team recommends reviewing this practice again as more research becomes available.

Self-consolidating concrete (SCC) pavement uses a concrete mix that consolidates under its own weight (K. Wang et al., 2005, p. 9). It is made up of cementitious material (cement and SCMs such as slag cement or fly ash), aggregate, other additives, and supplementary cementitious material in proportions chosen specifically on account of the inverse relationship between shear rate and yield stress/viscosity; this design creates a concrete cement mix that flows easily and fills voids, so the paving process requires little or no mechanical vibration of the concrete (Pan, Tarefder, & Hossain, 2016; K. Wang et al., 2005, pp. 2, 10).

SCC for use in pavement applications has been evaluated as part of an FHWA Pooled Fund study, which included Iowa, New York, and Washington and dry-freeze states Kansas and Nebraska (Lomboy, Kejin, & Ouyang, 2011). As part of this study, two demonstration projects were constructed in Ames, Iowa: a bike path and a replacement of a deteriorated asphalt pavement on a low-volume road (Lomboy et al., 2011). Construction of both projects was performed with relative ease and both projects were experiencing good performance after several years (Lomboy et al., 2011). Research and field tests in Iowa and Wisconsin have also reported that three-year-old SCC pavement test sections had no evidence of shrinkage cracking (K. Wang et al., 2005, p. 107). However, laboratory testing performed by K. Wang et al. (2011) showed that SCC mixtures have a higher potential for shrinkage cracking than traditional PCC mixtures mainly because of a higher paste volume in the mixtures evaluated.

Unlike common SCC mix designs, the SCC used in slip-form paving would need to hold its shape once extruded from the paver. A high level of understanding is required by the mix designer to develop such a mix although a mix design procedure was developed as part of a pooled fund study. Researchers at the National Concrete Pavement Technology Center at Iowa State University (ISU) in collaboration with the Center for Advanced Cement-Based Materials at Northwestern

University found that SCC could be mixed in such a way that achieves both flow-ability and shape stability, thus making a slip-form SCC paving possible (K. Wang et al., 2005, pp. ii, 26).

SCC mixtures also have a higher material cost than traditional PCC paving mixtures because of the multiple admixtures that the mix requires. Only a few field trials have been performed within the United States and its use as a paving material is still not fully demonstrated.

Laboratory tests have shown that SCC mixtures had higher strengths, faster rate of strength gain, and used lower cement contents than traditional PCC paving mixes. The production and placement of SCC mixtures does not require any specialized batching or placement equipment. In fact, the use of SCC in slip-form paving can enable the removal of a paver’s internal vibrators and can eliminate the problem of over-consolidation of the concrete and its associated distresses, which have been attributed to a pavement’s lower freeze-thaw resistance. Self-consolidating concrete (SCC) paving has demonstrated some properties—specifically its ability to prevent shrinkage cracking, which make a pavement susceptible to water infiltration—that could make this innovation important for paving design in wet-freeze climates.

3.3.13 High-Performance Portland Cement Concrete

MDOT considers Grade P1M to be high-performance paving-grade concrete. HPC and UHPC are commonly used for structural applications.

High-performance concrete (HPC) and ultra-high-performance concrete (UHPC) are two different classifications of concrete materials. According to the American Concrete Institute (ACI), HPC is concrete meeting special combinations of performance and uniformity requirements that cannot always be achieved routinely using conventional constituents and normal mixing, placing, and curing practices. Kosmatka and Wilson (2016) provide a list of potential attributes for HPC including compressive strengths in the range of 8,000 to 20,000 psi (55.16 to 137.90 mpa). UHPC is a relatively new material, often proprietary such as Lafarge’s Ductal, that combines high-strength (up to 29,000 psi [199.95 mpa] compressive strength and 7,000 psi [48.26 mpa] flexural strength) and ductility achieved by combining high volumes of portland cement, silica fume, quartz flour, fine silica sand, high-range water-reducer, water, and steel and organic fibers (PCA http://www.cement.org/learn/concrete-technology/concrete-design-production/ultra-high-performance-concrete). Based on these definitions, HPC and UHPC are used almost exclusively in structural applications.

This being said, it is not uncommon for agencies to have a higher grade of paving concrete that they reserve for use for long-life pavements or for their most important pavement structures. For example, Minnesota has been using “HPC” since 2000 as the standard paving-grade concrete for most of the state’s high-volume urban highways. For example, I-35 in Minneapolis was constructed with HPC for the anticipates a 60-year design life in comparison to their normal paving-grade PCC that would have a 35-year design life (T. Burnham, Izevbekhai, & Rangaraju, 2006). MDOT considers the Grade P1M paving grade concrete to be "HPC" as it uses the optimized aggregate grading, higher quality aggregates, and higher SCM replacement levels that what are required for their conventional paving-grade concrete. In both the cases of Minnesota and Michigan, their HPC paving-grade concretes use higher quality aggregates, conventional cementitious materials, and conventional batching and paving operations.

UHPC has been used sparingly on a few bridges in Iowa, Michigan, New York, and Virginia; however, UHPC has been used extensively in Ontario on a number of bridges (Russell & Graybeal, 2013). To date, no example of UHPC applications for pavements has been found. As UHPC require unconventional materials and methods, it is expensive compared to conventional and HPC paving concrete. For UHPC to be feasible for pavement applications, the slab thickness would have to be significantly reduced in order to reduce the amount of UHPC used and it would have to have exceptional long-term performance to make a project cost-effective. As it is a relatively new material, no long-term performance data for UHPC is available.

Composite Pavement

3.3.14 Bonded Concrete Overlay of Asphalt (BCOA)

This is *not* an MDOT current practice. The research team recommends reviewing this practice and consider implementing.

While concrete overlays have long been a rehabilitation method for fatigued pavements, recent research on the nature of the bond that can be created between concrete and asphalt has allowed for implementation of thinner, short-jointed concrete overlays of asphalt. Many wet-freeze states have adopted bonded concrete overlays of asphalt (BCOA) as an acceptable means to resurface asphalt pavement. Currently, based on the National Concrete Overlay Explorer, over 640 BCOAs are currently in place in the United States with most of these being concentrated in the wet-freeze states of Minnesota, Michigan, Wisconsin, Iowa, Illinois, and Indiana (see Figure 9).

BCOAs typically have thickness of 4 to 6 inches (10 to 15 cm), although BCOAs as thin as 2 inches (5 cm) have been tried ((Yu & Tayabji, 2007, p. 1). Thinner BCOA are an excellent choice for urban streets, particularly to address localized areas suffering from rutting or shoving due to slow moving channelized traffic such as intersections. Thicker BCOAs (6 inches [15 cm] thick) have been used effectively on interstate pavements in Colorado and Kansas with a 6 foot by 6 foot (1.8 m by 1.8 m) joint configuration. This design is being adopted in other locations and is likely to become a standard rehabilitation design.

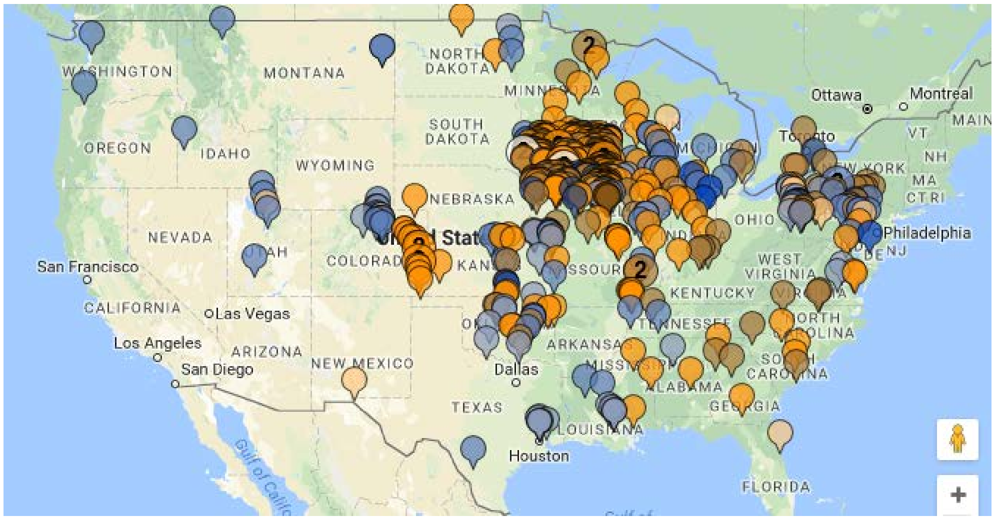


Figure 9: Map showing locations of BCOAs reproduced from American Concrete Pavement Association National Concrete Overlay Explorer (American Concrete Pavement Association, 2017)

A number of design methods have been developed, the most popular of which is the BCOA-ME procedure from the University of Pittsburgh.[2] Recently, a BCOA design procedure has been added to the AASHTOWare Pavement ME Design software. A series of experiments completed at MnROAD contributed to the calibration of these design procedure (Harrington & Fick, 2014). Yet, the need to calibrate design procedures for local climates or roadway conditions limits confidence in the BCOA design procedures (Harrington & Fick, 2014, pp. 6-7).

At least 3 inches (7.6 cm) of the existing asphalt pavement must be available and it must be brought into "good condition" through the use of spot repairs or milling and minor spot repairs for a BCOA to be a feasible alternative (Harrington & Fick, 2014, pp. 6-7). Construction of a concrete overlay also requires an understanding of the in-place pavement design, such as thickness and strength; this understanding could require coring, falling-weight deflectometer testing, and finding and reviewing historic project information (Harrington & Fick, 2014, pp. 6-7). BCOA can experience premature failure if the top 3-inch (7.6-cm) asphalt layer experiences stripping; to avoid this, the asphalt layer and subgrade drainage should be assessed (Harrington & Fick, 2014, pp. 27-28).

BCOAs have been successfully used in wet-freeze states. The most promising feature of a BCOA is the reduced amount of concrete needed for this rehabilitation technique (Harrington & Fick, 2014, p. 3). Since the structural integrity of the existing pavement is considered in design calculations, bonded concrete overlay only needs a minimal thickness in order to restore the functional properties (e.g., smoothness and friction) of the pavement (Harrington & Fick, 2014, p.

[2] The bonded concrete overlay of asphalt mechanistic-empirical design procedure (BCOA-ME) web site: http://www.engineering.pitt.edu/Vandenbossche/BCOA-ME/

3). Examples of Michigan BCOA projects include the left-turn lane between Ann Arbor-Saline Road and Pleasant Lake Road in Washtenaw Country in 1997, Wealthy Street in Grand Rapids in 2001, and Main Street in Capac City in 2007 (Waalkes, 2008).

3.3.15 Unbonded Concrete Overlay on Asphalt Pavement (UBCOA)

This is *not* an MDOT current practice.

Using relatively thick PCC (typically greater than 6 inches [15 cm]) to overlay an existing HMA is a technique known as white topping. It is regarded as a rehabilitation technique for renewing asphalt pavements that are too deteriorated to be treated with a BCOA. In UBCOA design, the existing asphalt pavement is treated as a base for the new concrete pavement. The existing pavement is expected to provide uniform stable support, but is not expected to contribute structurally to the to the concrete overlay through composite action as it is in BCOA design (Harrington & Fick, 2014, pp. 28-29).

UBCOA has been successfully implemented on interstates, highways, state roads, secondary roads, intersections, and airport pavements. The American Concrete Pavement Association National Concrete Overlay Explorer list 430 UBCOA in its database, most of which are located in the upper Midwest (http://overlays.acpa.org/webapps/overlayexplorer/index.html). These projects have spanned such states as Minnesota, Iowa, Illinois, Wisconsin, and Indiana. UBCOA is not currently considered a best practice by MDOT.

UBCOA can be appropriate for asphalt pavements having significant distress such as severe rutting, potholes, alligator cracking, subgrade/subbase issues, shoving and pumping (Harrington and Fick 2014, p. 38). Milling should be conducted to remove surface distortions greater than 2 inches (5 cm) in depth and full-depth repairs should be conducted at isolated locations where the asphalt pavement has lost its structural integrity. One limitation is that the asphalt pavement should not be stripping.

Adding a relatively thick (greater than 6 inches [15 cm]) concrete pavement overlay is similar to constructing a new concrete pavement on a stabilized base, and is expected to yield similar, long-life performance.

3.3.16 Unbonded Concrete Overlay of Concrete (UBCOC)

This is an MDOT current practice.

Unbonded concrete overlays (UBCO) are a suitable rehabilitation strategy for deteriorated concrete and HMA pavements (Harrington & Fick, 2014). They are designed to act independently from the underlying old pavement layer, treating the existing pavement as a base for the new overlay. The behavior of the underlying pavement is somewhat isolated from that of the overlay through the use of a separation layer, commonly a thin asphalt layer (the strategy most commonly used in Michigan) or more recently, a thick, nonwoven geotextile. Thus the reason for being referred to as "unbonded", even though in truth some bonding occurs if the concrete is placed directly on an existing asphalt pavement or an asphalt separation layer is used between the existing pavement and the overlay. This type of concrete overlay is typically more costly to construct than and BCOA due to its thicker layer of concrete, but is considerably less expensive than a pavement reconstruction.

The benefits of a UBCO in a wet-freeze climate include additional pavement thickness, moving the riding surface further above grade and potentially frost susceptible soils. Construction is expedited in comparison to removal and reconstruction, allowing more paving to occur within a shortened construction season. And by working on top of an existing pavement, many of the issue of constructing in poor soils can be avoided, although it is noted that drainage issues that may exist must be corrected to avoid moisture damage in the new pavement. MDOT has constructed a number of UBCO throughout the course of over 30 years and is recognized as a national leader in their use.

3.3.17 Asphalt over New Concrete Pavement

This is not an MDOT current practice.

A high-quality, relatively thin (1 to 4 inch [2.5 to 10 cm]) asphalt concrete surface (typically hot mix) can offer "excellent surface characteristics (low noise; very smooth, non-polishing aggregates; and durability) that can be rapidly renewed and [have] long-lasting structural capacity for any level of truck traffic" (Rao et al., 2013a). Such asphalt concrete surfaces are commonly applied as an overlay for a rehabilitated concrete pavement, thus producing a composite pavement; however, newly constructed composite pavements that have an RCC structural base have been used in Columbus, Ohio, and Quebec, Canada (N. J. Delatte, 2008, p. 197).

Asphalt concrete as a surfacing for concrete pavement often uses "dense HMA, stone matrix asphalt (SMA), porous HMA, asphalt rubber friction course (ARFC), or Novachip® gap-graded asphalt rubber hot mix" (see Figure 10) (Rao et al., 2013a, p. 1). Constructing a good composite pavement of this type relies on the proper preparation of the sublayers; the placement of the PCC layer and tied shoulders; the texturing, curing, saw-cutting of joints of the PCC layer; the application of sufficient tack coat; the proper placement of the asphalt concrete layer; and the finishing (placement of shoulders, sawing joints, and sealing joints) (Rao et al., 2013a, p. 122).

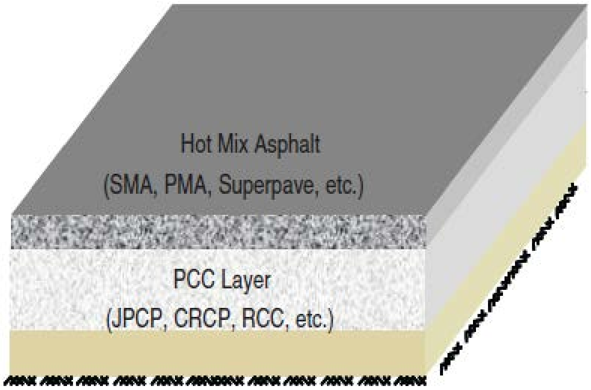


Figure 10: Cross section of asphalt-surfaced composite pavement (Rao et al., 2013a, p. 15)

In 2013, HMA/PCC pavement variations have been used in Illinois, Minnesota, New York, Ohio, and Virginia as well as locations in Arizona, Ontario, Germany, and the Netherlands—all of which have wet-freeze climates similar to Michigan—according to Rao et al. (2013a) (see Figures 11 and 12) (p. 23). Amongst these locations, there are 24 test sections of asphalt-surfaced composite pavements in wet-freeze climates Arizona—20 instances are HMA/JPC, one is HMA/RCC, and three are HMA/CRC.

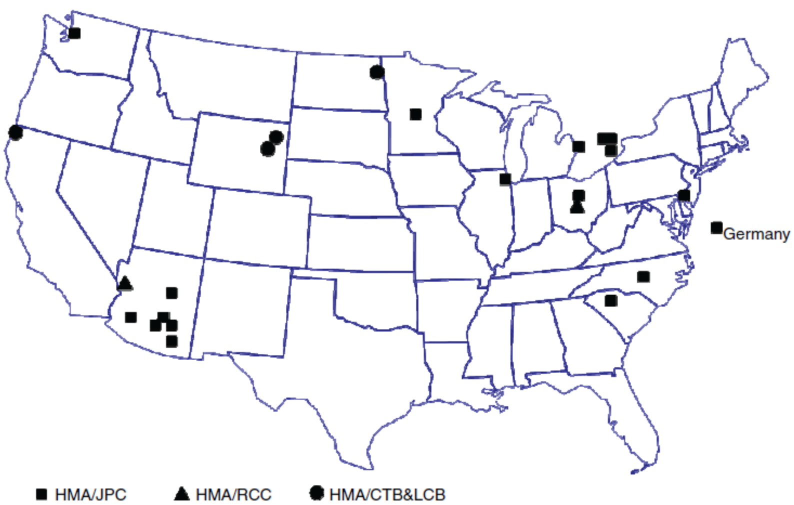


Figure 11: Map showing the locations of HMA/JPC, HMA/CTB and LCB, and HMA/RCC composite pavements (Rao et al., 2013a, p. 23)

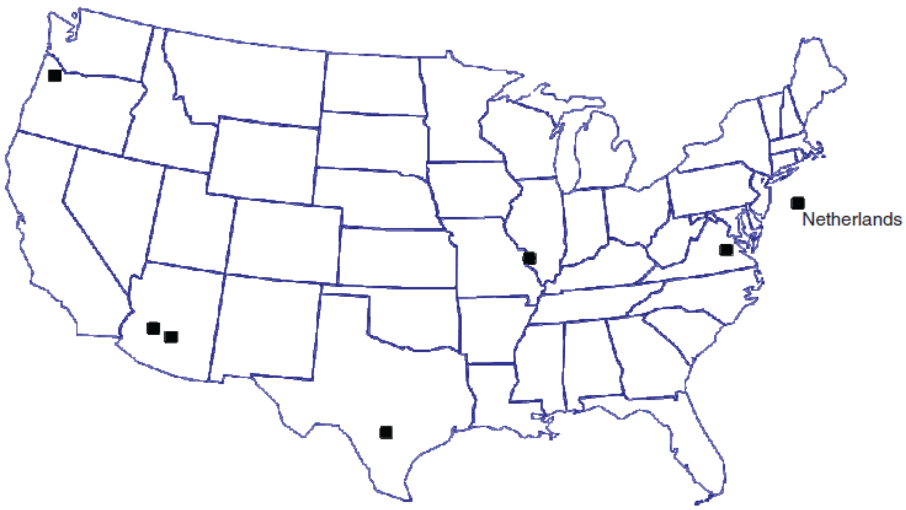


Figure 12: Map showing the locations of HMA/CRC composite pavements (Rao et al., 2013a)

The test sections that were analyzed for the study experience heavy truck traffic and severe weather conditions. Two HMA/JPC test sections on Minnesota's I-94 exhibited diverse results: one of the sections had no transverse fatigue cracking and low to moderate reflective cracking along the transverse joints after one year, while the other section had up to 45% transverse cracking (it was predicted to have 52% transverse fatigue cracking) and had structurally failed within two years (Rao et al., 2013a, pp. 98-100). Almost all sections in Illinois, New York, Ohio, Ontario, and Germany that were paved with HMA/JPC and HMA/RCC had no transverse cracking, which aligned closely with the service life predictions (Rao et al., 2013a, pp. 98-100). Similarly, test sections in Illinois, Virginia, and the Netherlands that used HMA/CRC composite pavements exhibited no reflective cracking while they were being assessed, a period that ranged from 5 to 13 years (Rao et al., 2013a, p. 104). Thus, HMA/JPC, HMA/RCC, and HMA/CRC composite pavements have exhibited promising results in wet-freeze climates.

In Michigan, asphalt-over-concrete composite pavements is primarily used as a low-cost, stop-gap measure to improve ride quality and delay moisture damage to old concrete pavement until funding is available to perform substantial rehabilitation or reconstruction of the old concrete pavement.

For asphalt-over-concrete composite pavements, reflective cracking is a common distress (note that one innovation that has been successfully addressing reflective cracking in Michigan is the Texas underseal—see section 3.6.16). Significant reflective cracking requires maintenance and sometimes rehabilitation; if jointed plain concrete was used, joints need to be properly sawed and sealed (Rao et al., 2013a, pp. 17, 129).

Adding a thin asphalt surface to a concrete pavement can be a cost-effective use of higher-quality surfacing materials (Rao et al., 2013a, p. 8). A high-quality asphalt surface can effectively reduce road noise, enhance friction, and improve ride quality (Rao et al., 2013a, p. 127). It may also decrease negative temperature gradients or absorb excessive tensile stresses that can lead to cracking (Rao et al., 2013a, p. 106). Further, if continuously-reinforced concrete was used under the asphalt surface, it can achieve a longer service life due to continuously-reinforced concrete's ability to minimize crack movement, thus delaying reflective cracking (Rao et al., 2013a, p. 129). Finally, if an asphalt surface needs replacing, it can be done rapidly; this is typically necessary every 10 to 20 years (Rao et al., 2013a, p. 129).

3.4 MATERIALS

Subgrade

3.4.1 Subgrade Stabilizer

This is not an MDOT current practice, even though MDOT has several projects; however, it is a current best practice for some agencies outside of MDOT. The research team recommends reviewing this practice and consider implementing.

MDOT mainly uses the undercutting process to deal with weak soils. MDOT currently has two projects using subgrade stabilization and a third project is going in 2018. MDOT has performed lime stabilization for some projects. In addition, MDOT has conducted research project (RC-1635) to use recycled materials for stabilizing subgrade. The selected recycled materials are available in large quantities within Michigan, which included cement kiln dust, lime kiln dust, fly ash and concrete fines. It is found that cement kiln dust and mixture of lime kiln dust and fly ash at rates of between 4 to 12 percent were considered as feasible long-term stabilizers.

Stabilized subgrade can improve soil behavior during and after pavement construction. There are serval subgrade stabilizers such as (TJ Van Dam et al., 2015, p. 3.66: FHWA FHWA-HIF-15-002):

- Lime -- Lime stabilization dramatically changes the features of a soil to provide long-term permanent strength and pavement structure. In this stabilization, lime in the form of quicklime (calcium oxide), hydrated lime (calcium hydroxide), lime slurry (a suspension of hydrated lime in water), or byproducts of the lime manufacturing process (such as lime kiln dust) can be used to treat soil. Lime stabilization has been very common used on stabilizing clay soils. It has been widely used in Illinois and Texas.

- Fly ash -- Fly ash is a common used subgrade stabilizer. Attention must be paid to avoid swelling resulting from the expansion of sulfate minerals. Additional information on the use of fly ash for subgrade stabilization can be found at: http://www.fhwa.dot.gov/pavement/recycling/fach07.cfm

- Portland cement -- Portland cement “can be used to stabilize both fine-grained plastic, non-plastic, and granular materials”.

- Asphalt stabilizers -- Asphalt can be used to stabilize non-plastic granular materials.

- Geo-grid stabilization -- Geo-grid can be used to improve the stiffness and shear strength of granular soils layers, especially when placed on soft subgrades.

Base

Base course is a layer of selected materials used to provide a uniform and stable support for the surface course. The selected materials can be aggregate, reclaimed HMA, asphalt treated materials, and cement-treated materials.

3.4.2 HMA Base Crushing and Shaping

This is an MDOT current practice.

HMA base crushing and shaping creates a new base course by pulverizing the entire base layer. HMA base crushing and shaping can result in an enhanced pavement structure; however, HMA base crushing and shaping does not perform well in areas with drainage problems.

3.4.3 Permeable Base

The use of permeable bases, especially in concrete pavement designs, is a practice that MDOT has used in the past and will continue to use in the future due to reported good performance.

Permeable bases including unbound granular permeable base, asphalt-treated permeable base (ATPB), and cement-treated permeable base (CTPB) function by using an aggregate gradation that purposefully provides sufficient void space to permit water to flow through the base and into an engineered underdrain system. A permeable base must have a properly engineered particle size distribution (gradation) to obtain an acceptable level of drainage while still providing the necessary stability to perform (without deformation or breakdown) during construction and while in service. ATPB and CTPB have also been used, in which the open-graded aggregate is bound either asphalt or cement binder, respectively.

ATPB is contained in the specifications of the Minnesota DOT (Section 2363), Pennsylvania DOT (Section 360), and the Ministry of Transportation of Ontario (OPSS.PROV 320) (Ministry of Transportation of Ontario, n.d.; Minnesota Department of Transportation, 2017b; Pennsylvania Department of Transportation, 2016). In addition, trial sections in Vermont have shown that ATPB proved "more effective in reducing fatigue, equally effective in reducing transverse cracking and comparable in ride quality in the ensuing decade after construction" (Kipp, Walters, & Ahearn, 2013, p. 11). CTPB is contained in the specification of the Pennsylvania DOT (Section 303).

Although very early generation unbound aggregate bases (referred to as open-grade drainage course or OGDC by MDOT) developed by MDOT represented a particle size distribution that was highly permeable (over 2000 ft/day), these bases were shown, over time, to be quite unstable relative to their in-service support characteristics and, therefore, lead to pavement performance issues. This was due to incompatibility between the OGDC and the underlying sand subbase, which led to intermixing of the two pavement layers. This was more evident in instances when an adequate separation layer was not installed. MDOT modified the aggregate gradations, which improved stability but lowered permeability. As an alternative, MDOT has used of ATPB and CTPB on around 15 projects that are considered some of the best performing concrete pavements in their network. MDOT is planning to construct three stabilized base projects in 2018, including two long life pavements and one $80 million reconstruction project of I-696. The research team recommends developing the use of stabilized permeable bases as a standard practice and monitoring the long-term effects of permeable bases.

3.4.4 Semi-Rigid Base

This is not an MDOT current practice.

It has been widely used in wet-freeze and all other climate regions in China for decades; therefore, the research team recommends conducting research on the cost and performance of semi-rigid base in Michigan.

Asphalt pavement on a semi rigid base has been a dominant pavement structure used in China in the past a few decades. The semi rigid base layers constructed with cement-treated base (CTB) or cement-stabilized base (CSB) in wet-freeze and all other climate regions in China (Zheng, 2012). This base performs satisfactorily under high traffic volume and heavy truck loads. The strength of semi-rigid base material can be mixed with a broad range of cement content from 4 percent to 10 percent by weight according to treated (stabilized) materials and the requirement of pavement structure (Sha, 2008). This type of design has not been widely used in the United States, even though such base will resist heavier traffic loads. It may be beneficial for MDOT to study such a pavement structure.

3.4.5 Geotextile Separators

This is an MDOT current practice.

Geosynthetics are synthetic materials that are used on or beneath surface soil to perform a geotechnical function. Multiple studies have concluded that soils reinforced with geosynthetic materials exhibit stronger properties than identical unreinforced soils, both in normal conditions and when subjected to freeze-thaw cycles (Ghazavi & Roustaei, 2013; Gray, ASCE, & Ohashi, 1983; Zaimoglu, Calik, Akbulut, & Yetimoglu, 2016). Experimentation with geosynthetics began in the 1950s and, since the 1970s, they have been in widespread use nationally as well as internationally (Anderson & Gesford, 2007). Illinois DOT has conducted a study on geotextiles; refer to Heckel (2009). In Michigan, state and local road-owning agencies have used geosynthetic materials for drainage as well as for filtration, reinforcement, and separation (Kern & Torola, 2015, p. 4). Because geosynthetics can provide benefits such as “separation, filtration, reinforcement, stiffening, drainage, barrier, and protection”, geosynthetics can be used to reduce reflective cracking, to stabilize both pavement bases and soft subgrades, and for lateral drainage (Zornberg, 2017, p. abstract). These latter two applications offer a significant benefit for pavements in wet-freeze climates that often encounter differential soils and water retention in the pavement structure.

Plant-produced Hot-mix Asphalt

3.4.6 Conventional Hot-mix Asphalt

This is an MDOT current practice.

Hot-mix asphalt (HMA) is a type of asphalt pavement construction that is widely used and not exclusive to wet-freeze climates. HMA is asphalt binder that is heated and then mixed with heated, dense-graded aggregates; the resulting mixture is 275 to 329 °F (135 to 165 °C). HMA is well suited for the structural layer of an asphalt pavement as well as the surface layer of asphalt or composite pavements (T. J. Van Dam et al., 2015, p. 3.18). However, HMA experiences decreased stiffness and fatigue when subjected to multiple freeze-thaw cycles (Barlas, 2013, p. vi). Like other states, MDOT has various guidance documents on HMA mixture requirements, such as minimum and maximum specifications for crushed aggregate, fine aggregate angularity, sand equivalent, Los Angeles (LA) abrasion, soft particles, and flat particles and elongated particles, Superpave™ mix design, voids filled with asphalt (VFA), Superpave™ Gyratory Compactor (SGC) compaction, and aggregate gradation (Michigan Department of Transportation, 2007). This is a best practice that is not unique to wet-freeze climates.

3.4.7 Warm-mix Asphalt

This is an MDOT current practice.

Warm-mix asphalt (WMA) is a construction technique that could extend the paving season window under low-temperature construction. Many different products can be used to create WMA with the purpose of decreasing the construction temperature of asphalt pavements by around 25 to 80 °F (14 to 25 °C). The variability of this temperature reduction depends on such things like “mix, plant, climate, lift thickness, and hauling distance” (T. J. Van Dam et al., 2015, p. 3.18). There are three categories of WMA technologies: chemical additives or surfactants, non-foaming additives, and foaming processes that use water. Some technologies use combinations of the other categories (Prowell, Hurley, & Frank, 2012):

- A few in the chemical additives or surfactants category include Cecabase RT, Evotherm™, HyperTherm/QualiTherm, and Rediset. The Cecabase RT additive is a water-free surfactant that has been used worldwide for over 2.0 million tons of WMA since 2004. The Evotherm™ additive is an asphalt emulsion product that enhances coating, adhesion, and workability; it has been used to produce approximately 7.5 million tons of WMA. The HyperTherm/QualiTherm additive is a "non-aqueous, fatty-acid based chemical." The Rediset additive merges "cationic surface-active agents and rheology modifiers" (Prowell et al., 2012).

- A few in the non-foaming additives category can include BituTech PER, LEADCAP, SonneWarmix, Thiopave, and Sasobit®. The BituTech PER additive is a U.S. product that is used for high-RAP or RAS mixes. The LEADCAP additive is "wax-based" and has a "crystal controller and adhesion promoter." The SonneWarmix additive is a "high melt point, paraffinic hydrocarbon bend (wax)" that has been used on several projects in Maine and Massachusetts. The Thiopave® additive includes sulfur in its composition and has been used worldwide to modify approximately 450,000 tons of mix. Sasobit® is a synthetic paraffin wax using the Fisher-Tropsch method, which has been used for approximately 3.0 million tons of WMA in North America (Prowell et al., 2012).

  Sulfur-extended asphalt is the use of sulfur to replace, in part, the asphalt binder and to increase the stiffness of the mixture (Shiraz Tayabji, Kurt D Smith, & Thomas Van Dam, 2010). The Shell Thiopave® additive is a commercial sulfur modifier that improves the performance of asphalt mixtures. The experimental tests of laboratory mixtures have shown that the Thiopave®-modified asphalt mixture can "significantly increase the Marshall Stability and deformation resistance of asphalt mixtures in the laboratory after a 2-week curing period" (Shiraz Tayabji et al., 2010, p. 29). The Thiopave®-modified asphalt has been field tested in Canada. Sulfur-extended asphalt is an emerging technology. Harmful levels of hydrogen sulfide and sulfer dioxide have been known to occur at elevated temperatures; therefore, future recycling of sulfur-extended pavement should be performed at reduced temperatures (Prowell et al., 2012). More research work on the performance of sulfur-extended asphalt in wet-freeze climates is needed.

  Sasobit® has various applications in many countries including some countries with wet-freeze climates, such as the United States, Canada, Russia, Norway, Sweden, and Switzerland (Jamshidi, Hamzah, & You, 2013). In the United States, several states in wet-freeze climates have made use of Sasobit® mixed with WMA. In Virginia, two trial sections were built in 2006. It was found that Sasobit®-WMA mixture and HMA perform similarly during the first two service years. According to a study by Hurley, Prowell, and Kvasnak (2010), Missouri used 2,100 tons of Sasobit®-WMA mixture in during a 10-day road construction porject. Their HMA sections had approximately 0.02 inches (0.45 mm) of rutting while the Sasobit®-WMA mixtures had 0.03 inches (0.8 mm) of rutting. Over a 20-month period following the paving, the Missouri study found that Sasobit®-WMA stayed at a constant 0.03 inches (0.8 mm) of rutting while the HMA increased from 0.015 inches (0.4 mm) to 0.02 inches (0.5 mm); nonetheless, Hurley et al. (2010) did not decisively declare either material as superior (p. 16). Similarly, a Wisconsin field investigation found the Sasobit®-WMA mixtures have less than 0.04 inches (1 mm) of rut depth after four months. In Canada, the MTO conducted a trial project to evaluate the performance of Sasobit®-WMA mixture in 2007. It was reported that no fumes were observed when paving with the mixture, that the compaction process was successful, and that fuel use was reduced by 30%. These results have motivated Canada to use more Sasobit®-WMA mixture (Aurilio, 2009).

- During the foaming process, the water turns into steam, spreads throughout the asphalt, and enlarges the binder, resulting in a temporary increase of the binder phase of around 5 to 10 times. This increase of fluids content improves coating and compaction. A few but not limited to the foaming process category can include Advera WMA, AQUABlack WMA System, and Astec Green Systems. The Advera WMA is a synthetic zeolite that can provide a controlled and prolonged foaming effect; it has been used to produce over 1 million tons of WMA in the United States since 2006 (Prowell et al., 2012, p. 17). The AQUABlack WMA System uses "uses a patented, stainless-steel foaming gun in conjunction with a center convergence nozzle to produce foaming"; around 250 AQUABlack units are operated at drum plants and around 25 units are on batch plants (Prowell et al., 2012, p. 19). The Astec Green Systems "use a multi-nozzle device to microscopically foam the asphalt binder with water"; to date, 453 Astec warm mix systems have been installed around the world (Prowell et al., 2012).

  Foaming additives that use water usually have the lowest cost per ton, at around $0.08/ton; incorporating other warm-mix additives reportedly adds between $2.00 to 3.50 per ton to the mixture costs (West et al., 2014).

WMA has been evaluated and is being increasing used by several agencies in the United States (see Figure 13, data from (Hansen & Copeland, 2015)). NCHRP Project 9-49A assessed the long-term field performance of several WMA technologies. There were 28 WMA projects selected for the study, including 10 WMA projects in wet-freeze climates(Washington State University, 2017, pp. 8-9) . It concluded that HMA and WMA pavements have similar performance at a service life between 4 and 10 years (Washington State University, 2017, p. 47). A study on a demonstration project in Iron Mountain, Michigan determined that the advantages of WMA included lengthening truck haul distances, emission reduction, an extended paving window due to a longer cooling time, and fewer associated health concerns for road crews (Goh & You, 2009, pp. 292-295; Shiraz Tayabji et al., 2010, p. 34). It was found that WMA may be workable—or compactable—for as much as 27 minutes longer than HMA (Goh & You, 2009).

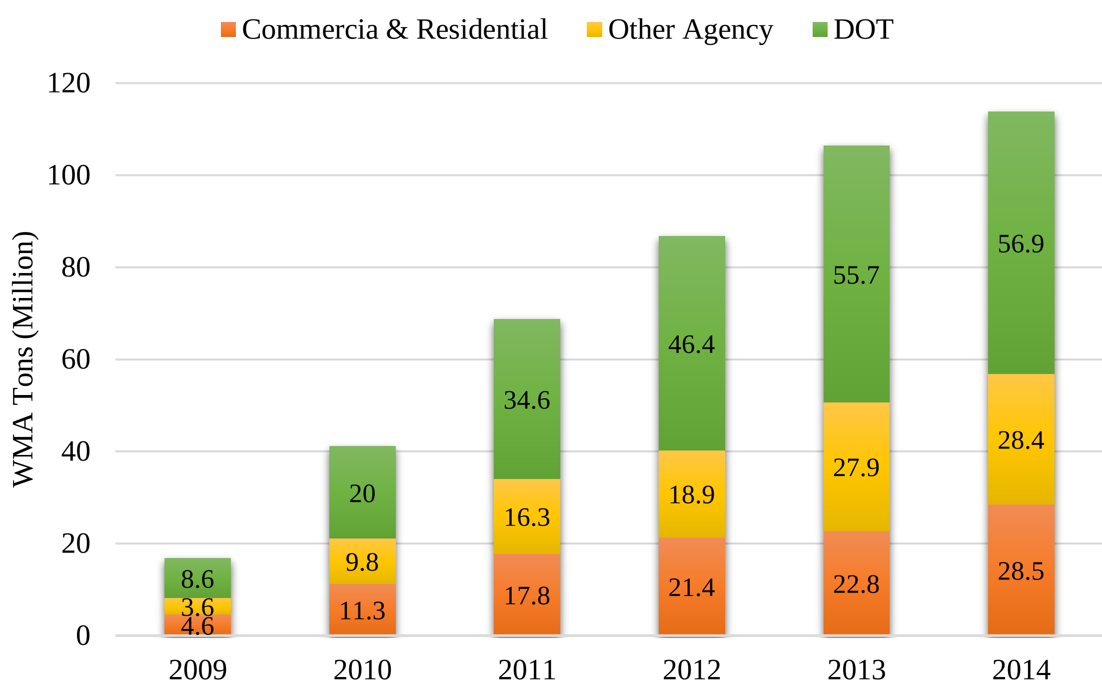


Figure 13 Estimated tons of WMA usage by industry sector 2009-2014 in the United States

WMA's main drawback is its vulnerability to rutting and moisture retention (Kristjansdottir, 2006, p. 80). However, WMA may be beneficial in wet-freeze climates for its extended paving window. A study by Kristjansdottir (2006) showed that WMA can have better results for cold-weather paving when WMA processes are used with regular HMA production temperatures (p. 81). In addition, a WMA field trial on M-95 in Iron Mountain, Michigan, in 2006 found that Sasobit® WMA was successfully paved and compacted at temperatures that were 50°F (28°C) less than the HMA test section (Hurley, Prowell, & Kvasnak, 2009, p. 19). Furthermore, adding anti-stripping agents to WMA reduces a WMA pavement's vulnerability to moisture retention and rutting, helping it to meet state and Federal requirements (Kristjansdottir, 2006, p. 81). The recent NCHRP report surmised that the addition of anti-stripping agents can likely alleviate the potential for moisture susceptibility of WMA pavement (Martin et al., 2014, p. 2). For more information on anti-stripping agents (see section 3.4.8). To control the temperature when placing WMA, MDOT has temperature limits for when the water-foaming method can be used or when a chemical additive can be used (Michigan Department of Transportation, 2016f). In wet-freeze environments, compaction, moisture susceptibility, and binder grade may play critical roles in a wet-freeze environment during the paving process. WMA is itself an innovative outgrowth of HMA; since it is still in various stages of experimentation, WMA's innovative applications require more experimentation and field trials.

3.4.8 Anti-stripping Agents

This is an MDOT current practice.

Anti-stripping agents help prevent asphalt binder from stripping off aggregate particles in hot-mix asphalt pavement production and can also help with the warm-mix asphalt pavement construction. Anti-stripping agents are usually classified into two groups—slurries and liquids. Slurries often make use of hydrated lime, which is calcium oxide, that has been hydrated with water (D. Watson, Moore, & Taylor, 2012, p. 10). Liquids are surfactants that modify asphalt by enabling "the asphalt to coat the aggregate surface more evenly by reducing surface tension" while also "displac[ing] adsorbed water on or near the aggregate surface" (D. Watson et al., 2012, pp. 7-8). The tensile strength ratio (TSR) test is the standard test for evaluating moisture susceptibility of asphalt mixture. According to AASHTO T 283, the threshold for TSR is a minimum of 80 %. The Hamburg wheel-track testing (HWTT) test is an alternative for evaluating moisture susceptibility, but there are no national HWTT threshold specifications; in a study by Martin et al. (2014), Iowa—which is a wet-freeze state—uses the HWTT with a focus on moisture susceptibility, so its HWTT specifications are a water temperature of 122 °F (50°C) and a minimum stripping inflection point (SIP) of 10,000 or 14,000 loading cycles depending upon the equivalent single axle loads (Martin et al., 2014, p. 23).

Anti-stripping agents can help with the warm-mix asphalt construction method. In a national survey conducted by Colorado DOT, Michigan and its two neighboring states—Minnesota and Wisconsin—make use of liquid anti-stripping agents to improve the moisture resistance of HMA mixtures (R. Gary Hicks, Santucci, & Aschenbrener, 2013, p. 69).

3.4.9 PPA Extenders

This is *not* an MDOT current practice.

See *Polyphosphoric Acid* in *Polymer-modified Binder* in section 3.4.31 for a discussion on a PPA extender.

3.4.10 Half Warm-mix Asphalt

This is *not* an MDOT current practice. It is still an emerging technology; therefore, the research team recommends reviewing this practice again as more research becomes available.

As with standard WMA, the lower paving temperature of half warm-mix asphalt (HWMA) gives it a longer paving season window than HMA; this is a useful attribute in dry- and wet-freeze climates. HWMA is normally manufactured at a temperature less than 212°F (100°C), usually in the range of 158-203°F (70-95°C). The common method of producing HWMA is to heat aggregates up to 194-203°F (90-95°C) and then mix them with emulsions around 140-149°F (60-65°C) in temperature (del Carmen Rubio, Moreno, Martínez-Echevarría, Martínez, & Vázquez, 2013, pp. 1-2). No published evidence of HWMA use in Michigan could be found, and very little research on the mechanical performance of HWMA (del Carmen Rubio et al., 2013, p. 5).

In comparison to WMA, HWMA has reduced greenhouse gas emissions and similar non-point source emissions (del Carmen Rubio et al., 2013, p. 5). Half warm-mix asphalt (HWMA) is newer type of asphalt construction with only limited research available, and studies on innovations of this process have yet to be published.

3.4.11 Cold-mix Asphalt

This is *not* an MDOT current practice; and, the research team considers this technology not viable or practical in Michigan's wet-freeze climate at this time (it is included in this report for completeness).

Cold-mix asphalt (CMA) is not a good performer when compared to HMA or WMA; it also requires warm weather with no rainfall for the duration of its curing, complicating its applicability in wet-freeze climates. However, CMA can be produced at temperatures less than 60°C (140°F), which greatly reduces the amount of energy required to produce it. CMA has been used for rehabilitating low-volume roads (del Carmen Rubio et al., 2013, pp. 1-2). Innovative research into CMA has included mixing natural and synthetic fibers into the asphalt, which has had results that suggest these additions can increase in the pavement service life (Shanbara, Ruddock, & Atherton, 2017). Laboratory investigations have also been made into the performance of CMA that has been mixed with fine millings from reclaimed asphalt pavement; in those test, pavement performance was acceptable (Barzegari, Stoffels, & Solaimian, 2017).

3.4.12 Reclaimed Asphalt Pavement

This is an MDOT current practice.

Reclaimed asphalt pavement (RAP) describes the material commonly removed from resurfacing, rehabilitation, or reconstruction operations of existing asphalt pavement materials. RAP is used for economic and environmental reasons, and it offers the benefit of lessening the amount of virgin material required for pavement construction (Copeland & Federal Highway Administration, 2011).

In Japan, asphalt mixture has been recycled since 1970s and RAP has been recommended by law since 2000 (Kubo & Leader, 2014). Because Japan is a dense-populated country with limited space for large disposal of waste. Plant recycling is the most popular recycling method with two technical highlights which are rejuvenator and secondary drier. Rejuvenator can modify aged asphalt binder by softening it. The secondary drier technique is two dryers for heating aggregates, one for heating virgin aggregate and the other one for heating recycled aggregate. This technique improves the ratio of recycled aggregate.

3.4.13 Recycled Asphalt Shingles

This is an MDOT current practice.

The use of recycled asphalt shingles (RAS) comes from both manufacturers' waste and tear-off scrap shingles. RAS is used for economic and environmental reasons, and it offers the benefit of lessening the amount of virgin binder required for pavement construction.

Some states in the wet-freeze climates have been using RAS in asphalt mixture since 2009. For example, the Illinois Department of Transportation (IDOT) has been adding RAS in asphalt mixture since 2010. Illinois Public Act 097-0314 became effective in January 2012. It aimed to the use of RAS as a pavement materials, which can promote environmental control while reduce project costs (Lippert & Brownlee, 2012).

The MDOT permits that up to 17 percent RAS by weight of total binder as cited in its special provision (12SP-501G), titled Special Provision for Recycled Hot Mix Asphalt and Recycled Asphalt Shingles in Superpave Mixtures.

To increase the usage of the RAS, there are obstacles to overcome, including lack of documented performance, lack of material specification, lack of practice experience, and additional tests when using tear-offs RAS (Stroup-Gardiner & Wattenberg-Komas, 2013a).

3.4.14 Recycled Tire Rubber Modified Asphalt

This is a MDOT allowable practice, but it has not been widely used.

Crumb rubber—primarily from recycled tires—can be used to modify asphalt, thus creating a crumb rubber modified asphalt (CRMA). According to Papagiannakis and Lougheed (1995, pp. 2-3), crumb rubber is composed of three main ingredients—natural rubber, synthetic rubber, and carbon black (a byproduct of incomplete combustion of petroleum products)—that provide elasticity, thermal stability, and durability respectively. CRMA can be used in structural-layer asphalt, surface-layer asphalt, and even chip seals. There are different methods of adding crumb rubber into asphalt mixtures. In the dry process, crumb rubber is added to the aggregate before mixing with asphalt binder, while in the wet process, the crumb rubber is added to the asphalt binder before mixing with aggregate. It seems like a little different between the two processes, but the selected process dramatically affects the interaction between the crumb rubber and asphalt binder resulting in a significant difference on the final product. Due to construction and performance issue, the dry process has limited usage, and therefore, the focus is on the wet process.

There are currently two kinds of wet-process crumb rubber modified asphalt used in asphalt pavement in the wet-freeze climates zone of the United States. Field blend is crumb rubber particles blended with asphalt at a hot-mix plant (Hicks, Cheng, & Duffy, 2010, p. 54). As opposed to field blend, terminal blend CRMA incorporates the crumb rubber into the binder at a refinery or terminal before being shipped to the hot-mix plant (Hicks et al., 2010, p. 54). This technique, which uses a finer size of crumb, makes CRMA similar to other types of polymer-modified asphalt (Hicks et al., 2010, p. 54).

In wet-freeze climate, New Jersey DOT uses rubberized asphalt in Open Graded Friction Course (OGFC). They experienced the longevity of the OGFC and a reduction of wet weather accident and noise with OGFC. Pennsylvania DOT constructed a demonstration seal coat project in 2007 and the project is appeared to provide good performance with minimal stone loss. In addition, Pennsylvania DOT considers rubberized asphalt is very fit for gap-graded or OGFC mixtures. The MTO improves the resistance to reflection cracking by using rubberized asphalt in dense-graded and gap-graded mix (Cheng & Hicks, 2012, pp. 7-8). At the same time, the agencies noted several drawbacks: limited amounts of crumb rubber meeting specifications, difficulty with binder performance grading, variable performance outcomes with dense-graded HMA, unknown long-term performance, inexperience of hot-mix industry with materials and specifications, and costs (Cheng & Hicks, 2012, pp. 8-9).

In a 2015 Michigan trial conducted by Michigan Technological University, two pavement sections were paved with rubber-modified asphalt in terminal blend. One section was in Keweenaw County and the other was in Muskegon County. After the pavements' first winter, two field surveys in April and October 2016 assessed pavement sections in Keweenaw County. Because the CRMA was used as an asphalt pavement overlay, some reflective cracking was observed. With only one year of monitoring, it is too early to make a determination on the effectiveness of this project (You, Yang, & Dai, 2016).

The barriers to using rubberized asphalt products include high costs related to processing finer crumb sizes, high construction temperatures required for paving, difficulty with compacting CMRA, and the unknown environmental implications of recycling CRMA (Papagiannakis & Lougheed, 1995, p. 4). Warm-mix asphalt technology is now being combined with CRMA to reduce the temperatures required for paving and emissions.

However, the limited research into rubberized asphalt products has suggested possible increased resistance to reflective cracking, possible increased fatigue performance of asphalt (fatigue performance is the ability of the pavement to withstand loading without failure (Harvey, Deacon, Tsai, & Monismith, 1995, p. 1)), possible cost savings due to replacement of the polymers, and a wide range of gradation applications (i.e., gap graded, open graded, and dense graded (R Gary Hicks, Cheng, & Duffy, 2010, p. 54)).

Due to insufficient research and conflicting experiences with CRMA, it is not advisable for MDOT to adopt this practice at this time. Research would need to demonstrate more consistently the improved resistance to reflective cracking and the cost-effectiveness of CRMA.

3.4.15 Fiber-modified Asphalt

This is *not* an MDOT current practice.

Fibers have since become a common modifier to reinforce asphalt pavements and improve their performance. There are many kinds of fiber applied for the modification of asphalt binders, including polypropylene fibers, polyester fibers, asbestos fibers, cellulose fibers, carbon fibers, glass fibers, and nylon fibers. According to Abtahi, Sheikhzadeh, and Hejazi (2010), fiber reinforcement of asphalt pavement principally intends to offer extra tensile strength, which can increase the strain energy absorbed when the deformation occurred in asphalt pavements (Abtahi et al., 2010, p. 873). Reinforcing asphalt pavements with fibers also enhances cohesive and tensile strength of mixtures (Abtahi et al., 2010, p. 872). While no extra equipment was required for the field construction of fiber-modified pavements, life-cycle costs have been problematic (Abtahi et al., 2010, p. 874; D. A. Maurer & Malasheskie, 1989).

Using fibers to reinforce asphalt pavements was first recorded in the 1960s (Mahrez, Karim, & Katman, 2003, p. 794). Polypropylene-fiber-reinforced asphalt pavement on I-74 in Indiana, a state in the FHWA wet-freeze zone, was found to have reduced transverse cracking, improved rutting resistance, and decreased overall cracking in its base and binder layers (Jiang & McDaniel, 1993, p. 159). Polypropylene fibers as well as polyester fibers are useful for preventing reflection cracking in asphalt overlays (D. A. Maurer & Malasheskie, 1989, Abstract; Tapkin, 2008, p. 1065).

Woven cotton layers, for example, were used in South Carolina as early as the 1950s to strengthen road performance and provide waterproofing; in 1976, New Jersey found cotton-reinforced asphalt "showed good results" (Abtahi et al., 2010, p. 873; Von Quintus, Mallela, & Lytton, 2010, p. 2) . Four fibers—asbestos, rock wool, glass wool and cellulose fibers—were examined in Nantes, France, for characteristics such as resilient modulus, low-temperature direct tension, rutting resistance, and fatigue resistance (Abtahi et al., 2010, p. 873). In one of the Nantes tests, fiber-modified asphalt pavements were subjected to two million load applications and showed no sign of fatigue distress, no cracking, and no rutting compared to unmodified samples (Abtahi et al., 2010, p. 873).

Life-cycle costs related to paving fabrics and fibrous treatments have, thus far, made these technologies prohibitive in 1989, according to D. A. Maurer and Malasheskie (1989, p. 266).

However, recent research into cellulose-fiber, carbon-fiber, and glass-fiber reinforcement of asphalt pavements have yielded test sections with attributes like improved crack resistance and thermos-electrical snow removal capabilities, both of which can be beneficial in wet-freeze climates. On a test section of road in Belgium with cellulose fiber reinforcement, the drainage time doubled with the use of cellulose fibers than the pavements without fibers (Abtahi et al., 2010, pp. 874-875). For asphalt roads containing carbon fibers, the pavement demonstrates improved resistance to cracks and mechanical properties and increased electrical conductivity, which can facilitate removal of snow and ice via thermo-electrical techniques; obviously, this would not be cost-effective on a large scale, but it may be worthwhile in small applications like bridge decks or dangerous curves (Abtahi et al., 2010, p. 875; Wu, Mo, Shui, & Chen, 2005, p. 1358). Finally, the crack propagation of asphalt pavements containing glass fibers decreased, and the stability and deformability improved (Abtahi et al., 2010, p. 875). The use of cellulose fibers is a current practice for HMA mixtures that follow Superpave™ specifications and are gap graded (MDOT, 2016).

Cement and Lime

3.4.16 Portland Cement (ASTM C150)

This is an MDOT current practice.

MDOT's *2012 Standard Specifications for Construction*, Section 9 permits the use of ASTM C150 Type I (General Purpose), Type II (Moderate Low Heat, Moderate Sulfate Resistant), and Type III (High-Early Strength) portland cements(Michigan Department of Transportation, 2017e, p. 737).

3.4.17 Blended Cement (ASTM C595)

This is an MDOT current practice.

Blended cement are a mixture of portland cement and one or more supplementary cementitious materials (SCMs), and/or ground limestone. They are commonly used in practice and are designated by ASTM C595. MDOT's 2012 *Standard Specification for* Construction permits the use of blended cements that meet ASTM C595. ASTM C595 outlines these blended cements, which are split into four different classifications, given below (Harris, 2012):

1. Type IS – Portland blast-furnace slag cement – up to 95% slag permitted

2. Type IP – Portland-pozzolan cement – up to 40% pozzolan permitted

3. Type IL – Portland-limestone cement – up to 15% limestone permitted

4. Type IT – Ternary blended cement – up to 70% of pozzolan + limestone + slag, with pozzolan being no more than 40% and limestone no more than 15%

3.4.18 Supplementary Cementitious Materials (Slag Cement and Fly Ash)

This is an MDOT current practice.

Slag cement is a byproduct of the steel industry, produced by granulating molten iron blast furnace slag (a granulator quenches the molten slag is water) to create glassy calcium alumino silicates, which is then ground to a fineness similar to portland cement. Fly ash consists of spherical particles of glassy alumino silicates collected from the flue gases of power plants that burn powderized coal. These two materials are the most commonly used supplementary cementitious materials (SCMs) added to concrete, either as an ASTM C595 blended cement or added at the concrete plant. The use of these SCMs offset the use some of portland cement in the mixture, improve the workability of the concrete during construction, decrease permeability, increase long-term strength, and enhance the durability of the concrete in service.

MDOT paving concrete Grade P1M , which MDOT considers to be HPC, requires 25 to 40 percent replacement of the portland cement in the concrete mixture with a SCM (MDOT 12SP-604B-07). For other grades of concrete, they are not to exceed 40 percent replacement of the portland cement in the concrete mixture with a SCM. Further, they are not to exceed 40 percent total replacement of the portland cement if more than one SCM is used in the concrete mixture (MDOT Special Provision 12SP-604B-07, *Quality Control and Acceptance of Portland Cement Concrete).*

3.4.19 Portland Limestone Cement

This is permitted under MDOT specifications, but not in practice because it is not currently sold in the Michigan market.

Portland limestone cement (PLC) is specified under ASTM C595 as a Type IL blended cement. Type IL cement acts very similarly to ASTM C150 Type I cement in terms of strength, freeze-thaw resistance, shrinkage, permeability, and resistance to scaling while reducing the carbon footprint up to 10% ("The Advantages of Portland-Limestone Cement," 2014; Arambula, Masad, & Martin, 2007; Shannon, Howard, Cost, & Wilson, 2014). While ASTM Type I cement can contain up to 5% interground limestone, Type IL cement can have up to 15% ground limestone, although 12% is a practical to ensure the limit is not exceeded.

PLC has been utilized in Europe for over three decades. However, only a limited amount of PLC work has been performed in the United States (Shannon et al., 2014). In the United States, approximately 200 miles (332 km) of concrete pavement has been constructed using PLC. An I-94 project in Wisconsin used 40,000 cubic yards (30,600 cubic meters) of PCC made with PLC. The wet-freeze states of Colorado, Minnesota, Wisconsin, Utah and Iowa as well as the non-wet-freeze states of Missouri, Utah, and parts of Colorado have all used PLC for paving applications as of 2014 (National Concrete Pavement Technology Center, 2014). To date, PLC is not available in the Michigan market.

PLC research is on-going, but within the last few years significant progress has been made in resolving some important issues. One issue that has been resolved is whether PLCs are more susceptible to a form of low-temperature sulfate attack called thaumasite sulfate attack (TSA). This research concluded by finding that PLC systems shared similar performance to pure portland cement systems. Early results on other research on potential interaction with deicers and early age shrinkage/cracking potential show no adverse effects. Additional studies are evaluating the PLC's resistance to chloride attacks and its potential for early-age volume change.

Laboratory tests have shown that PLC is, on average, finer than traditional OPC. This is due to intergrinding of the limestone with the cement clinker resulting in the softer limestone being ground more finely than the cement. A "scaffolding" effect has also been observed where early-age hydration product precipitate on the smaller limestone particles. In combination, the finer grind, improved particle packing, and scaffolding effect in the PLC systems results in higher early-age compressive strengths. In general, concrete made with PLC has roughly equivalent physical properties to that made with portland cement. In one case, PLC has been shown to have improved performance over pure portland cement. I has been found that when PLC is combined with high-alumina supplementary cementitious materials (SCMs) such as fly ash and slag cement, that an additional hydration product called carboaluminates forms. This results in additional solids fill pore space increasing strength and reducing permeability, and may allow for the addition of larger amounts of fly ash to be used in the PCC mixture (Barrett, Sun, Nantung, & Weiss, 2014).

3.4.20 Geopolymer and Alkali-activated Cement

This is *not* an MDOT current practice. It is still an emerging technology; therefore, the research team recommends reviewing this practice again as more research becomes available.

Geopolymer concrete is a material "characterized by chains or networks of inorganic molecules" (Geopolymer Institute in: T. Van Dam, 2010, p. 1). Alkali-activated cement (AAC) is a classification of geopolymer concrete that is defined by its binder being hardened by the polymerization of its "thermally activated natural materials…which is dissolved in alkaline activating solution" (T. Van Dam, 2010). AAC is another emerging alternative to ordinary portland cement (OPC). First commercially introduced in the 1960s, AAC has displayed preferable durability to OPC with a similar reduction in environmental impact as geopolymers (Pacheco-Torgal, Castro-Gomes, & Jalali, 2008, pp. 1305-1312). AAC is formed by the reaction of industry byproducts, such as granulated blast furnace slag from the steel industry or fly ash from the coal industry, and an alkaline activator, such as silicates, aluminates, and aluminosilicates (Pacheco-Torgal et al., 2008, pp. 1305-1312). When properly combined, these reactants go through a reaction process, which is variable for each byproduct and alkaline activator used. This reaction forms the AAC, which then goes through a hydration process comparable to OPC, and achieves its functionality as a binder (Pacheco-Torgal et al., 2008, pp. 1305-1312).

Geopolymer and alkali-activated concretes are low CO_2 emission materials that can be used to replace portland cement in some concrete applications. Unfortunately, wet-freeze states—and the United States at large—have not made widespread use of this technology; however, the adoption of this technology has been much higher in Europe and Australia (Shiraz Tayabji et al., 2010).

These materials are often not cost effective when compared to OPC, and they may require special handling due to the inherent safety risks of working with high-alkalinity solutions. Many geopolymers also require consistent, high-temperature curing conditions, which are often difficult to obtain. Because of this, these materials are more widely used in the precast industry than for cast-in-place applications.

This technology would vastly decrease the environmental impacts of OPC by reducing CO_2 emissions generated from the production and use of portland cement.

Aggregates—Non-conventional (Non-mined Sources)

3.4.21 Construction Demolition Waste (Building rubble)

This is an MDOT current practice. MDOT defines building rubble as building brick, wood, plaster, or other materials. It is allowed to use less than 5 percent building rubble to produce dense-graded aggregate base or open-graded aggregate 4G base.

As of now, there is very limited research or application of construction demolition waste (CDW) in the United States. CalRecycle in California is actively promoting recycling and reuse of CDW material. Several case studies provided by CalRecycle show that economic savings from recycling and reusing CDW can be realized by the contractor (Burgoyne, 2017). While there is limited research in the United States, CDW materials in Europe and Asia are recycled and reused at a significant rate. In fact, some European countries recycle/reuse an average of 28% of total CDW material, and Spain had even set a goal of recycling/reusing 55% of total CDW material by 2015 (Stroup-Gardiner & Wattenberg-Komas, 2013b, pp. 55-69).

CDW materials can have a high level of variability, and these materials need to be processed to remove potentially harmful foreign matter as well as hazardous waste and to produce a more consistent material. The economic benefits of recycling and reusing CDW are not easy to quantify and will require a lot of planning by the contractor to be successful and efficient. Hence, there is a belief that some kind of policy or specification is needed that will require the contractor to recycle or reuse CDW material. CDW is a practice that depends upon having a nearby recycling center that can properly process the CDW material; otherwise, the costs of shipping the CDW to a recycling center would detract from any positive economic benefits. Since the cost of landfilling CDW is relatively low, there is less of an incentive to reuse the material in construction.

Several environmental benefits are associated with recycling and reusing CDW. The contractor can reuse materials that would traditionally be sent to landfill, saving the contractor time and money while also reducing the amount of virgin material used. The contractor can also realize marketing benefits of recycling and reusing CDW, such as receiving awards from local professional associations.

3.4.22 Slag Aggregates

This is an MDOT current practice under certain conditions as specified.

Air-cooled blast furnace slag (ACBFS), reverberatory furnace slag, or steel furnace slag can be used as an aggregate replacement to produce HMA, whereas ACBFS aggregates are permitted for use in PCC, except for MDOT Grade P1M mixtures that required the use of aggregate from geologically natural sources (Michigan Department of Transportation, 2012a, p. 744). ACBFS is permitted for use in open-graded drainage course layers.

Slag aggregates are by-products of iron, copper, or steel. A number of states with wet-freeze climates have used steel furnace slag: Connecticut, Indiana, Illinois, Iowa, Kentucky, Minnesota, Ohio, Pennsylvania, Virginia, West Virginia and Wisconsin. The Chicago area, for example, has used steel furnace slag as a high-friction aggregate because of an absence of high-friction natural aggregates. Pennsylvania DOT addresses steel furnace slag in their standard specifications for fine aggregate (Washington State Department of Transportation, 2015, pp. 13-16). Likewise, MDOT addresses steel furnace slag in their standard specifications for fine aggregate but also for coarse aggregate (Michigan Department of Transportation, 2012a, p. 744).The detriments of using steel furnace slag in asphalt pavements include high volume-expansion potential in the presence of moisture, increased binder content, high specific gravity, higher transportation costs, and overall higher costs. The detriments of using steel furnace slag in concrete pavements include volume expansion, high density, high porosity, lack of lone-term field evidence and questionable freeze-thaw durability (Washington State Department of Transportation, 2015, p. 12).

Steel furnace slag, in particular, can benefit asphalt pavements by improving skid resistance, stripping resistance, rutting resistance, fatigue resistance, and compatibility with asphalt binder. In general, steel furnace slag should not be used as aggregate in concrete as many types are highly expansive and will result in concrete failure (electric arc furnace slag is an exception, but it is often co-mingled with other sources making its use problematic).

3.4.23 Reclaimed Asphalt Pavement

This is an MDOT current practice.

The use of old HMA pavement millings, referred to as reclaimed asphalt pavement (RAP), can be reused in the production of new asphalt pavement. This is done to offset a portion of the asphalt binder and fine aggregate needed for the new mix depending on the mix design. This practice is not specific to wet-freeze climates.

3.4.24 Recycled Concrete Aggregate

This is an MDOT current practice under limited circumstances; the research team considers this technology not to be viable or practical in Michigan's wet-freeze climate at this time as aggregate in new paving concrete. The use of RCA as a base material is a current MDOT practice.

Recycled concrete aggregates (RCA) have been used throughout the United States for many decades. A survey by Gonzalez and Moo-Young (2004) showed that almost every wet-freeze state used RCA as an aggregate in base layers in a pavement structure; at that time, states not using RCA were Missouri, Vermont, New Hampshire, Maine, and Maryland (Gonzalez & Moo-Young, 2004). Also, Illinois, Minnesota, Michigan, West Virginia, and Virginia were reported as using RCA in new PCC mixtures (Gonzalez & Moo-Young, 2004). In Minnesota, base layers made with RCA performed better than those made from virgin aggregates; Minnesota also views the reuse of RCA as a long-term source of aggregates (Stroup-Gardiner & Wattenberg-Komas, 2013b). Michigan has made use of RCA as a coarse aggregate in the past, but did not have good results for longer jointed JRCP, where the RCA coarse aggregate did not provide adequate load transfer across mid-panel cracks, resulting in severe crack deterioration and faulting. MDOT commonly uses RCA as coarse aggregate in open-graded and dense-graded base courses, as well as in asphalt-treated and cement-treated permeable bases. When used in an open-graded drainage base course, issues with leachate (calcium hydroxide leaching and reacting with atmospheric carbon dioxide, forming calcium carbonate) have been observed, clogging the drainage system and resulting in highly alkaline affluent.

The source of the RCA material will have an effect on RCA properties. For instance, RCA from a concrete sidewalk experiencing alkali-silica reactivity (ASR) will still have the potential for future ASR occurrence; thus, using this RCA in a new concrete mixture could cause ASR to occur in it as well. Laboratory test results have shown that RCA has higher absorption, lower specific gravity, lower abrasion resistance, lower sulfate soundness, and higher chloride content when compared with virgin aggregates. PCC made with RCA has been shown to have lower compressive strengths, lower modulus, higher permeability, and higher drying shrinkage when compared to PCC made with virgin aggregates.

Nonetheless, the use of RCA in base/subbase layers has been proven as a cost-effective practice. RCA can be used as an aggregate source in new PCC mixtures, replacing virgin aggregates, but this is more problematic and must be addressed during mixture design and in the design of the concrete pavement itself. In some applications (like base layers), RCA can have improved performance over traditional materials. Using RCA can reduce material trucking costs as well as reduce quantity of virgin materials that need to be purchased. The ability to reuse existing materials in new applications has a positive environmental impact as it reduces the material that will end up in a landfill (reducing landfill disposal fees) while reducing the need for mining new aggregate sources. The economic benefits of RCA reuse can also lead to a reduction in bid prices.

Admixtures and Curing Materials

3.4.25 Water Reducing Admixtures

This is an MDOT current practice.

As the name implies, water-reducing admixtures (WRAs) reduce the water required to obtain concrete with a given slump. A WRA can be used to reduce the amount of water added while maintaining the same slump or can be used to increase the slump of the concrete without the need for additional water. WRAs conform to AASHTO M 194 (ASTM C494) and can be formulated to have normal, retarding, or accelerating setting characteristics (ACI Committee 212, 2010). They are classified based on water-reducing capabilities and set-control characteristics, as follows (Kosmatka & Wilson, 2016):

- Type A, water-reducing.
- Type D, water-reducing and retarding.
- Type E, water-reducing and accelerating.
- Type F, water-reducing, high-range.
- Type G, water-reducing, high-range and retarding.

It is common to characterize WRAs based on their effectiveness in reducing water requirements as follows (Kosmatka & Wilson, 2016):

- Normal (conventional) water-reducers – Can reduce water content by approximately 5 to 10 percent without exceeding the AASHTO M 194 time of set limit. These are typically classified as Type A, D, or E.

- Mid-range water-reducer – Provide water reduction between 6 and 12 percent without retardation associated with high dosages of normal water-reducers. These products should show compliance with AASHTO M 194 Type A and often meet Type F requirements.

- High-range water-reducer – Provide water reduction between 12 and 40 percent, and are often used to produce high strength concrete with very good workability and a bit low *w/cm*. These products often meet the requirements of AASHTO M 194 Type F or G. Not often used in paving grade concrete.

For pavement applications, it is common to use normal or mid-range water-reducers.

Most WRAs disperse cement grains through electrostatic and steric repulsive forces (Kosmatka & Wilson, 2016). The water-reducing compounds will bind to the cement grains giving them a slight negative charge as well as a creating a layer on the surface. In combination, these electrostatic and steric repulsive forces separated the cement grains, breaking up particle agglomerations and making the mixing water much more efficient. To a lesser degree, electrostatic forces also repel aggregates and entrained air bubbles (Kosmatka & Wilson, 2016).

Polycarboxylates represent the newest WRA technology. They use the same concepts as other WRAs, only are far more efficient as the longer polycarboxylate molecular chains adhere to the surface of cement grains dispersing them in a mechanism referred to as steric hindrance (Kosmatka & Wilson, 2016). Because the mechanism is highly dependent on physical separation, the effectiveness of polycarboxylate-based WRAs is not influenced by the dissolved ions in solution to the same extent as is the electrostatic repulsion mechanism. Thus the water-reducing effect is longer-lasting and highly efficient. Polycarboxylate-based high-range WRAs are very common, and this technology is becoming more common as a mid-range WRA and are thus seeing increased application in paving grade concrete.

As discussed, WRAs are used to reduce the water required in the mixture while maintaining the same level of concrete workability. For paving grade concrete mixtures that are typically low slump, the use of normal-range and mid-range WRA (Type A, and to a lesser degree Types D and E) is common practice to reduce the *w/cm* and/or cementitious materials content while maintaining workability. It is not common to use high-range WRAs for paving grade concrete as high slumps and/or high strength are not often sought.

It is noted that Type A WRA are often formulated with a water-reducing retarding component, and an accelerating compound is added to achieve normal set. In these formulation, this limits water reduction to around 10 percent before excessive retardation occurs and is one reason why Type A WRA are often used in hot weather (ACI Committee 212, 2010). A difficulty can arise under these circumstances as the accelerating compound may accelerate the hydration of the aluminate phase, which can lead to false or early set. The problem can be particularly acute when some supplementary cementitious materials, particularly ASTM C618 Class C fly ash, are used. Under these circumstances, the problem can be alleviated by trying another Type A WRA, cooling the concrete mixture, or changing the batching sequence by delaying the WRA addition (P. C. Taylor, Kosmatka, & Voigt, 2006).

Some problems have been encountered in the air-void system with the use of polycarboxylate-based WRA (The Concrete Producer, 2012). Some early studies noted that mixtures made with polycarboxylate-based WRA had acceptable total air contents, but that the air bubble were large and spaced far apart (T. Van Dam et al., 2005). Others have reported issues of uncontrollable air in the presence of polycarboxylate-based WRA. Polycarboxylate-based WRA are surfactants that will have a tendency to entrain air and most all are currently formulated with a defoamer to counteract this tendency (Jeknavorian, 2016; MacDonald, 2009). But if not properly balanced, this can either entrain more air than desired or result in air-void instability. For this reason, additional care should be exercised when using polycarboxylate-based WRA to ensure that the total air content and the air-void system are adequate for the anticipated environmental conditions.

3.4.26 Non-chloride Accelerators

This is an MDOT current practice for concrete pavement repairs.

Set-accelerating admixtures, commonly referred to as accelerators, are used to accelerate the rate of hydration and thus promote early setting and strength gain. For pavement applications, they are most often used to support early strength gain to facilitate the early opening to traffic, and often in conjunction with other mixture strategies including the use of a high-early strength cement (e.g. Type III), a WRA that permits the use of a low *w/cm*, and increased cementitious materials content (Kosmatka & Wilson, 2016; T. Van Dam et al., 2005). Accelerators are also often used during cold weather placements to initiate hydration so that the heat generated by the exothermic reactions can be used, in conjunction with insulation, to support continued hydration.

Accelerators are specified under AASHTO M 194/ASTM C494 Type C as set-accelerating without affecting water requirements and Type E as set-retarding and water-reducing. Type C accelerators are also commonly characterized as being chloride-based (calcium chloride is the most widely used accelerator) or non-chloride (NC). Currently a new generation of accelerators based on nano-particles is being brought to market with early results showing promise (ACI Committee 212, 2010; Kosmatka & Wilson, 2016).

The most common accelerator for non-reinforced concrete is calcium chloride (Kosmatka & Wilson, 2016). The popularity of calcium chloride is based on its reliability, ease of use, and cost effectiveness (ACI Committee 212, 2010). Yet a major drawback of calcium chloride as an accelerator is that the chlorides can initiate and propagate corrosion in embedded steel. Calcium chloride can also affect other concrete properties including increased drying shrinkage and negative impacts on durability. For these reasons, non-chloride accelerators are becoming more common. Commercially available non-chloride accelerators are most often based on organic compounds such as triethanolamine (TEA) and inorganic salts such as sodium and calcium salts of formate, nitrate, nitrite, thiocyanate, and lactate (Kosmatka & Wilson, 2016) .

In addition to the conventional accelerators discussed above are newly commercialized accelerators based on aqueous solutions of nanoparticles. These “nanoscale nucleation seeds” act as nucleation sites for the rapid growth of cement hydration products, most notably calcium silicate hydrate (CSH), away from the cement grains themselves, resulting in dramatically improved early strength gain (ACI Committee 212, 2010; Kosmatka & Wilson, 2016).

In concrete paving, accelerators are commonly used to accelerate set and strength gain when 1) low temperature paving is encountered and/or, 2) when early opening to traffic is desired. With regards to the former, the proper use of accelerators along with other cold temperature concrete pavement construction techniques will permit construction under climatic conditions that would normally shut down operations. The latter application of accelerators addresses a common complaint that concrete is too slow in gaining strength, and that long curing times prevents access to homes and businesses making concrete paving infeasible in many urban settings. As a result, accelerating concrete strength have allowed the opening of concrete pavements to traffic within a day, and even within 4 to 6 hours, of paving (T. Van Dam et al., 2005).

As is true of all admixtures, the supplier’s guidance must be followed in the use of accelerators. As noted previously, calcium chloride can be used in dosages of up to 2 percent by mass of cementitious materials, but lower dosages should be used if possible. For all accelerators, laboratory trial batching should be conducted to determine the dosage needed to achieve the desired set time and early strength development as well as ensuring that all other mixture properties are achieved. The laboratory testing should use job mix materials and testing should be conducted over a range of temperatures simulating what is expected to be encountered in the field. It is common to test mixtures with a variety of dosages so that dosage can be varied as ambient conditions change.

The primary effect of accelerators on fresh concrete is what they are designed to do; accelerate setting and early strength gain. In addition, accelerators can negatively impact air entrainment requiring increased dosage of air entraining admixture. In some cases, it has been observed that accelerators increased bubble size and spacing factor, effectively reducing the benefit of entrained air (ACI Committee 212, 2010). In areas where freeze-thaw cycles and chemical deicing are common, it might be advantageous to microscopically examine the nature of the entrained air-void system in accordance with ASTM C457 to ensure that the bubble sizing and spacing is adequate if an accelerator is to be used.

As with most other admixtures, accelerators are sensitive to the properties of multiple mixture constituents as well as ambient conditions. Evaluating the impact when changing a mixture component and thoroughly testing the admixture during mixture design over a range of temperatures can help avoid problems.

3.4.27 Liquid Membrane-Forming Curing Compound

This is an MDOT current practice.

Curing supports cement hydration by ensuring that sufficient moisture and temperature are maintained until the desired engineering properties of the concrete are achieved. Although all cast-in-place concrete pavement requires curing, certain conditions dictate that greater care is warranted in the application of curing to avoid early-age plastic shrinkage cracking. These conditions include:

- Use of mixtures with reduced amount and rate of bleeding.
- Slow setting mixtures.
- Highly evaporative environments (see ACI 308R).

Liquid membrane-forming curing compounds are composed of waxes, resins and other materials applied to retard the evaporation of moisture from the pavement surface. They are specified under ASTM C309). ASTM C309 curing compounds include Type 1 – clear, Type 1D – clear with fugitive dye, Type 2 – white pigmented, Class A – unrestricted composition (usually used to designate wax-based products), and Class B – resin-based compositions. It is noted that membrane-forming curing compounds that meet the requirements of ASTM C309 have a variable capacity to reduce moisture loss, with some moisture loss occurring depending on how the compound is applied and ambient conditions (ACI Committee 308, 2016). Work conducted by Hajibabaee, Moradllo, and Ley (2016) found that a solvent-based curing compound (i.e., poly alpha methylstyrene) was more effective than two water-based curing compounds (i.e., wax-based and resin-based) in providing water-retention, possibly due to better surface wetting that produces fewer imperfections.

Membrane-forming curing compounds should be applied as soon as finishing is completed and bleeding has ceased. At this stage, the bleed water has just left the surface and the texturing has increased the surface area resulting in increased evaporation. It can be difficult to determine if bleeding has ceased in highly evaporative environments with mixtures with low bleeding rate. Under such conditions, the use of an 18-inch (46 cm) square of transparent plastic sheeting can be placed on the uncured surface to assess bleed water accumulation (ACI 2016a). This is a critical time, as a delay in the application of the curing compound under adverse conditions can result in plastic shrinkage cracking.

Curing compounds should be applied to all exposed concrete surfaces at a rate equal to or in excess of the manufacturers' recommendations, noting that deep texturing such as an aggressive broom finish or tining will require higher application rates (ACI Committee 308, 2016). The application must be uniform and complete, and it is recommended that it be applied in two passes sprayed at right angles to one another (Hajibabaee et al., 2016). For mainline paving, spray equipment mounted on self-propelled unit should be used with hand spray applications being limited to small placements or irregular areas inaccessible to the self-propelled unit. For slipform paving, make sure the exposed sides of the slabs are also covered. If the concrete pavement is formed, exposed sides of the slab should be coated if the forms are stripped within 7 days of placement. Some agencies also require that the curing compound to be applied to the saw cut joints. The use of curing compounds with fugitive dye or white pigmented facilitates verification of coverage. White-pigmented curing compounds are recommended for use on hot, sunny days as they increase surface reflectivity, which reduces concrete temperature (Kosmatka & Wilson, 2016).

Prior to application, the curing compound should be agitated in accordance with the manufacturer's instructions. Hand or power sprayers with appropriate wands and nozzles with pressure usually in the range of 25 to 100 lb/in^2 (0.2 to 0.7 MPa) are commonly used to apply curing compounds, with power sprayers being recommended for large jobs (ACI Committee 308, 2016). If the pavement was formed, the sides should be kept uniformly moist following form removal until curing compound can be applied to the exposed sides at the same rate as for the pavement top surface.

Wax-free curing compounds are recommended for areas that will be subjected to traffic before the desired curing period is over (ACI Committee 308, 2016). Further, it should be determined if the curing compound will interfere with bonding of striping or other surface treatments. If testing indicates that this may be a problem, the curing compound must be removed from the surface prior to application of the striping or surface treatment. Membrane-forming curing compounds are only effective if they are applied uniformly, in sufficient quantity, and at the proper time. Poor coverage will result in unacceptable moisture loss.

In Michigan, white membrane-forming curing compound that meet ASTM C309, Type 2 requirements are specified.

Asphaltic Materials

3.4.28 Cut-back Asphalt

Even though cut back asphalt is in MDOT standard specifications, it is not currently widely used. Cutback is produced "when asphalt cement is dissolved in a petroleum-based solvent". The cutback curing time is determined by the solvent type, for example, gasoline or naphtha is a rapid curing type, kerosene is a medium curing type, and low-volatility oils are slow curing types (T. J. Van Dam et al., 2015, pp. 3-18). Cut-back asphalt is not used as much anymore because of the volatility of the solvents used and obvious environmental concerns.

3.4.29 Emulsified Asphalt

This is an MDOT current practice.

Emulsified asphalt is used as a way to deliver asphalt binder in road projects such as chip seals and bond coats for asphalt layers. Emulsified asphalt is asphalt binder that is blended with water and kept in suspension by a surfactant. After the emulsion is applied the water separates from the asphalt which is the change in color from brown to black. This is commonly referred to as "breaking". The emulsion is said to have "set" when it no longer is being picked up from the existing pavement. The final stage of the emulsion is "full cure" which can sometimes take up to 90 days depending on the type of emulsion. Emulsions are safer than cut-back asphalts and are a best practice that is not unique for wet-freeze climates but are used to prevent problems encountered in wet-freeze climates such as decreasing water infiltration and increasing skid resistance when used with other items such as chip seals and overlays. This is a best practice that is not unique to wet-freeze climates.

3.4.30 Neat Asphalt Binder

This is an MDOT current practice.

Neat asphalt is refined from crude oil that is directly used in paving. The performance grade (PG) system – a part of SuperPave™ mix design - is used to characterize the performance of neat asphalt on HMA pavement. The different asphalt binders have varying minimum and maximum temperatures that affect pavement design. For example, a binder categorized as PG 58-28 will meet the physical property requirement of a maximum temperature up to 136.4°F (58°C) and a minimum temperature as low as -18.4°F (-28 °C) (Asphalt Institute, 2001). See SuperPave™ in section 3.2.1 for more information. This is a best practice that is not unique to wet-freeze climates.

3.4.31 Polymer-modified Binder

This is an MDOT current practice.

Early polymer-modified asphalts were designed to accommodate different climatic areas and exhibited such traits as "decreased temperature susceptibility, increase cohesion and modified rheological characteristics" (Airey, 2003, p. 1709). These features would make polymer-modified asphalts potentially promising for use in wet-freeze climates; as such, these asphalts were commonly selected in Michigan or other states. The performance-modifying effects of various polymers on asphalt pavements were investigated by MDOT in the 1990s; comprehensive testing included dynamic shear rheometer (DSR), bending beam rheometer (BBR), viscosity, differential scanning calorimeter (DSC), Fourier transform infrared (FTIR) spectroscopy, thermal mechanical analysis (TMA), and gel permeation chromatography (GPC) (Hawley, Drzal, & Baladi, 1997, p. 8). The research team found that the performance-enhancing polymers included styrene-butadiene rubber (SBR), styrene-butadiene-styrene (SBS), styrene-ethylene-butylene-styrene copolymer (SEBS), crumb rubber modifiers (CRM), and epoxy terminated ethylene terpolymer (Elvaloy® AM or EAM) (Hawley et al., 1997, p. 5). For bonding and reactive or chemical compatibilization between the polymer and asphalt binder to occur during blending, the materials must be thoroughly mixed, there must be reactive functional groups present in the mix, the reaction needs to occur within a reaction-specific time frame staying in the proper time frame, and the newly-developed bonds should have a stable structure (Becker, Mendez, & Rodriguez, 2001, p. 44). Using SBS- and SBR-modified binders is a current practice by MDOT (MDOT, 2012).

Styrene-butadiene-styrene (SBS): Styrene-butadiene-styrene (SBS) is a block copolymer, and its strength and elasticity derives from its physical cross-linking of its molecules that can create a durable pavement even in cold climates (Airey, 2003, p. 1). To modify asphalt with SBS, no specific equipment is needed either in the laboratory or the field (Woolley, Goumans, & Wainwright, 2000, p. 943). Some studies have found (although some disagreement exists) that the use of SBS in the modification of asphalt improves the flexibility at low temperatures, thereby enhancing the cold weather performance of the modified asphalt (Becker et al., 2001, p. 41). In other studies, SBS-modified asphalt binder experienced lower oxidation levels than the control binder, and the modified asphalt's SHRP performance grade improved two grades with the addition of 3% - 5% SBS (Hawley et al., 1997, p. 12). Furthermore, indirect tensile testing also showed that the moisture susceptibility of SBS-modified asphalt mixture was improved relative to control asphalt mixture, offering more resistance to freeze-thaw cycles (Al-Hadidy & Yi-qiu, 2011, p. 506). At present, SBS is a widely used polymer that can enhance pavement durability in wet-freeze climates

Styrene-butadiene rubber (SBR): Styrene-butadiene rubber (SBR) is also one of the more common polymers for modifying asphalt binders and mixtures (Hawley et al., 1997, p. 12). SBR polymer increases the adhesion and cohesions between the asphalt and aggregates, and crack resistance at low temperatures (Yildirim, 2007, p. 69). When SBR is incorporated into asphalt at higher amounts, it forms "a network" that improves the rutting resistance (Hawley et al., 1997, p. 12). Modifying asphalt with SBR improves its low-temperature ductility, elastic recovery, and viscosity (Becker et al., 2001, p. 41; Yildirim, 2007, p. 69).

Polyphosphoric Acid: PPA can improve the high-temperature performance to resist rutting distress and may also improve the low-temperature performance to mitigate low-temperature cracks. PPA is a polymer of orthophosphoric acid. When used to chemically modify asphalt binder PPA can improve the high-temperature performance grade (PG) rating and may improve the low-temperature PG rating while not leading to oxidation or lower m-values of the asphalt (Buncher & D'Angelo, 2009, p. 12).

The Ministry of Transportation of Ontario (MTO) conducted a survey in 2007 to gain insights into poor performance of PPA-modified binder (D'Angelo, 2009, p. 6). The task group established to investigate the issue identified an upper limit of PPA usage: for high-volume roads, polymer could be added to the asphalt binder at less than 0.5% PPA while, for low-volume roads, PPA could account for up to 1% (D'Angelo, 2009, p. 6).

One survey, conducted by the MTO, took place in 2007 and a second survey, conducted by Pennsylvania DOT, took place in 2008-2009. Pennsylvania DOT later combined the data from both surveys regarding the usage of PPA for a dataset of 48 responses. They divided the survey responses into five categories: allow, neutral, restrict, don't allow, and no response. MDOT allows unrestricted use of PPA along with other wet-freeze states such as Minnesota, Ohio, Vermont, New Hampshire, and Maine. However, some states and provinces with wet-freeze climates restrict or ban the use of PPA, including New York, Pennsylvania, and Ontario; cited among their reasons for restricting PPA a "preference for polymers; possible adverse reaction with other additives such [as] hydrated lime; unknown long term performance; and negative reports by others" (Buncher & D'Angelo, 2009, p. 24; D'Angelo, 2009, p. 1; Federal Highway Administration, 2012; D. Maurer & D'Angelo, 2009).

The Minnesota DOT investigated the field performance of PPA-modified binders by placing the PPA-modified binder on five test sections of the Minnesota Road Research Project's (MnROAD) low-volume road in 2007 (Buncher & D'Angelo, 2009; Minnesota Department of Transportation, 2017a). The five sections of road that used PPA-modified binder experienced rutting depth that was less than 0.12 inches (3 mm) and no signs of moisture damage after 18 months (D'Angelo, 2009, p. 5). As of March 2016, the average rutting depth of a section using 0.75% PPA was 0.27 inches (6.8 mm) and 0.07 inches (1.8 mm) for inside and outside lanes, respectively; the average rutting depth of a section using 0.3% PPA and 1.0% SBS polymer was 0.31 inches (8.0 mm) and 0.09 inches (2.3 mm) for inside and outside lanes, respectively (Minnesota Department of Transportation, 2016).

Other wet-freeze states, Pennsylvania, New Hampshire, and Maine have conducted PPA field trials and found the condition of PPA modified segments similar to control segments (Von Quintus, 2014).

Michigan conducted a rehabilitation project along US-31 north of Muskegon in 2005. The project included placing a HMA overlay on the existing jointed concrete pavement. Two mixture designs were used, one with PPA and one without PPA. A survey conducted in 2013 after 8 years in service found similar surface conditions and performance between the PPA-modified asphalt and the control segments (Von Quintus, 2014, pp. 23-25).

A barrier to implementation of this practice is MDOT's limited usage experience. Nonetheless, the research team recommend field trials and monitoring for 5 to 10 years and the development of a standard or specification for the use of PPA.

3.4.32 Tack Coat

This is an MDOT current practice.

The goal of a tack coat is to increase the bonding strength between layers to improve the performance of pavement structure. A tack coat consists of either hot asphalt cement or emulsified asphalt (asphalt cement diluted with water and an emulsifying agent). It is applied to a road surface in order to help bond the existing layer and forthcoming overlays, increasing the effectiveness of the pavement for both the short term and the long term (Hasiba, 2012, p. 10). Tack coat is a cost-effective bonding method, costing 0.1-0.2% of the total project costs for new or reconstruction work and 1.0-2.0% of total project costs for mill and overlay work (Federal Highway Administration, 2016b, p. 6). However, if a tack coat's bond fails, correcting the problem could run as high as 30-100% of the original total project costs (Federal Highway Administration, 2016b, p. 6). This is a best practice that is not unique to wet-freeze climates.

3.4.33 Low-tracking Bond Coat Emulsified Asphalt

This is an MDOT current practice.

Trackless tack coats are designed to serve the same purpose as standard tack coats (Ohio Department of Transportation, 2013, p. 450) , except they are designed to not be tracked off the pavement in a shorter amount of time. An additional benefit is the potential to prevent pavement markings from being covered by the tracked off tack coat (Clark, Rorrer, & McGhee, 2012, p. 2). Various contractors in Ohio, Missouri and Tennessee, and around the southeast quarter of the U.S. all offer trackless tack coat products (Blacklidge, 2017; Heartland Asphalt Materials, 2011; Jurgensen Companies, 2017); the Virginia DOT and Illinois Center for Transportation have also performed studies into the performance and implementation of trackless tack coats, respectively (I. Al-Qadi et al., 2012; I. L. Al-Qadi et al., 2012; Clark et al., 2012).

In 2016, MDOT release a special provision for the permissive use of low-tracking bond coat (trackless tack coat) emulsified asphalt instead of standard tack coats (Michigan Department of Transportation, 2016e)=.

3.4.34 Bio-derived Binder

This is *not* an MDOT current practice. It is still an emerging technology; therefore, the research team recommends reviewing this practice again as more research becomes available.

Bio-derived binders are generated from bio-mass materials such as vegetable oils (i.e., soybean, corn, sunflower, and canola) and waste wood (Shiraz Tayabji et al., 2010; Yang, You, Dai, & Mills-Beale, 2014). The bio-derived binders can be used to replace partially the asphalt binder in asphalt pavement. Vegetable-oil-based modifiers are considered renewable resources, and product made from them include rejuvenators (extender oils), bio-polymers, and resin-like synthetic binders (Shiraz Tayabji, Kurt D Smith, & Thomas Van Dam, 2010, p. 30). MDOT has sponsored research on using Michigan wood bio-asphalt as an alternative material (You, Mills-Beale, Yang, & Dai, 2012). In Ohio, ODOT has several field trials using the bio-derived rejuvenator Biorestor. According to four-year monitoring data found in FHWA/LTPP surveys, the use of Biorestor as a penetrating sealer has been shown to be cost effective (Von Quintus & Raghunathan, 2017). Commercially available bio-derived binders, such as Vegecol and Ecopave, are also available in Europe and Australia.

Steel Dowel and Tie Bars

The use of smooth round dowel bars have effectively extended the service lives of concrete pavements by transferring load from one slab to the next at transverse joints, preventing faulting along joints. Dowel bars are placed at the mid-depth of the slab, either by baskets staked to the base or inserted by the slipform paving machine. Typically 18 inches (46 cm) long and varying in diameter from 1 to 1.5 inches (2.54 to 3.8 cm) , dowels are commonly placed 12 inches (30 cm) on center along the length of the joint (although there has been some experimentation with reducing the number of dowel by placing four in each wheel path). At least one half the length of each dowel is coated with a bondbreaking agent (MDOT requires that the entire dowel be coated with bondbreaking agent) that will prevent the concrete from bonding to the dowel when the pavement shrinks due to moisture loss and as it expands and contracts. As the joints open, the slabs effectively slide apart with the dowels permitting one-dimensional movement. The application of load to the joint is thus transferred from one slab to the next primarily through the dowels, which reduce deflection and slab stress while maintaining the two slabs in alignment.

Tie bars function differently. They are smaller diameter (typically 0.5 to 0.625 inches [1.3 to 1.588 cm] in diameter), longer (typically 30 inches [76 cm]), spaced further apart (commonly 24 to 36 inches [61 to 91 cm]), and made of deformed steel bar. Unlike dowels which are sized to carry load independently across the joint while allowing the joint to open and close, tie bars instead hold the joint tightly together. The load is thus carried by the interlock of the aggregate particles which bridge across the crack face. Tied joints are most often in the longitudinal direction.

Commonly made of solid steel, dowel bars used in freeze-thaw environments are coated with epoxy coating to resist corrosion. Dowel bars were commonly used with long-jointed JRCP but it wasn't until the 1990's that their use became common in short-joint JPCP in the Western US (Shiraz Tayabji et al., 2010; Washington State Department of Transportation, 2013, p. 47).

Coatings can provide corrosion resistance to dowels and tie bars, which is a crucial benefit in wet-freeze climates because the pavements joints are subjected to chloride-based deicers. Chlorides accelerate the initiation and propagation of corrosion, and it was observed that uncoated dowel bars (problem is far more acute for dowel bars because they have to accommodate movement) could rapid corrode at the joint resulting in joint lock up, spalling, and necking down of the dowel. MDOT is switching to ASTM A1078 Type 2 coating, which specifies A934 epoxy powder coated dowels (see section 3.4.35).

Some agencies in the United States that have sought to construct long-life concrete pavement (those expected to have a service life of 50 or more years) have made use of several alternative corrosion-resistant dowel bars in lieu of epoxy-coated steel. These include stainless steel, stainless steel clad, basalt, zinc clad, glass-fiber reinforced polymer, and corrosion-resistant steel (such as MMFX). The State of Washington, which has dry-freeze, wet-freeze, and wet, non-freeze climates, has tried several types of corrosion-resistant dowel bars, including MMFX and stainless steel. The use of stainless steel dowel bars was discontinued in Washington due to the material's high cost. The selection of the dowel bar type was dependent on the potential for corrosion: a project located in a mountain pass that would be exposed to higher amounts of corrosive deicing salts would need a dowel bar with higher corrosion resistance (Uhlmeyer & Russell, 2013).

The dowel bars' corrosion resistance appears to be directly proportional to the cost of the bars, with dowel bars with higher corrosion resistance having higher cost. Knowing whether a pavement is at high risk for corrosion and how critical it is to the transportation infrastructure are important considerations when deciding if the higher cost of alternative corrosion resistance is justified.

3.4.35 Epoxy-coated

This is an MDOT current practice.

Epoxy-coating provides a barrier to prevent moisture and chloride ions from reaching the steel surface, and is commonly used on embedded steel in wet-freeze climates where moisture and deicing/anti-icing agents are expected to infiltrate the pavement structure. Epoxy-coated steel dowel bars, tie bars, and reinforcement have long been a standard for use in concrete pavements by state DOTs. Epoxies are highly adhesive, polymer materials that are applied to the outside surface of steel and form a strong, rigid coating that prevents undesired chemical reactions. These epoxies give the steel resistance to corrosion that would otherwise deteriorate the steel and its strength. It has been shown that epoxies can prevent loss of cross-sectional area in steel and, consequently, lead to a longer pavement lifespan (Kahhaleh, Vaca-Cortés, Jirsa, Wheat, & Carrasquillo, 1998, pp. 141-143). This corrosion protection is especially crucial in wet-freeze environments, as water and deicing materials intrusion into the pavement can occur regularly, especially when cracks are present, and extensive corrosion damage can occur.

In Michigan, bridge decks made with epoxy-coated rebar (ECR) demonstrated a potential service life of approximately 70 years in one study (Boatman, 2010, p. 11), and of approximately 86 years in an update to that study (Valentine, 2015, p. 12). Michigan has had only one ECR bridge deck rated receive an inspection rating of "poor" after 35 years of ECR use (Valentine, 2015, p. 12). Recently, MDOT has moved to the use of a more robust ASTM A1078 Type 2 dowels coated with ASTM A934 epoxy (specified as being purple or gray) dowels to provide a tougher coating to resist damage during handling and construction and provide added corrosion resistance (MDOT 12SP-602I-01 2017). The Type 2 is a 934 epoxy, which although is less flexible than the Type 1 775 epoxy, is more resistant to wear and damage, thus less likely to be broached during construction or in service.

3.4.36 Stainless Steel and Stainless Steel Clad Dowels and Tie Bars

This is *not* an MDOT current practice. The research team recommends reviewing this practice and consider implementing.

Use of stainless steel in concrete has exhibited superior corrosion resistance to conventional epoxy-coated steel in wet-freeze environments where heavy use of chloride-based deicers is common. Generally, epoxy-coated steel exhibits acceptable corrosion resistance. But in pavement applications where extensive water and deicing material is expected to infiltrate the joint and wear is an issue for dowels, stainless steel may prove desirable for long-life pavement applications.

Stainless-steel-clad bars offer an alternative to full stainless steel bars, which are very costly. With the cladding, the corrosion resistance of the stainless steel is achieved at reduced cost compared to full stainless steel. A study by the University of Kansas found that stainless steel cladding has "significant chloride corrosion resistance, making the reinforcement a good candidate for use in concrete structures subjected to deicers" (Kahrs, Darwin, & Locke, 2001, p. 36). It was also noted that, even with a hole drilled through the cladding, the corrosion resistance was still significantly superior to conventional steel, although it stated that further research should be performed (Kahrs et al., 2001, pp. 35-38). Further, a study in Michigan found that stainless clad steel "can provide more than 100 years of bridge deck maintenance-free service life," with the main drawback being material cost (S. C. Kahl, 2012, p. 21).

3.4.37 Basalt

This is *not* an MDOT current practice. The research team recommends reviewing this practice and consider implementing.

Basalt reinforcing bars are manufactured from melted basalt fibers formed into bars with a shape similar to other fiber-based steel rebar alternatives. They are an experimental non-metallic, non-conductive alternative to traditional steel bars that exhibit many desirable properties for use in concrete pavements, such as excellent corrosion resistance, light weight, simplified transportation of all lengths, comparable compressive and tensile strengths, and cost effectiveness. Tests revealed that basalt exhibited higher tensile strengths than what was specified by suppliers, however further research is required before these bars can be used in practice (Palmieri, Matthys, & Tierens, 2009, pp. 165-168).

3.4.38 Galvanized and Zinc-clad

This is *not* an MDOT current practice. The research team recommends reviewing this practice and consider implementing.

According to Shiraz Tayabji et al. (2010), zinc-alloy cladding provides corrosion resistance for Grade 60 carbon steel bars in laboratory studies and in field trials in Minnesota, Pennsylvania, and Ohio (p. 47). Zinc cladding has limited real-life testing but is showing early success. To date, zinc-clad dowel bars have been used in states with wet-freeze climates, including Minnesota and Ohio as well as Michigan (Shiraz Tayabji et al., 2010, p. 47) . Michigan has approved of the use of zinc clad III HS on MDOT projects (Michigan Department of Transportation, 2017b).

3.4.39 Glass-fiber-reinforced Polymer

This is *not* an MDOT current practice. The research team recommends reviewing this practice and consider implementing.

Shiraz Tayabji et al. (2010, pp. 44-45) highlight fiber-reinforced polymer (FRP) as a non-corroding, lightweight, non-conductive alternative to steel rebar. FRP is made of "polymeric material (polyester, vinyl ester, or epoxy) that is reinforced by fibers or other reinforcing materials (fiberglass, carbon fibers, or graphite fibers)" (Shiraz Tayabji et al., 2010, p. 45). FRP bars are "lighter" than steel bars and can be used in CRCP as "longitudinal reinforcement, transverse reinforcement on chairs, and transverse tie bars between adjacent lanes or ramps" (Shiraz Tayabji et al., 2010, p. 45).

Designers expected fiber-reinforced polymer bars to provide continuously-reinforced concrete pavements with a better resistance to temperature-induced cracking and corrosion. A study in Michigan evaluated four bridge decks constructed with FRP rebar and found that the "FRP rebar bridge deck is not performing as well as ECR [epoxy-coated rebar] in the early age year" (Valentine, 2015, p. 12). However, each one of those bridges were constructed with differing design and material, and that another Michigan bridge constructed with a single mat of FRP is performing well (Valentine, 2015, p. 12). A Wisconsin study looked at the effect of using glass fiber reinforced polymer (GFRP) rebar in continuously reinforced concrete pavements. Corrosion of the reinforcing steel has been a problem for CRCP in Wisconsin, resulting in steel rupture and delamination. The findings of the study showed that the use of GFRP reinforcement in CRCP resulted in a stress reduction in the concrete slabs while also being an economically feasible alternative to the steel reinforcement typically used in CRCP (Choi & Chen, 2005).

3.4.40 Corrosion-resistant Steel (MMFX™)

This is *not* an MDOT current practice. The research team recommends reviewing this practice and consider implementing.

Some studies have found that corrosion-resistant steel known as MMFX™ Steel exhibited higher corrosion resistance than conventional steel and is beginning to be used in state DOT projects. This steel has a chloride threshold superior to conventional steel, implying that more chlorides are required for corrosion to occur (Ji, Darwin, & Browning, 2005, pp. 323-325). However, it was found that MMFX™ steel and conventional steel have "nearly identical corrosion potentials, indicating that both steels have a similar tendency to corrode", meaning that both bars will corrode but MMFX™ will take more chlorides to initiate (Ji et al., 2005, pp. 323-325). Also, there are conflicting reports about cost effectiveness; one study found that "bridge decks containing MMFX™ steel do not appear to be more cost effective than decks containing epoxy-coated steel" (Ji et al., 2005, pp. 323-325) while another found that epoxy-coated steel was "far less cost-effective per unit than MMFX™ 2 when both anticipated and unanticipated costs of epoxy-coated-rebar in this study are estimated" (Sharp & Moruza, 2009, p. 45).

This type of steel has been studied for structural applications in Michigan and, compared to both conventional and epoxy coated steel, it has shown improved corrosion resistance and a higher yield strength. However, it was recommended that the use of MMFX™ be restricted to "highly congested urban areas when life cycle costs are justified" (S. Kahl, 2007, p. 17).

Concrete Joint and Crack Sealing Materials

Joint and crack sealing reduces water penetration into a pavement structure. As such, these techniques can be beneficial in mitigating freeze-thaw deterioration, pumping, frost heaving, and weakening of unbound pavement layers due to saturation. Joint and crack sealing are maintenance techniques applied to both asphalt and concrete pavements. There are many different types of sealant materials—the most common being polymerized asphalts which are applied hot to prepared joints or cracks. MDOT currently has a moratorium on the use of silicone sealants on concrete pavement joints since 2000 due to "excessive failures" (Michigan Department of Transportation, 2017c, p. 6.04.04.E.05)). MDOT commonly used preformed compression seals in the past for long-jointed JRCP, but not currently with JPCP.

Joint resealing or crack sealing have been widely used in Michigan (Ram and Peshkin, 2013, pp. vi). If crack sealing is done correctly, it can restore the service life of a concrete pavement by one to three years if the pavement is in good to fair condtions (Michigan Department of Transportation, 2017a, pp. 5-29).

MnDOT considers joint/crack (re-)sealing as one of its four concrete pavement repair treatments. It recommends that "before sealing, the joint/crack [must be] cleaned by sand blasting and air blasting (Minnesota Department of Transportation, 2003). While both air and pavement temperature play a role in the successful application of joint/crack sealant, Morris (2016) emphasizes that "having a dry road is even more important" (Morris, 2016, p. 78). The FHWA notes that hot-applied (re)sealant can be used in the winter but recommends "softer, more flexible sealant for working cracks (Morris, 2016, p. 78).

MnDOT describes seven different types of joint/crack (re-)sealing treatments, primarily using hot-pour or silicone sealants as repair materials (Minnesota Department of Transportation, 2003, pp. 3-4). According to New Mexico DOT, the main properties of a good sealant are durability, extensibility, resilience, adhesiveness, and cohesiveness (New Mexico Department of Transportation, 2007, pp. 210-211). The New Mexico DOT's *Pavement Maintenance Manual* provides a list of sealant materials with their physical properties, corresponding ASTM standard, and their estimated cost (New Mexico Department of Transportation, 2007, p. 208).

3.4.41 Hot-pour Joint Sealant

This is an MDOT current practice.

Hot-pour sealant is a maintenance material designed to seal pavement cracks from the intrusion of debris and water, helping to prevent spalling and pumping of joints. It is also a transverse joint sealant. Some types of hot pour sealants include coal tars and silicones (N. J. Delatte, 2008, p. 312). Hot-pour sealants can be used to treat cracks that are $^1/_8$ to $^1/_2$ inch (3 to 12 mm) in width (N. J. Delatte, 2008, p. 312). Hot-pour sealants typically last 3 to 5 years, before resealing is necessary (N. J. Delatte, 2008, p. 312).

3.4.42 Pre-formed Joint Sealant

This is *not* an MDOT current practice.

Pre-formed compression joint sealants have been used throughout the United States and were a standard feature in the long-jointed JRCP used in Michigan prior to the adoption of short-jointed plain concrete pavements in the 1990s. A study by Eacker and Bennett (2000) conducted in Michigan found that the performance of the pre-formed compression joint sealant greatly exceeded that of five poured-sealant products applied to a section of newly-constructed concrete pavement on I-94 near Hartford. Since all six products cost roughly the same, the report recommended that pre-formed compression sealant continue to be used as the standard sealant type for newly constructed concrete pavements (Eacker & Bennett, 2000), noting that when MDOT switched to short-jointed JPCP in the early 2000's, hot-pour rubberized sealant became the standard. A study by Bakhsh and Zollinger (2016) similarly showed that pre-formed compression joint sealants had better performance than most of the other types of sealants evaluated, with the results suggesting that pre-formed compression joint sealers could last over 20 years.

Pavements in climates that experience a wide range of temperatures can result in excessive joint movement that can damage the preformed compression sealant, especially for long-jointed JPCP. Preformed compression sealants contain an internal structure that generates compression that holds the sealant in place when inserted into the joint. These sealants can be damaged (known as compression set) in the summer months when the joint tightly closes and can become loose and dislodge during winter months when joints open.

Other Materials

3.4.43 Nanomaterials

This is *not* an MDOT current practice. It is still an emerging technology; therefore, the research team recommends reviewing this practice again as more research becomes available. Even though adopting nanomaterial modification at this time is not recommended, future research may find that this practice may be promising for increasing the service life of pavements in wet-freeze climates.

Nanomaterials—such as nano-silica and nano-titanium oxide—can be introduced into concrete in order to modify the pavement material's mechanical behavior and performance (Birgisson, Mukhopadhyay, Geary, Khan, & Sobolev, 2012, p. iii). Many studies have been conducted to address problems related to nanomaterials, such as proper dispersion; compatibility of the nanomaterials in cement; processing, manufacturing, safety, and handling issues; scale-up; and cost (Birgisson et al., 2012; Sanchez & Sobolev, 2010). Pavements that have been modified with nanomaterials have shown increased resistance to thermal-induced cracking, a valuable property for pavements in wet-freeze climates. Based on several recent studies, incorporating nanomaterials into concrete may possibly offer increased compressive strength increase tensile strength, and improved bound force between the aggregate and paste; as a result, a nanomaterial-modified pavement can have increased resistance to thermal cracking (Birgisson et al., 2012; Kumari et al., 2015; Norhasri, Hamidah, & Fadzil, 2017; Shah, Hou, & Konsta-Gdoutos, 2015). Nanomaterials can also reduce a pavement's permeability, which mitigates its vulnerability to freeze-thaw deterioration (Birgisson et al., 2012; Norhasri et al., 2017).

3.4.44 Phase Change Materials

This is *not* an MDOT current practice. It is still an emerging technology; therefore, the research team recommends reviewing this practice again as more research becomes available.

Phase change materials (PCMs) are substances that may be organic (either paraffin or non-paraffin PCMs), inorganic (either salt hydrates or metallic PCMs), or eutectic (composed of two or more different components) (George, 1989; Lane, Kott, & Rossow, 1977; Sharma, Tyagi, Chen, & Buddhi, 2009). PCMs have relatively high latent heats of fusion. Adding PCMs to concrete pavements increases their thermal inertia and reduces a pavement's susceptibility to damage caused by freeze/thaw cycles. Sakulich and Bentz (2011) have suggested that incorporating PCMs into pavement materials is a promising method for constructing and maintaining pavements in wet-freeze climates (Sakulich & Bentz, 2011). However, even though non-wet-freeze states have seen an additional service life of more than one year for PCM-modified bridge decks, states with wet-freeze climates that have used PCMs in bridge decks have typically seen less than one year of additional service life (see Figure 14) (Sakulich & Bentz, 2011).

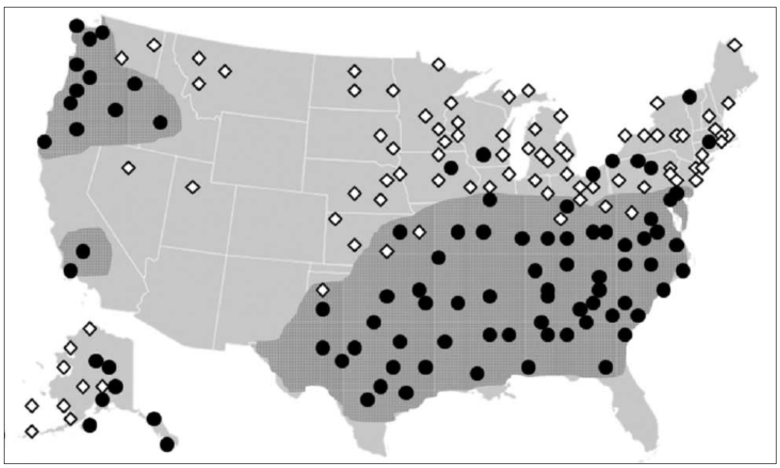


Figure 14: Locations in which incorporation of the maximum 120 kg⁄m3 of PCM increases bridge deck service life by less than 1 year (◊) or more than 1 year (•) (Sakulich & Bentz, 2011)

A study by Bentz and Turpin (2007) showed that the presence of a PCM in the concrete pavement can efficiently decrease the "number or intensity of freeze/thaw cycles experienced by a bridge deck or other concrete exposed to a winter environment" (p. 527). While the average decrease for 12 U.S cities was approximately 29%, the freeze-thaw-related cycles in concrete with PCM decrease by as much as 100% for Tampa, Florida (the control concrete experienced 4 freeze-thaw cycles), and as little as 19% for Cheyenne, Wyoming (the control pavement experienced 131 freeze-thaw cycles) (Bentz & Turpin, 2007, p. 531). Alpena, Michigan, experienced a 24% decrease (the control pavement experienced 107 freeze-thaw cycles in comparison to 81 for the PCM concrete) showing that PCMs may be helpful in extending a pavement's service life in Michigan's wet-freeze climate (Bentz & Turpin, 2007, p. 531).

3.5 CONSTRUCTION

Earthwork

3.5.1 Machine-guided Excavation (Total Station)

This is an MDOT current practice.

Use of the Global Positioning System (GPS) to for grading equipment on pavement projects is quickly becoming common technique.

In wet-freeze climates, Iowa, Maryland, Missouri, MnDOT, New York, and Wisconsin have experience with GPS machine guidance and have developed specifications or guidelines (Vonderohe, 2007; Wisconsin DOT, 2018).

Machine guided construction is a growing technology, being used more and more in the future.

3.5.2 Automated Grade Control

This is an MDOT current practice, and it is an emerging technology.

Automated—or automatic—grade control provides an improvement in efficiency and project completion times; although this benefit is not specific to pavements in wet-freeze climates, those pavements nonetheless receive the general, all-around benefits of automated grade control. Automated grade control simplifies and accelerates grading procedures by automatically adjusting the height and angle of equipment blades to produce a programmed grade for a particular construction site, allowing operators to concentrate on controlling the vehicle's speed and direction. It is used prior to placement of pavement during the grading process. Automated grade control works using either 2D or 3D positioning systems that transmit information to an on-board computer, which then compares the current grade with a programmed desired grade and adjusts the vehicle's blade as-needed (Caterpillar, 2017). Most construction projects that require a surface to have specific slope or grade can benefit from using automatic grade control. John Deere advertises benefits that can be obtained from grade control technology, like efficient site work for a shopping mall with parking lots, and other companies advertise capabilities such as flatwork, path construction, and a variety of grading options for their automated grade control systems (Bobcat, 2017; Caterpillar, 2017; John Deere, 2017). Automated grade control technology has been in use for years, both in and out of Michigan.

Drainage

Drainage problems result from the failure of one of the two standard drainage processes (Virginia Asphalt Association): surface drainage that sheds surface water and subsurface drainage that allows free water to drain vertically through the drainage layers of a pavement. When free water infiltrates the subsurface and is retained there, pore pressure can increase, which can lead to reduced load transfer properties (Ridgeway, 1982, p. 4) as well as decreased pavement performance in terms of roughness, rutting, and cracking (Kathleen Theresa Hall & Correa, 2003, pp. 48-49). Water retention in the base or sub-base becomes further complicated in a wet-freeze environment because the water is a source of moisture for frost generation on the surface of the road (Ridgeway, 1982, p. 4). Therefore, a well-performing subsurface drainage system is necessary in wet-freeze climates like Michigan to guarantee optimal pavement service life and safe driving surfaces. Maintaining surface and subsurface drainage systems aids in keeping a pavement structure in a good condition (N. J. Delatte, 2008, p. 314).

3.5.3 Pipe Culvert

This is an MDOT current practice.

Culverts—or embedded pipes, typically made of concrete or steel, surrounded by soils—are critical for directing water underneath a road. For several reasons, culverts may not keep up with the water flow amounts in some cases. Undersized culverts can lead to road damage like blowouts or collapse. Therefore, Maine DOT has developed a prototype diffuser and, in 2016, demonstrated success in one highway application (Mann, 2016). The design of the diffuser was based on the flared design of draft tubes in the hydroelectric field. When culverts are submerged, outlet loss tends to be the greatest contributor to total head loss; the diffuser reduces this loss, resulting in an increased culvert capacity (Larson and Morris, 1948, in Mann, 2016, p. 4). Their diffuser system is easy to make and install, inexpensive, and effective at increasing pipe capacity (Mann, 2016, Abstract).

3.5.4 Drainage Structures

This is an MDOT current practice.

Drainage structure includes all types of manholes and inlets such as grate inlets, curb inlet, slotted inlets, catch basins, and leaching basins. Drainage structure are used to limit the spread of water on the driving lanes.

In Michigan, MDOT designs and constructs its drainage structure according to the *Road Storm Drainage System*, which introduces inlet locations, inlet spacing, and manholes (Michigan Department of Transportation Design Division, 2000).

The maintenance of drainage structures consists of removing debris that collected on covers and in sumps. Covers are recommended to be inspected and cleaned twice a year and sumps are recommended to be cleaned once or twice a year when needed.

Hot-mix Asphalt Pavements and Surface Treatments

3.5.5 Percent Within Limits Acceptance

This is an MDOT current practice.

Percent Within Limits (PWL) is defined as "the percentage of material within the specification limits or tolerance for a given quality index parameter". The quality index parameters include air voids content, voids in mineral aggregate, binder content, and mat density. PWL is a statistical method of acceptance, which can use an excel spreadsheet for pay calculation. MDOT published a special provision— 12SP-501U. In this special provision, the quality control and quality assurance procedures will be obeyed for acceptance and payment for Superpave HMA.

3.5.6 Use of Warranties

This is an MDOT current practice.

To protect the MDOT from specific defects found in the project, MDOT published a series of special provisions on warranty work. For example, the materials and workmanship pavement warranty (12SP-500A) protects the MDOT from defects in materials and workmanship; the pavement performance warranty (12SP-500B) warrants the MDOT against specific defects found in the pavement.

In terms of new/reconstructed HMA pavement on unbounded or stabilized base, a special provision (12SP-501N) requires a 5-year warranty period and a warranty bond equal to one million dollars or five percent of the total contract amount whichever is less. The warranted work limits in all HMA driving lanes included in the project.

3.5.7 HMA Material Transfer Device

This is an MDOT current practice.

HMA Material Transfer Device (MTD) assists to obtain continuous movement of the paver and a uniform flow of consistent mix. In a specific provision (12SP-501CC), MDOT requires the use of HMA MTD on the following situations: (1) all mainline paving of rehabilitation and reconstruction projects on Interstate routes, limited access U.S. routes, and limited access M routes with more than 7,500 tons of HMA for an individual paving course except for gap graded Superpave; (2) Shoulder paved in a separate operation with inadequate base conditions and more than 5,000 tons of HMA for an individual paving course; (3) all rehabilitation and reconstruction projects and Capital Preventative Maintenance projects with more than 5000 tons of gap graded Superpave on the project.

3.5.8 HMA Longitudinal Joint Specification

This is an MDOT current practice.

A longitudinal joint is the interface between two connected and parallel HMA mats. Low longitudinal joint density can lead to premature deterioration of HMA pavement, such as cracking and raveling.

MDOT published special provision on acceptance of longitudinal joint density in HMA pavement (12SP-501Y). The longitudinal joint density will be obtained by the average of five consecutive longitudinal joint cores. Any longitudinal joint section density equal to or greater than 90.50 percent will have an incentive payment, while any longitudinal joint section density less than 90.50 percent will have a negative quality adjustment.

3.5.9 Echelon Paving

Echelon paving has been used in Michigan. But MDOT does not currently have a frequently used special provision for echelon paving.

Echelon paving is a construction method to eliminate longitudinal joints. It paves adjacent mats simultaneously so that the two mats can be compacted as one operation.

3.5.10 Regression of Air Void

This is an MDOT current practice.

Regression of air void is to obtain higher asphalt binder content due to some performance and durability concerns resulted from low asphalt binder content.

The idea of regression is to design a mix for 4.0 percent air void and then predict the amount of additional virgin asphalt binder needed to achieve 3.5 or 3.0 percent air voids. This will increase design asphalt content up to 0.4 percent. Michigan have done this to address the issue of dry mixes. In a published special provision (12SP-501J), “for mixtures meeting the definition of top or leveling course, field regress air void content to 3.5 percent with liquid asphalt cement unless specified otherwise on HMA application estimate; for mixtures meeting the definition of base course, field regress air void content to 3.0 percent with liquid asphalt cement unless specified otherwise on HMA application estimate”.

3.5.11 Ride Quality Requirement

This is an MDOT current practice.

MDOT published a ride quality special provision (12SP-501K) that uses profile data for acceptance testing of the final riding surface. This special provision is applicable for either HMA pavement or concrete pavement. The international roughness index (IRI) is used to quantify the level of ride quality obtained from construction.

3.5.12 HMA Production Manual

This is an MDOT current practice.

To provide highest quality HMA, MDOT published HMA production manual to provide guidance to administrative, engineering, and technical staff. This manual consists of four parts from HMA design, to HMA production, and to HMA testing. It provides the mix design guideline for Marshall and Superpave HMA mixtures. The details on Superpave mix design can refer to section 3.2.1. In addition, it also provides the requirements for certifying HMA plants and the checklists for field testing as well as criteria used in sampling and testing HMA.

3.5.13 Intelligent Compaction

This is *not* an MDOT current practice. It is still in field trials and monitoring; therefore, the research team recommends reviewing this practice again as more research becomes available.

Intelligent compaction (IC) could improve the compaction uniformity and increase the quality of asphalt pavement. Without good compaction, a pavement will have higher air-void content, which increases the likelihood of raveling, water infiltration and increased hydraulic pore pressure, and consequently premature stripping (Kandhal, 1992, p. 8). Controlling the amount of moisture present within an asphalt pavement structure is important for preventing moisture-related damage in a wet-freeze climate. IC is a new technology that can apply to field compaction of pavement materials, such as soils (Camargo, Larsen, Chadbourn, Roberson, & Siekmeier, 2006), aggregate bases, or asphalt pavement materials (Chang, Xu, Rutledge, & Garber, 2014). IC measures "soil stiffness…to estimate or compute in situ soil modulus"; these measurements are made by the compactor and can provide real-time feedback, allowing the compactor to adjust the amount of compaction 'on the fly' (Petersen & Peterson, 2006, p. 1).

IC has met with success in trials in wet-freeze climates. First, the Transportation Pooled Fund TPF-5(128) project team conducted a study that included 12 state DOTs: Georgia, Indiana, Kansas, Maryland, Minnesota, Mississippi, New York, North Dakota, Pennsylvania, Texas, Virginia, and Wisconsin (Chang et al., 2011); some of those states have wet-freeze climates, such as Minnesota and Wisconsin (see Figure 15). HMA IC proved to be effective at identifying weak support areas and tracking roller passes and HMA surface temperatures. Furthermore, IC data provided a compaction curve for a specific material in a specific project and can produce semivariograms that are usable as a metric of compaction uniformity. Second, in 2005, Minnesota implemented IC on the Mn/DOT TH 53 project in Duluth, Minnesota (Petersen & Peterson, 2006). Compared with the *in situ* testing, the IC data has poor correlations on a point-by-point basis while it has good correlations with dynamic-cone penetrometer for depths ranging from 8 to 19 inches (20 to 48 cm) (Petersen & Peterson, 2006). Up through 2015, MnDOT applied IC on 37 projects of asphalt pavements and 26 projects of bound/unbound materials (Embacher, 2015).

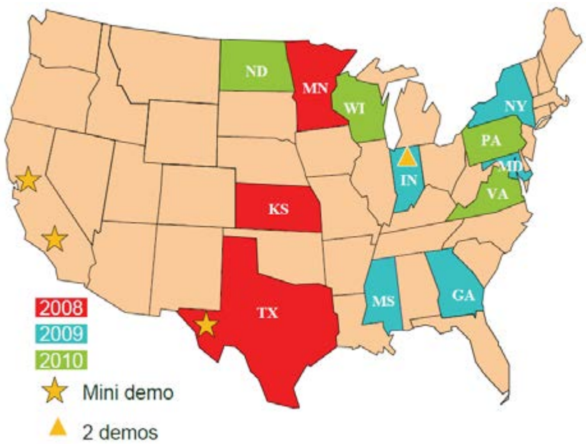


Figure 15: Participating TPF State DOTs and schedule for IC field demonstrations (Chang et al., 2011)

Concrete for Pavements

3.5.14 Percent Within Limits Acceptance

This is an MDOT current practice.

Percent Within Limits (PWL) is used to “determine acceptance and payment for mainline, shoulder, miscellaneous concrete pavement (including ramps), and concrete pavement overlays”. MDOT published a special provision— 12SP-604B. In this special provision, the quality index parameters include 28-day compressive strength and air content of fresh concrete.

3.5.15 Slip-form and Fixed-form Paving

This is an MDOT current practice.

Concrete paving can be done in one of two ways: via slip-form paving and via fixed-form paving. The goal of slip-form paving is to “consolidate, form into geometric shape, surface finish a concrete mass (vertical or horizontal) by a ‘slipping’ or pulling the forms continuously through and surrounding the plastic concrete mass”, which allows workers to pave concrete with high production and a very smooth surface (N. J. Delatte, 2008, p. 264). For doweled JPCP pavements, basket assemblies or dowel bar inserters may be used to install dowel bars; and, tie bars that cross longitudinal joints are placed on chairs before the paving or inserted into the fresh concrete (N. J. Delatte, 2008, pp. 267-270). Fixed-form paving, on the other hand, makes use of “molds staked to the subgrade or base to hold the concrete in place”, which dowel basket and tie bar assemblies are installed with chairs like slip-form paving (N. J. Delatte, 2008, pp. 267-270). Common applications for fixed-form paving include streets, local roads, and pavements with “complicated geometry, short length, or variable width” (N. J. Delatte, 2008, p. 271).

3.5.16 Stringless Paving

This is an MDOT current practice.

Traditional pavement construction technology depends upon physical guidance systems. These systems rely on lines strung tautly on each side of a slip-form paver that demarcate the paving area and elevation. Setting string lines for and adjusting string lines during the concrete paving process is cumbersome, and a source of error if done incorrectly or if a string line is accidently shifted during paving (for example if tripped on or run over by equipment).. To simplify this process, Cable, Bauer, Jaselskis, and Li (2004) studied the use of global positioning systems (GPS) in hopes of developing a multidimensional design model that feeds the automated paving machine control system for control of the top of subgrade elevation and the top of paving elevations” (Cable et al., 2004, p. 1) (see Figure 16). GPS is known to have less precision than ideal for paving operations, and thus modern stringless paving systems rely heavily on total stations that are set up and moved as the paving operation progresses.

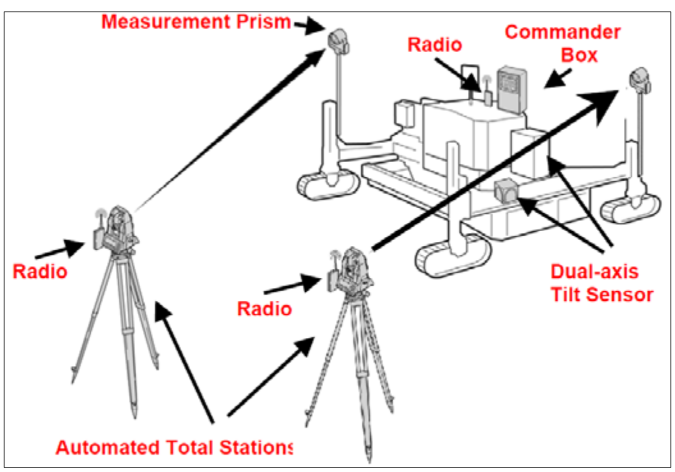


Figure 16: Stringless paving

Stringless paving has been used in two separate projects in Washington County, Iowa, in 2003 (Cable et al., 2004); a tunnel paving project in the United Kingdom in 2003 (Pope, 2015, pp. 16-

17); a tunnel paving project in Germany in 2009 (Pope, 2015, pp. 16-17); and a sidewalk, barrier, curb, and gutter project in Verona, Wisconsin, in 2015 (American Concrete Pavement Association, 2015). It is a commonly used technique for slipform paving in many locales around the country.

3.5.17 Real-time Smoothness

This is *not* an MDOT current practice. The research team recommends reviewing this practice and consider implementing.

Real-time smoothness refers to "measuring and evaluating the concrete pavement surface profile during construction, somewhere along the paving train while the concrete surface is still wet (plastic)" (Fick, & Sohaney, 2013). The measured profiles indicate which factors that affect pavement smoothness. With such information, paving operations can be adjusted on the fly.

Real-time smoothness measurement of concrete pavements has been evaluated on paving projects in Michigan, New York, and Pennsylvania although there is limited published information about these demonstration projects (Fick, 2016; Rasmussen, Torres, Karamihas, Fick, & Sohaney, 2013). This work continues at the National Center for Concrete Pavement Technology and shows great promise in reducing the as-constructed roughness of concrete pavements.

During many of the field evaluations of real-time smoothness measures, it was observed that the contractor had a significant degree of difficulty mounting the measurement device onto the paver. Also noted was that the vibrations of the paver can affect the smoothness measurements, which limit the use of these surface movements to control the construction process. Therefore, the contractor must be willing to embrace the use of real-time smoothness technology as a system and a process since installation of the device alone will not result in improved smoothness. The contractor must actively monitor the smoothness measurements and act on its feedback to see smoothness improvements.

The use of real-time measurements has been demonstrated to reduce the pavement's International Roughness Index (IRI) by 20% while also allowing for easier locating/repairing of surface irregularities. Once the technology is purchased and installed by the contractor, the contractor can continually make use of the technology. The value of real-time measurements is that the contractor receives instant feedback that can then be used to see the effects of process changes, like paving speed or vibrator frequency, on the pavement smoothness.

3.5.18 Two-lift Concrete Paving

This is *not* an MDOT current practice. It is still in field trials and monitoring.

Two-lift concrete pavement construction can produce pavements (see *Two-lift Concrete Pavement* sub-section in the *Pavement Types: Concrete* section of this report) that can optimize the use of materials to cost-effectively create a more wear-resistant, durable surface (Federal Highway Administration, 2007). According to the International Road Foundation (2016), two-lift concrete paving can have a surface layer composed of a coarse exposed aggregate (that is, "double broken and double screened chippings with high angularity, grain shape, and resistance to polishing"), which is placed on a structural concrete bottom-lift using a wet-on-wet slip-form paving technique (p. 37). Sometimes the paving process is followed by brooming of the surface in order to expose the aggregate (International Road Foundation, 2016, p. 37). The bottom lift is typically 200-240 mm thick and 350 kg cement/m^3; while the wear-resistant top lift is typically 50-80 mm thick with 420 kg cement/m^3 (International Road Foundation, 2016, p. 37). If an exposed aggregate surface is desired, the pavement is sprayed with a retarding agent (International Road Foundation, 2016, p. 37) to delay setting of the concrete surface until it can be broomed off. When done correctly, this technique creates a pavement that reduces road noise with improved skid resistance.

Two-lift concrete paving has been used in various segments along Germany's high-speed Autobahn network. In particular, a 2.8-mile (4.5-km) section and a 3.3-mile (5.3-km) section of the A1 highway were rehabilitated and rebuilt, respectively; a 1.4-mile (2.3-km) section of the A5 highway was improved; and a 3-mile (4.8-km) section of the A9 underwent improvement. Two layers of concrete were laid using a wet-on-wet standard slip-form paving process. "To achieve wet-on-wet slip-form paving, the bottom-layer paver is equipped with dowel bar and tie bar inserters while the top-layer paver uses a finishing beam and super smoother to produce a level surface. The pavers feature an intelligent control system to optimize quality, with a texture curing machine providing the finish." During the curing process, this German project used a surface retarding agent and a dispersion for the exposed aggregate surface; the purpose of the retarding agent was to "[delay] the setting and initial hardening of the concrete surface for a limited time, while the dispersion prevents the surface from drying out and cracking" (International Road Foundation, 2016).

3.6 MAINTENANCE/PRESERVATION

Drainage

3.6.1 Open-graded Underdrain Outlet Cleaning and Repair

This is an MDOT current practice. This practice is uncommon but gaining momentum.

In order to provide effective drainage, edge drains must be properly maintained over the life of the pavement. Cleaning of these drains must be performed regularly or else the drain outlets can become damaged or plugged, which results in system backup and permanent saturation of the pavement system. Additionally, installation damage can be prevalent with these systems, particularly with geocomposite edge drains, which can lead to backups and pavement damage (Baumgardner, 2002). Daylighted drainage systems are commonly used as an alternative to reduce or mitigate the effects of these backup problems because of improper cleaning and can be used in roadways with flat grades and shallow ditches. Gisi, Brennan, and Luedders (2004) reported that both full and partial daylighted drainage systems can perform as well as a drainage system consisting solely of pipes and outlets (such as edge drain systems) and they are not inherently prone to problems of system pipe plugging. The FHWA's Concrete Pavement Technology Program's TechBrief *Daylighted Permeable Bases* provides guidance for materials, design, construction, and maintenance of daylighted drainage systems (K. Hall & Tayabji, 2009). Daylighting drainage systems may not be desirable in harsh freeze environments due to winter freeze effects on outflowing water from base materials (Gisi et al., 2004, pp. 16-17).

In Michigan, MDOT bases its pavement drainage system designs on the drainage section of its *Road Design Manual*, which introduces drainage outlets, ditches, design criteria for roadway culverts, and underdrains (Michigan Department of Transportation Design Division, 2000). For purposes of storm sewer design, the manual delineates Michigan into four zones based on rainfall.

Drainage systems can also consist of ditches and French drains (perforated pipes buried in a trench and backfilled with gravel or rock). The Ontario Ministry of Transportation (MTO) specifies rural roads in the wet-freeze climate of Ontario, Canada, have ditches that collect and remove excess surface water should have an invert of at least 1.6 feet (0.5 m) below the top of subgrade in earth cut sections and of at least 0.8 feet (0.25 m) below the base of the fill sections (MTO Materials Engineering and Research Office, 2013, p. 129). The MTO specifies protocols for an open-graded drainage layer and also requires installation of a filter protection for drainage systems to prevent clogging due to fine aggregates (MTO Materials Engineering and Research Office, 2013, pp. 129-133).

3.6.2 Drainage Retrofit

This is an MDOT current practice. In the past, MDOT has done some conventional drainage retrofitting in which a 4 to 6 inch (10 to 15 cm) slot was cut at the lane/shoulder joint using a wheel saw and a fin drain (a plastic core wrapped in geotextile) was inserted and connected to lateral drainage pipes. Today, when they do an unbonded concrete overlay, for example, if drainage is an issue they remove the shoulder and install a 6 inch (15 cm) diameter perforated pipe, which is connected to lateral drains.

Drainage retrofit is generally used in rehabilitation, restoration, or maintenance projects on newer roads (i.e., less than 15 years) where pavement damage is visible and no functioning subsurface drainage system exists. The purpose of the retrofit is to restore proper drainage of a pavement subsurface. The State of New York uses two approaches to drainage retrofitting; conventional stone trench and pipe edgedrains (Figure 17) and prefabricated geocomposite edge drains (PGED). Conventional stone trench and pipe edge drain retrofits are commonly used in rubblized projects, where PGED retrofits tend to experience clogging of the geofabric pores, and in crack & seat projects. PGEDs can be placed directly in the subgrade as long as the soils are not excessively fine-grained, and are most effective when runs are less than ninety meters. The stone trench and pipe method is preferred by New York State DOT due to an estimated service live of 10-25 years versus 5-10 years with PGED (New York Department of Transportation, 2002).

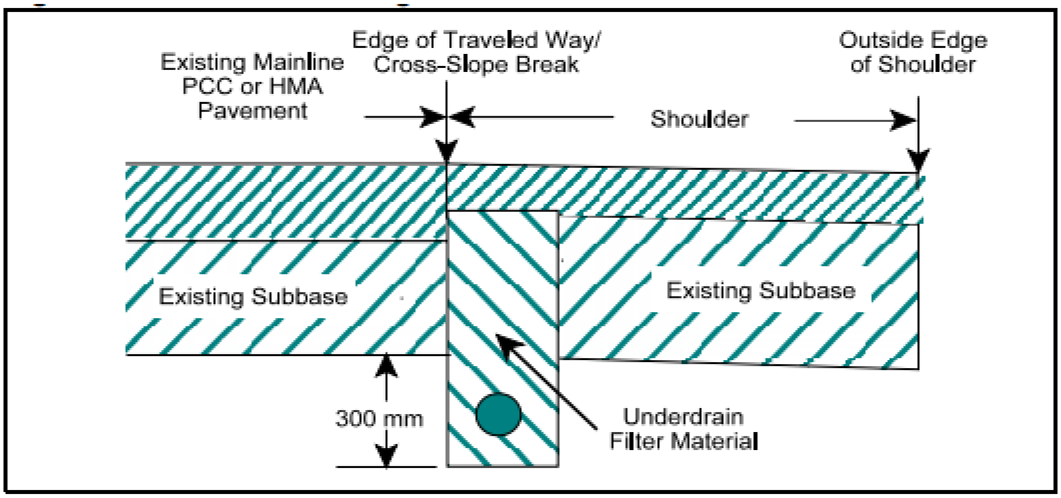


Figure 17: Prefabricated geocomposite edge drain (New York Department of Transportation, 2002)

Drainage problems lead to pavement damage in wet-freeze locations. Drainage retrofits provide a means of restoring proper drainage to a pavement system.

3.6.3 Drainage Information Analysis and Mapping System

Drainage system inspection is conducted by MDOT, however, MDOT does not currently inspect drainage systems on a network level, although it is advancing a mechanism to do this in the future. This is a current best practice for some agencies outside of MDOT.

An inspection system for drainage infrastructure is necessary to ensure a well-functioning transportation network. Since drainage systems operate 'behind the scene', it is challenging to maintain drainage structures in a good condition for a long time because it is easy to forget about drainage structures until they fail, causing catastrophe and potential closures of portions of a transportation network (J. Meegoda et al., 2012, p. 2). One available solution for evaluating underground drainage infrastructure assets and developing financially-sound preservation and maintenance strategies is the Drainage Information Analysis and Mapping System (DIAMS), developed by New Jersey DOT. DIAMS creates a condition assessment database consisting of cleaning and inspection information; cost analyses for preservation, maintenance, and repair; and best management practices (J. Meegoda et al., 2012, pp. 6-7; J. N. Meegoda, Tang, Juliano, Potts, & Agbakpe, 2017, p. 1).

Once a pipeline is in place, state agencies should mark or map their drainage pipelines in order to locate them and provide adequate maintenance (Baumgardner, 2002). Marking or mapping drainage pipelines has been known to help find pipe outlets if they become buried and lost (Baumgardner, 2002). Periodic video inspection of drainage systems can be used to determine developing problems before they lead to system failure (Baumgardner, 2002, p. 6). Pipe flushing units can clear clogged pipes; these units operate by forcing water through the clogged pipe sections by use of water jets (Baumgardner, 2002, p. 6). Pipe outlets should also be closely monitored and maintained to prevent plugging and backups (Baumgardner, 2002, p. 6). Sediment buildup and excessive vegetation growth at these pipe outlets can plug the outlets, causing backups; additionally, unmaintained pipe outlets can become lost under the debris that are causing backups (Baumgardner, 2002, p. 1). This practice is not specific to a wet-freeze climate.

Hot-mix Asphalt Pavements and Surface Treatments

3.6.4 HMA Patching

This is an MDOT current practice.

Patching is a maintenance treatment that can be used to fill potholes and other distresses that result from freeze-thaw cycles with asphalt concrete. The benefits of HMA patching include a relatively short wait time before traffic is allowed to pass over the patched area and a temporary solution for distresses like alligator cracking and potholes. Patching can be limited by the availability of HMA throughout the year (A. M. Johnson, 2000, p. 57). Local agencies and contracting companies in Michigan use HMA patching as part of their preventive maintenance programs (City of Alpena Engineering Department, 2016; Michigan Paving & Materials Company, 2017).

In 2016, MnDOT published a report indicating that taconite-based pothole repair methods proved durable and cost-effective. The microwave method heats the pavement to a high temperature to encourage the material (often containing recycled asphalt pavement or recycled asphalt shingles) to bond to the pavement (Zanko, 2016). This method demonstrated good performance by lasting up to three years, in some cases (Zanko, 2016).

MDOT may try the microwave method to fill potholes based on the ability of the operator.

3.6.5 Crack Filling and Crack Sealing

This is an MDOT current practice.

Crack treatment prevents water and debris from entering pavement cracks by filling or sealing the crack. Crack filling treatments are applied to non-working, stable, cracks as a means of preventing infiltration of water and debris. Crack sealing treatments are applied to working cracks and generally require more preparation and specialized materials.

Longevity of a crack treatment depends upon reviewing the history of the pavement segment, evaluating the crack, and selecting the appropriate treatment methods and materials. A crack treatment can provide upon to three years of extended service life, although that extension is contingent upon the width of the sealed crack and movement of the pavement structure (Michigan Department of Transportation, 2010a, p. 19).

3.6.6 HMA Longitudinal Joint Sealer

This is *not* an MDOT current practice. Even MDOT has several trials, the research team recommends implementing this practice in more projects.

The longitudinal joints on hot-mix asphalt pavements are usually the first location that fails. The goal of a longitudinal joint sealer is to fill air voids and reduces the permeability at joints (Illinois Department of Transportation, 2012) to delay water infiltration damage. Longitudinal joint sealers are a part of Illinois DOT and New York DOT specifications. According to the research team's investigations, Illinois DOT will use 100% of J Band® (or similar) material in all of their longitudinal joints. Illinois DOT and New York DOT have made special provisions to guide regional engineers on how to accept and use longitudinal joint sealants (Illinois Department of Transportation, 2017; New York Department of Transportation, 2017). In addition, Ohio DOT is preparing to draft specifications and to execute two pilot projects related to longitudinal joint sealer in 2017.

Longitudinal joint sealer is not a new technology but is relatively new with regard to its application in Michigan. Ingham County participated in a manufacturer-initiated trial about a year ago. A barrier to MDOT implementation of longitudinal joint sealer would be the limited usage that this technology has had in Michigan. The research team believes that five- and ten-year field and monitoring trials would be beneficial, and they also recommend investigation into developing a standard specification for longitudinal joint sealer.

3.6.7 Chip Seal (Seal Coat)

This is an MDOT current practice.

Chip seal (seal coat), also known as bituminous surface treatment (BST), is a road surface treatment that consists of a spray-on asphalt covered with aggregate. Chip seal treats non-load-related cracking, which is commonly caused by moisture-related damage, and protects a pavement against sun and water related deterioration; it also provides a wearing course with improved friction and helps prevent freeze-thaw damage (Michigan Department of Transportation, 2016a) . The application of chip seal has been regarded as a preventive maintenance tool to enhance the pavement preservation benefits since the 1920s (Gransberg & James, 2005, p. 1). MnDOT conducted a study in 1998 to address one of the most commonly cited problems associated with chip seal: loose aggregate, especially on high-volume (greater than 2000 average daily traffic) roadways (Thomas J Wood, 1999). By evaluating the use of larger-sized aggregates, polymer-modified emulsion, and different design methods, the study determined that chip seal retention could be improved by a combination of factors such as the quality of materials used, the rates and timing asphalt binder application followed by aggregate application, and cleaning of the pavement before application as well as sweeping of the pavement after application (Thomas J Wood, 1999, pp. 1, 15). Subsequently, in 2006, MnDOT published *Minnesota Seal Coat Handbook 2006* to provide field inspectors with a better understanding of the "materials, equipment, design, and construction" for chip seal use (Thomas J Wood, Janisch, & Gaillard, 2006). Furthermore, MnDOT developed the Seal Coat Design Program, software to help agencies "determine the materials, the application rates, and the quantities" for chip seal (Minnesota Department of Transportation).

MDOT used chip seal extensively prior to 1972 (Michigan Department of Transportation, p. 6.03.20). However, between 1972 and 1987, MDOT adopted a practice of paving with a single course of HMA for effectively sealing a road to prevent water infiltration from joints and both large and small cracks (Michigan Department of Transportation). Due to results that other states were having with chip seal, MDOT resumed its use of chip seal in 1987 as a preventive measure to seal small cracks and improve ride quality (Michigan Department of Transportation). Local agencies in Michigan regularly use chip seal as part of their preventive maintenance programs (Michigan Department of Transportation, 2016b). MDOT specifies chip seals for only low-volume rural roads and/or HMA-surfaced shoulders (Michigan Department of Transportation, 2010b, p. 16).

3.6.8 Slurry Seal

This is an MDOT current practice.

Slurry seal increases the friction of pavement surface which, in turn, can enhance pavement safety in wet-freeze climates. Slurry seal is a homogenous mixture of emulsified asphalt, well-graded fine aggregates, mineral fillers, and water. It is applied with a squeegee-equipped distributor to the pavement surface in order to "seal the underlying surface from water infiltration, fill cracks and voids, and improve friction and appearance of an existing pavement" (Merritt, Lyon, & Persaud, 2017, p. 30).

Though a slurry seal cannot act as a structural layer or reinforcement, its cost-effective nature and its ability to increase friction on the road and seal pavement from water infiltration make it an important treatment in wet-freeze climates (Merritt et al., 2017, p. 30). In Michigan, a 1982 study evaluated the use of slurry seal as a surface treatment for the asphalt lanes on the Mackinac Bridge; it concluded that slurry seals that have a 9.5% cationic emulsion and used slag sand had fast curing rates and optimal performance (Felter & Norton, 1982, pp. 1, 3-5). In 2012, MDOT issued the *2012 Standard Specifications for Construction*, which prescribed a mixture of Type I portland cement, fine aggregate 2FA, asphalt emulsion CSS-1h, water, and other additives for making a slurry seal (Michigan Department of Transportation, 2017e, p. 279). Slurry seal is a preservation treatment that is considered to have limited application for high-traffic-volume roads in wet-freeze climates (Peshkin et al., 2011, p. 8).

3.6.9 Fog Seal

This is an MDOT current practice.

Fog seal is a low-cost preventive maintenance used to restore HMA surfaces by sealing minor low-temperature cracks. Fog seal is a slow-setting asphalt emulsion that typically has no aggregate cover (however, in some cases, it may be covered with a sand seal). It can be applied to an asphalt road surface to “seal minor cracks, prevent raveling, and provide shoulder delineation” as well as to restore the flexibility of an asphalt surface, which can help reduce water infiltration in wet-freeze climates.

Fog seals are an inexpensive way to restore an HMA surface and add binder to an aged surface. They can also be used along with chip seals to fix the chips firmly to the road, improving safety (California Department of Transportation, 2003, pp. 6-1). Fog seals require aggregates when used on smooth road surfaces in order to ensure that the road does not become slippery (California Department of Transportation, 2003, pp. 6-5). However, rain and cold temperatures will prevent the fog seals from fully curing, which likely leads to a more slippery surface as well (California Department of Transportation, 2003, pp. 6-5). Minnesota research found that fog sealing over a chip seal can limit the amount of snowplow damage on the pavement by increased embedment of the aggregate and through the combination of binders working together (Thomas J. Wood, 2012).

A fog-sealed road requires road closures for several hours to cure properly and creates a very smooth surface that can lead to loss of skid resistance (A. M. Johnson, 2000, pp. 38-39). Fog seal is often limited to shoulders and parking lots where pavement friction is not a critical consideration (A. M. Johnson, 2000, pp. 38-39). Fog seal is an infrequent preservation treatment for high-traffic-volume roads and is not effective as a long-term fix (Peshkin et al., 2011, p. 4). Furthermore, fog seal reduces surface friction after its initial application.

Local agencies in Michigan regularly use fog seal as part of their preventive maintenance programs (Michigan Department of Transportation, 2016b). In Montcalm County, Michigan, MDOT implemented a fog seal/ chip seal combination on a 9-mile (14.5 km) section of M-46 (Michigan Department of Transportation, 2017). MDOT's 2012 Standard Specifications for Construction addresses fog seal as an application that can be used in conjunction with chip seal (Michigan Department of Transportation, 2017e, pp. 273, 275).

3.6.10 Cape Seal

This is an MDOT current practice.

A cape seal is a pavement surface treatment combining an asphalt emulsion chip seal followed by an asphalt emulsion slurry seal. It is intended to be an economical and durable pavement layer or surface layer that can seal existing pavements from air and moisture, and provide a skid resistant driving surface. The cape sealing process limits loose stone, making this treatment suitable for high-traffic-volume pavements (Peshkin et al., 2011, p. 4; Washington State Department of Transportation, 2003). Cape seal can be used on pavements with high levels of distresses, such as significant cracking and raveling (Michigan Department of Transportation, 2010a, p. 16).

3.6.11 Rejuvenators

This is an MDOT current practice.

The main purpose of rejuvenators is to modify aged binder. Rejuvenators fall into two categories. The first category of rejuvenators, which is an MDOT current practice, is modifying agents for use in recycled asphalt pavement (RAP) used in new hot-mix asphalt pavement production, hot in-place recycling, cold in-place recycling, and full-depth reclamation. They work by restoring or freshening the asphalt binder (T. J. Van Dam et al., 2015, p. 7.15). This is a best practice that is not specific to wet-freeze climates.

The second category of rejuvenators is sealers for the pavement's surface, which minimize aggregate loss while improving the pavement's appearance (T. J. Van Dam et al., 2015, p. 7.15). Surface applied rejuvenators are products—like "refined tallow, waste vegetable or frying oils, waste motor oils, lube extracts, extender oils, emulsions, soft virgin binders, and bio-binders"—that "restore the physical and chemical properties of aged bitumen" (Farace, Buttlar, & Reis, 2016, p. 2). While rejuvenators are applied to asphalt surfaces, they are intended to be absorbed into the pavement (Farace et al., 2016, p. 2). Surface applied rejuvenators are still in the research stage and are not recommended as a best practice at this time.

3.6.12 Microsurfacing

This is an MDOT current practice.

Microsurfacing is a surface treatment typically used on asphalt pavements. It is made of polymer-modified asphalt emulsion, graded aggregates, mineral filler (e.g., non-air entrained portland cement or hydrated lime), water, and other special additives (e.g., emulsified solutions, aluminum sulfate, aluminum chloride, or borax) (Merritt et al., 2017, pp. 30-31). The polymer modification of the asphalt emulsion and the additives produce “a chemical break that is largely independent of weather conditions…[and that] forces water from the aggregate surface”; this contributes to a rapid setting of the microsurfacing treatment (California Department of Transportation, 2009, pp. 9-2). Microsurfacing is effective for preventing “raveling and oxidation of asphalt pavement surfaces…[and for improving] friction and appearance of both asphalt and concrete surfaces” (Merritt et al., 2017, pp. 30-31). Because microsurfacing is durable, it can be an effective treatment for high-volume roads (Merritt et al., 2017, pp. 30-31). Microsurfacing can improve the skid resistance of pavement surface and can seal pavements against water infiltration, thereby helping to prevent water from entering the base and causing thaw weakening of the base.

The International Slurry Seal Association (ISSA), now known as the International Slurry Surfacing Association, classified microsurfacing as a “slurry system” (International Slurry Surfacing Association, 2010). A slurry seal is a bituminous surface treatment composed of emulsified asphalt, fine aggregate, mineral filler, and water; it is used to protect the “underlying surface from water infiltration, fill surface cracks and voids, and improve friction and appearance of an existing pavement” (Merritt et al., 2017, p. 30). However, the modification of microsurfacing’s asphalt emulsion sets it apart from a standard slurry seal (Gransberg, 2010) because of the higher quality aggregates, which allow a thicker application of microsurfacing treatment (California Department of Transportation, 2009, pp. 9-2) .

MDOT has published guidelines for microsurfacing use in Michigan, which covers materials, construction, measurement, and costs, in its *2012 Standard Specifications for Construction* (Michigan Department of Transportation, 2017e, Section 504). Microsurfacing can be used on high-volume roadways to correct pavement surface conditions, like rutting, flushing, and low friction (Michigan Department of Transportation, 2010b). In addition, several states with wet-freeze climates have been using microsurfacing treatments (see Table 4).

Table 4: Microsurfacing Case Study (Gransberg, 2010)

Agency/Location	Case Study	Reason	Remarks
Maine DOT Caribou, Maine (Marquis, 2009)	Pavement preservation treatment	Pavement preservation; long-term performance in an area with heavy snowplowing	Demonstrates the performance of microsurfacing in cold, snowy climate; answers concerns that microsurface is not suitable for pavements with heavy snowplowing
Minnesota DOT Albertville, Minnesota (E. N. Johnson, Wood, & Olson, 2007)	Softer binder	Filling cracking and rut	Gives an alternative way to fill cracks
Minnesota DOT Monticello, Minnesota (Federal Highway Administration, 2011)	Improve safety	Reduce wet weather crash rates	Provides a cost-effective way for reducing wet-weather crashes
York Region Ontario, Canada (Erwin & Tighe, 2008)	Preventive maintenance treatment to improve safety	Safety; preventive maintenance	Demonstrates an application for microsurfacing in which pavement distress is not the primary issue

3.6.13 Stress-absorbing Membrane Interlayers and Texas Underseal

This is an MDOT current practice. MDOT published a special provision (12TM504-A630) for stress absorbing membrane interlayers.

Stress absorbing membrane interlayers (SAMIs) are used to help prevent reflective cracking over longitudinal and transverse joints and cracks as well as over patches prior to overlaying a pavement. The purpose of a SAMI is to allow the stress from an underlying crack to be distributed over the overlaying pavement. SAMI materials range from geotextiles to rubber-modified asphalt to Texas underseals.

Texas underseal is an application of a chip seal under an asphalt concrete overlay. The seal helps act as a moisture barrier keeping the underlying pavement and base layers from being infiltrated with surface water. Several Michigan local agencies have used the Texas underseal on their roadways; Wexford County and Kalamazoo County (Grossmann, 2017, p. 1). The Michigan agencies believe the underseal can act as a buffer between the distressed pavement and the overlay to help delay reflective cracking. The undersealed pavements were believed to have performed better than traditional HMA overlays (Grossmann, 2017, pp. 1,6). A survey of Texas districts found that many believe the application of an underseal can produce greater bond between the existing pavement and an HMA overlay, but the primary intent of the underseal is to serve as an effective moisture barrier (Estrakhri & Ramakrishnan, 2006, p. 16). The Texas survey indicated that some respondents noted a secondary effect of the underseal was the delay of reflective cracks (Estrakhri & Ramakrishnan, 2006, p. 26).

3.6.14 Conventional Overlay

This is an MDOT current practice.

Conventional HMA overlays are not unique to wet-freeze climates, but their benefits are applicable to wet-freeze problems. Overlays can be used to provide additional structural strength, provide increase skid resistance, and/or reduce water infiltration on older pavements.

3.6.15 Ultra-thin Overlay

This is an MDOT current practice.

Thin and ultra-thin bonded overlay can be used to treat minor surface distresses and restore surface friction and ride quality while minimizing traffic delays during the construction process (Peshkin et al., 2011, p. 38). Thin and ultra-thin HMA overlays consist of asphalt binder and aggregate and can be either dense graded, open graded, or stone-matrix asphalt (Peshkin et al., 2011). Thin and ultra-thin overlays are used as a surfacing, ranging in thickness from 0.75 to 1.50 inches (19 to 38 mm) for thin overlays to as little as 0.625 to 0.75 inches (16 to 19 mm) for ultra-thin overlays (Peshkin et al., 2011, p. 38). Thin HMA overlay using dense-graded HMA is referred to as a "non-structural" HMA overlay in Michigan's *Capital Preventive Maintenance Manual* (Michigan Department of Transportation, 2010a, p. 11). The overlays can provide a long service life when paved on "structurally sound" pavements as well as a surface that is smooth, easy-to-maintain, and recyclable (Watson, 2014, p3). H However, thin and ultra-thin overlays cannot correct for structural defects. Surface improvements from thin/ultra-thin overlays provide benefits in any weather, and can benefit roads in wet-freeze environments where water accumulation and infiltration are exacerbated by precipitation and the freeze-thaw cycle.

Ultra-thin bonded wearing course (UTBWC) is an HMA overlay that uses a gap-graded mixture with a polymer-modified asphalt binder. It is a routine option for thin overlays in Illinois, Minnesota, and Vermont (D. E. Watson & Heitzman, 2014, p. 6). Ohio DOT has been applying thin overlays on its highway systems for many years; it has found that project selection criteria play a critical role in guaranteeing a successful performance of thin overlays. Thin overlays are not suitable for correcting pavement surfaces with high quantities and severities of distresses (D. E. Watson & Heitzman, 2014, p. 21).

In Michigan, these overlays have been used for pavement maintenance. MDOT published a special provision—12SP-504C-04—for using ultra-thin overlays (Michigan Department of

Transportation, 2017d). For example, the Wayne County Department of Public Services cold-milled 0.9-miles (1.4 km) of Goddard Road and then paved the HMA overlays. In addition, Cass County Road Commission paved five sections on their road network. MDOT has also completed several HMA ultra-thin overlays in the Metro and Bay Regions, including I-94 from South River Road to 23 Mile Road, M-29 from Palms Road to Nook Road, and M-53 from north of the Macomb/Lapeer County Line to I-69.

3.6.16 Hot In-place Recycling

This is not an MDOT current practice. It is still in field trials and monitoring; therefore, the research team recommends reviewing this practice again as more research becomes available.

Hot in-place recycling (HIR) consists of three techniques: surface recycling, remixing, and repaving, which all share the common process of softening and mixing. Surface recycling is a process by which the existing asphalt surface is softened and then mixed with new asphalt and re-laid. Remixing is a process by which the existing asphalt surface is softened and then mixed with new HMA and re-laid. Repaving is a process by which the existing asphalt surface is softened and then mixed with new asphalt and re-laid in tandem with an HMA overlay (Peshkin et al., 2011, p. 39). Remixing and repaving can be used as preservation techniques, but they are often used as part of major rehabilitation efforts (Peshkin et al., 2011, p. 15).

HIR is used to treat distresses in the top 2 inches (5.1 cm) of an asphalt surface and can correct functional distresses, like surface cracking (affects thaw-weakening potential), raveling, and friction loss (affects skid resistance); however, HIR cannot address structural distresses (Peshkin et al., 2011, p. 39). HIR necessitates only minimal road closures, and roads receiving HIR treatment can be opened with traffic within 1 to 2 hours of treatment (Peshkin et al., 2011, p. 39). HIR has limited usage on high-volume roads in wet-freeze climates because HIR treatment should be conducted at temperatures higher than 50 °F (10°C) and there must be no rain (Peshkin et al., 2011, p. 39).

3.6.17 Cold In-place Recycling

This is *not* an MDOT current practice. It is best practice outside of MDOT, such as Iowa, Pennsylvania, and Wisconsin; therefore, the research team recommends reviewing this practice and consider implementing.

Cold in-place recycling (CIR) is a maintenance method for restoring an asphalt pavement surface. CIR involves pulverizing existing asphalt pavement, milling it, mixing it with new binder and new materials, and using the new mix as a base layer (Peshkin et al., 2011, p. 40). This mitigates surface distresses in the top 3 to 4 inches (7.6 to 10.2 cm) of a pavement (Peshkin et al., 2011, p. 40). It can be applied on moderate- to high-volume roadways together with an overlay or surface treatment (Peshkin et al., 2011, p. 40).

Cold in-place recycling (CIR) has been used throughout the U.S. for several years. Iowa, for example, has extensively used CIR, using this application in 53 projects and 1,800 lane-miles (2,900 lane km) constructed in the past five years (Schram, 2011). CIR treatments in Iowa have a predicted a service life of 21 to 25 years before requiring rehabilitation/reconstruction, although up to 34 years can be achieved when used in conjunction with high-quality subgrade (Jahren & Lee, 2007). Pennsylvania has had CIR projects that have performed an average of three years longer than their expected service life of 10 years (Morian, Oswalt, & Deodhar, 2004). Other states like New York, Virginia, and Wisconsin have been using CIR for over 10 years, according to a 2011 survey. Wisconsin uses CIR quite frequently, having constructed over 100 lane-miles (160 lane-km) of CIR each year. CIR is also used in several Canadian provinces; in these projects, CIR sections have typically been opened to traffic within about two days (Bergeron, 2005; Stroup-Gardiner, 2011).

One factor limiting the performance of CIR treatments is the subgrade quality, which supports the pavement layers above; using CIR on a pavement without a strong subgrade can result in a significant reduction in service life. CIR's materials mix design process also lacks a standard, to date. Most specifications currently used are method specifications, and only California, Tennessee and the District of Columbia have been using performance-based specifications. Finally, CIR needs warm, dry weather to cure properly, so the cold, damp weather in the late fall and early spring common in wet-freeze climates can be problematic.

CIR can be used in a variety of applications, and it is a cost-effective alternative to typical DOT rehabilitation strategies such as mill and overlay. CIR uses all of the existing materials of the pavement, which limits the amount of material the contractor has to bring to the site and reduces the amount of virgin material that has to be used. CIR treatments are relatively fast to construct, which allow for a quick turn-around time and minimal disruption to the traveling public.

3.6.18 Full-depth Reclamation

MDOT is current using HMA base crushing and shaping, which is part of full-depth reclamation process.

Full-depth reclamation (FDR) is a rehabilitation method that creates a new stabilized base course by pulverizing the entire thickness of an existing asphalt pavement—including its base, subbase, and subgrade—and optionally adding binders, additives, or water (T. J. Van Dam et al., 2015, p. 8.10). FDR can result in an enhanced pavement structure, restoration of the pavement surface, and reduction in frost susceptibility; however, FDR does not perform well in areas with drainage problems, it is not suited for high-volume and heavy-traffic-load roads, and it requires a pulverizer and specialized spreaders (T. J. Van Dam et al., 2015, p. 8.12).

Agencies have had mixed result using FDR. A 2011 NCHRP synthesis showed that Wisconsin had over 10 years of experience with FDR while such states as Illinois, Minnesota, and Iowa had between 5 and 10 years of experience using FDR treatments; most of these projects were performing well after several years of service (Stroup-Gardiner, 2011). In a survey conducted by the Minnesota DOT (MnDOT), numerous cities and counties in Minnesota reported regular use of FDR. Of these, several agencies stated they had a very good understanding of FDR, and have actively used FDR for several years. In one MnDOT study, Tang, Cao, and Labuz (2012) found that stabilized FDR had an average granular equivalency of 1.5 and had improved seasonal stiffness (p. 42). MnDOT has also conducted an economic analysis of FDR, which showed that FDR can be more cost effective than a traditional mill-and-overlay treatment (Hartman, Turos, Ghosh, & Marasteanu, 2016). Virginia DOT evaluated the condition of three FDR trial sections paved with a post-reclamation HMA overlay in 2008 and, according to Diefenderfer and Apeagyei (2011), have found that both the stabilizing agent and time determined the success of the FDR process (p. iii). They also recommended that refining a selection criteria list for future FDR projects (Diefenderfer & Apeagyei, 2011, p. iii). Wisconsin DOT and Maine DOT have published specifications for FDR techniques. In Quebec, Canada, both FDR and CIR techniques have been common practices since the early 1990s; these techniques have been used on nearly 932 miles (1,500 km) of pavement from 1990 to 2005 (Bergeron, 2005).

In Michigan, a 6-inch (15-cm) asphalt emulsion stabilized base course with FDR was used in Lenawee County, Michigan, in 2017 (Riga and Ogden township, Section 25&30 Mulberry Road from Berkey Highway to Loar Highway—2.07 miles x 20 feet (3.3 km x 6 m) wide (Lenawee County Board of County Road Commissioners, 2017).

The use of FDR is limited by the pavement structure's drainage: the pavement needs to be well-drained and the subgrade needs to be of moderate or high quality in order to support the FDR treatment. FDR also lacks performance-based specifications and, to date, predominantly relies on volumetric properties or batch weights. Finally, in urban areas, shallow utilities can limit the depth of excavation into the unbounded layers, meaning a thicker overlay may be required to provide the appropriate structural capacity.

On the other hand, economic analyses have shown that the use of FDR is cost-competitive with other typical DOT rehabilitation strategies. The relatively fast pace of the equipment train means that a quick turn-around time can be achieved with little disruption to the traveling public. FDR treatments can be low-maintenance rehabilitations that do not require any maintenance for several years following the rehabilitation procedure. FDR is also an environmentally sound treatment as it reuses the in-place materials of the existing pavement, reducing the amount of material sent to landfill and the virgin material needed.

Concrete for Pavements

3.6.19 Cross Stitching

This is not an MDOT current practice.

Cross stitching is a specialized treatment intended to tie together longitudinal joints and cracks, which can help prevent lane wander, base deterioration, and extend overall pavement life. The process involves grouting tie bars into holes drilled at angles of 35º to 45º across a joint or crack (Smith et al., 2014, pp. 179-181). Cross stitching can help inhibit the shifting and expansion of cracks and joints, which contributes to "maintaining good load transfer, and slowing the rate of deterioration" (N. J. Delatte, 2008, pp. 322-325; Smith et al., 2014, p. 179). Because cracking, water infiltration, and pumping can be exacerbated in wet-freeze environments, cross stitching is a potential preservation method for these environments.

Cross stitching is often used in new construction when situations arise where tie bars were accidently omitted along a relatively short length of longitudinal joint or where a relatively short longitudinal crack occurred during construction near and parallel to a tied longitudinal joint. In such cases, the only alternative would be to remove and replace the affected concrete pavement, which might be the right choice in a heavily trafficked area, but might not be justified in a lower traffic area. Cross-stitching provides and alternative that both the agency and contractor accept.

When used as a preservation technique, a study by (Chen, 2014, p. 502) found that "areas repaired with cross stitching had deteriorated significantly within the first 2 years" and, thus, concluded that cross stitch should only be used when "joint[s do] not have a large separation and/or faulted slabs". The technique should not be used on transverse cracks, due to the fact that cross stitching prevents the connected slabs from moving (American Concrete Pavement Association, 1995). Cross stitching should also not be used on "cracks that are severely deteriorated or functioning as a joint" (American Concrete Pavement Association, 1997, p. 11).

Several states in the United States have used cross stitching as part of their pavement preservation strategy (see Figure 18). In Utah for example, cross stitching has been found to help preserve highway pavement segments in a "generally good condition" (Smith et al., 2014, pp. 179-181) . Colorado study examined cross stitching and consider it one of the three primary techniques that has been used for maintenance of concrete pavements (Shuler, 2006, p. v).

In Michigan, a 1997 project made use of cross stitching in an attempt to maintain transverse cracking in a jointed plain concrete pavement on eastbound I-94 near Watervliet (D. Smiley &

Hansen, 2007, p. 9). Cross stitching was also used in 2010 on I-94 eastbound from Calhoun County line to Michigan Avenue (Jackson County, 2010).

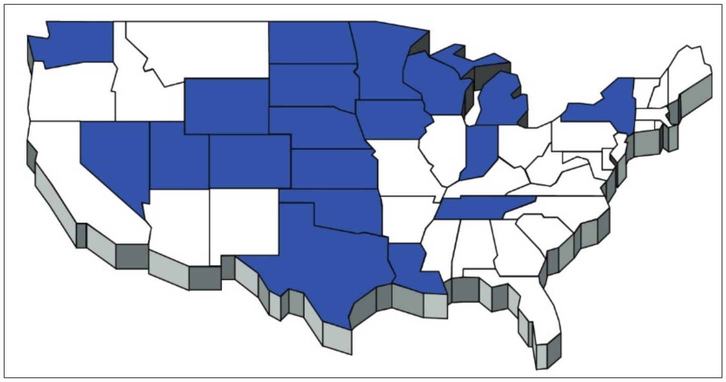


Figure 18: States that have used stitching to repair cracks are shown in blue (International Grooving & Grinding Association, 2010)

3.6.20 Dowel Bar Retrofit

This is an MDOT current practice.

A dowel bar retrofit (DBR) involves adding new dowel bars to pavement joints, most often applied to undowelled JPCP that was common in the Western US and to a limited degree though out the country (I-43 north of Milwaukee for example). The process uses a slot sawing machine to cut slots perpendicular to the joint. A new dowel bar is placed on chairs within the slot and plastic end caps help ensure that the dowels allow for pavement expansion. A concrete patch material is then placed into the slot and finished flush with the pavement surface. This restores load transfer between slabs (Federal Highway Administration, 2005) (Smith et al., 2014).

3.6.21 Diamond Grinding and Grooving

This is an MDOT current practice.

Diamond grinding has been widely used in the United States. Diamond grinding is a technique in which a thin layer (typically ¼ to 3/16 inch (4 to 6 mm)) of concrete is removed from the surface through gang-mounted diamond blades arranged in widths of 3 to 4 feet (0.9 to 1.2 m). This technique corrects surface irregularities, such as faulting, and provides functional improvement, such as a better ride quality, reduced noise, and increased skid friction resistance; at the same time, diamond grinding does not affect a pavement's durability (Correa & Wong, 2001, pp. 3-5). It is an appropriate preservation approach for worn surfaces or surfaces with irregularities (Correa & Wong, 2001, p. 4). A pavement that has structural distresses or material-durability-related problems will need to have the distresses or problems addressed before diamond grinding can provide any benefit; in these cases, a more extensive rehabilitation plan is necessary (Correa & Wong, 2001, pp. 5-6). Further, if the coarse aggregate has poor wear-resistance as is common with some limestone, the benefits of diamond grinding with regards to improved skid resistance will be lost in time as the surface polishes.

A related technique is diamond grooving, in which the diamond blades are separated by an inch (2.5 cm) or more. This technique improves wet weather skid resistance by providing channels for water to escape, and when done longitudinally will reduce noise and can assist vehicle tracking around curves (note that blade spacing is very important with regards to interaction with the vehicle as an improper spacing may provide a disconcerting feel to the driver).

Diamond grinding and grooving has experienced further innovation in recent years in what is called a next-generation concrete surface (NGCS), which creates a "different surface feature" through a combination of grinding and grooving, relying on conventional equipment but using "different blade spacing configurations…[and] several grinding drums" (Vorobieff & Carson, 2017, p. 4). This new low surface has improved skid resistance, low pavement-tire generated noise, good surface durability to ensure the profile remains intact for a long period of time (preferably 20 years), similar life of joint sealants and line marking as per conventional concrete paving surfaces, and a surface that minimizes splash at highway speeds (Vorobieff & Carson, 2017, p. 6).

In Michigan, diamond grinding has been used in applications other than correction of roughly-constructed or vertically-uneven slabs for such reasons as responding to complaints from the public on pavement noise due to longitudinal tining on a project that was only "a few years" old (Michigan Department of Transportation, 1993). MDOT has special provisions for managing diamond grinding slurry, collecting and hauling, controlling pH of the slurry, disposal, dewatering the slurry, and so forth (Michigan Department of Transportation, 2012b, pp. 1-8).

The skid friction resistance and the water-shedding problems due to slab warping are corrected by diamond grinding, potentially reducing accident rates (Correa & Wong, 2001, p. 3). Along with its improvement of a pavement's surface drainage, it may extend a pavement's service life (Snyder, Reiter, Hall, & Darter, 1989). It may also help extend pavement service life by reducing the dynamic loading created as trucks bounce vertically over irregularities in the road (Correa & Wong, 2001, pp. 14). Although diamond grinding reduces the slab thickness, Correa and Wong (2001) concluded that a concrete surface can sustain three diamond grinding procedures, with each of those procedures removing 4mm to 6mm, before the fatigue life of the pavement become jeopardized (p. 5). I-5 in California has been diamond ground 5 times and still remains in service.

The increased macrotextural friction that results from diamond grinding increases road traction and reduces the risk of hydroplaning from ponding created by permanent slab warping (Correa & Wong, 2001, pp. 3). Channeling of water off of a pavement's surface, which is a critical feature in wet-freeze climates, helps prevent snow and/or ice layers from forming on wet pavement surfaces during freezing cycles. A study in Wisconsin showed that in increase in friction was correlated with a safety increase: "the overall wet weather accident rate for diamond ground surfaces was only 57 percent of the rate for non-ground surfaces" (Diamond Surface Inc., 2017). As mentioned, the benefits of conventional diamond grinding on improved wet-weather friction can be short-lived if the coarse aggregate is susceptible to polishing. The grind and groove feature of the NGCS might help extend skid resistance due to the grooving increasing macrotexture.

3.6.22 Slab Stabilization or Slab Undersealing

This is an MDOT current practice.

Slab stabilization, or slab undersealing is a preservation treatment that inhibits cracking caused by traffic loading on concrete pavements that have voids beneath the slabs (N. J. Delatte, 2014, p. 344). In this method, the voids, which often occur near pavement joints and along the pavement edge, are filled by grout (American Concrete Pavement Association, 1994, p. 257). Slab stabilization (or slab undersealing) involves "pumping a grout [or urethane foam] through holes drilled through the slab surface, so as to fill voids that develop beneath the concrete pavement slab or base layers" (American Concrete Pavement Association, 1996, pp. viii-7).

Slab stabilization has been widely used all across the United States (American Concrete Pavement Association, 1994, p. 7). Various materials have been used for grouting in different states (Figure 19).

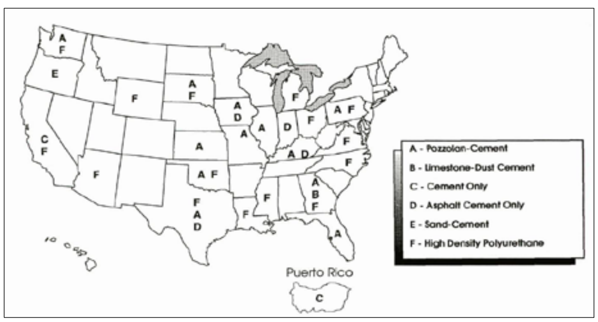


Figure 19: Typical slab stabilization materials used through the United States (American Concrete Pavement Association, 1994)

MDOT considers polymer injection slab stabilization to be a preventive maintenance treatment and further classifies it as an "emerging technology treatment" (Ram & Peshkin, 2013, p. 39) (Ram, Peshkin, 2013, p. 39). Local agencies in Michigan, such as the cities of Caro and Muskegon, have been making use of slab stabilization techniques (King Concrete Services, 2017a, 2017b). MDOT has used slab stabilization techniques on its trunkline.

This technique could play an important role in the maintenance of concrete pavements in wet-freeze climates. Because heavy loads of traffic can deflect concrete slabs at and around working cracks and transverse joints, voids may develop below the slabs (American Concrete Pavement Association, 1996, pp. viii-7). In wet-freeze climates, these cracks can fill with water due to high precipitation and humidity levels; during freezing cycles, the water expands as it changes into ice and leads to the development of more cracks. Therefore, slab stabilization may prove helpful for eliminating voids and preventing further failure in the pavement's structure.

3.6.23 Partial-Depth Repair

This is an MDOT current practice.

Partial-depth repair (PDR) is a maintenance technique used to repair localized concrete pavement surface distresses isolated to the top half of the slab. Distresses addressed through PDR include joint and crack spalling, minor joint deterioration, isolated areas of poor consolidation or delamination (N. J. Delatte, 2008, p. 317; Frentress & Harrington, 2012, p. 1; Smith et al., 2014).

This technique has been in use in such states as Minnesota, Wisconsin, Missouri, Iowa, Kansas, and Colorado (International Grooving & Grinding Association, 2011, p. 1). Iowa DOT considers PDR an appropriate technique to fix spalling in "isolated… upper portion[s] of the slab…[that is] caused by freeze-thaw damage" (Frentress & Harrington, 2012, p. 2). MnDOT makes extensive use of PDRs to repair joints affected by freeze-thaw damage. Information regarding the selection of pavements that are appropriate for partial depth repair in different states can be found in the *Guide for Partial-Depth Repair of Concrete Pavements* by Frentress and Harrington (2012) and in Concrete Pavement Preservation by Smith et al. (2014). This technique has also been in use in Michigan. MDOT has a detailed report that explains all the steps for material preparation, area preparation, concrete placement, and joint relief for partial-depth repair (Staton, 2013, pp. 47-49).

Traditionally, conventional or accelerated concrete has been used as a repair material. Although this practice remains common, proprietary materials that achieve high-early strength, high strength, and/or are flexible are becoming more common.

Partial-depth repair can be prone to failure if deteriorated concrete is not thoroughly removed from the area receiving the treatment and the surface is not adequately prepared to facilitate bonding of the repair material to the substrate; so, it can require "more extensive preparation of the patch area" (N. J. Delatte, 2008, p. 318).

Nonetheless, partial-depth repair has been shown to "slow or eliminate" spalling and keep joints free of water and other material (Frentress & Harrington, 2012, p. 1). Partial-depth repair can also remove cracks on the pavement surface, preventing water from penetrating the pavement's structure. Therefore, partial-depth repair can be an efficient means for repair freeze-thaw induced deterioration and preventing further deterioration.

3.6.24 Full-depth Repair

This is an MDOT current practice.

Full-depth repair is a maintenance technique that uses fresh concrete to replace the failed concrete slabs and to correct such problems as “joint deterioration, corner breaks, or multiple cracks in slabs”(N. J. Delatte, 2008, p. 317). It can also be used for addressing problems related to transverse cracking, longitudinal cracking, corner breaks, spalling, blowup, and D-cracking (Titus-Glover & Darter, 2008, pp. 5-6). A full-depth repair is traditionally 6 feet (1.8 m) or greater in length and extends the full width across the pavement (N. J. Delatte, 2008, pp. 318-319). The minimum length of 6 feet (1.8 m) is to allow for accurate drilling of the dowel bar holes into the existing pavement. With gang-mounted drilling equipment, it is possible to shorten this length to as little as 4 feet (1.2 m). Full-depth repairs should extend “past doweled transverse joints by at least 1 foot (0.3 m) to allow for drilling dowel bar holes and past CRCP cracks by at least 6 inches (15 cm) (N. J. Delatte, 2008, p. 319).

The full-depth repair technique has been used in Wisconsin for fixing freeze-thaw induced deterioration in concrete pavements (Titus-Glover & Darter, 2008). The state of Virginia also considers this technique to be efficient for fixing freeze-thaw induced “D” cracking in concrete pavements; however, full-depth repair is only a temporary fix for “D” cracking (Poullain, 2012, pp. 3-4). In Michigan, full-depth repair is mostly used for fixing longitudinal cracking and deteriorated transverse joints (Staton, 2013, pp. 20-25). MDOT has a detailed report that explains all the provisions for materials, equipment, construction steps, and finishing (Staton, 2013, pp. 50-51).

Full-depth repair is limited in that it does not address inadequacies in pavement structure and is not a long-term solution for distresses stemming from pavement materials (California Department of Transportation, 2008a, p. 7). However, this maintenance technique can provide “restored ride-ability, restored structural integrity, and prevention of further deterioration” (California Department of Transportation, 2008a, p. 6).

3.6.25 Silane/Siloxane Seal

This is *not* an MDOT current practice.

Silane and siloxane are penetrating sealants for concrete intended to prevent moisture infiltration into the microstructures of concrete, brick, and stone by making the material hydrophobic while allowing water vapor to escape. Each has unique properties and application processes that reflect their chemical and physical characteristics: silane is intended for sealing relatively dense pavements, while siloxane is intended for relatively porous pavement materials. Silane is more volatile, but can penetrate deeper into materials for a more durable application that withstands high wear conditions. Both of these products help prevent freeze/thaw damage to pavement surfaces by blocking water infiltration and can also inhibit deicing chemical (chlorides and others) penetration.

In tests designed to evaluate silane and siloxane effectiveness at inhibiting moisture and deicing compound infiltration, researchers tested 60 different types of sealers and found that (68%) of silane products tested and (31%) siloxane-based products tested reduced the water absorption into concrete test samples (to more closely duplicate conditions in northern climates, tests were conducted at 39.2°F (4°C) instead of the 73.4°F (23°C) tests described in NCHRP report 244) (Mirza, Abesque, & Bérubé, 2011, p. 9). This research found that the "sealer application temperature had little influence on the performance of the silane and siloxane-based products" (Mirza et al., 2011, p. 9). This research also tested immersion of treated samples in a 15% NaCl water solution to compare effectiveness against water with pH of 5 and found that the NaCl solution penetrated less than the pH 5 water on silane and siloxane treated samples (Mirza et al., 2011, p. 9).

Many states and foreign countries use penetrating concrete sealers such as silanes and siloxanes to increase durability through reduced moisture and deicing compound penetration (Attanayaka, Aktan, & Ng, 2002, pp. 10-16)(p. 10-16). Research in Michigan has shown silane and siloxane to be effective treatments against moisture and chloride penetration on bridge decks, and MDOT approves these treatments when they meet the requirements of NCRP Report 244 (Attanayaka et al., 2002, pp. i,9). Research continues to be conducted on the use of silane and siloxane penetrating sealants applied at joints to address joint deterioration. It is currently not well understood how long the hydrophobic nature of the sealant will remain under traffic but current thoughts are that the sealant will need to be reapplied every 2 to 3 years.

4. DISCUSSION & CONCLUSIONS

This research project gathered information regarding innovative engineering “best practices” in pavement materials, design methodologies, technologies of construction, and strategies of maintenance and rehabilitation used in regions with climates similar to that of Michigan. Michigan has a wet-freeze climate, which has long winters of temperatures below freezing with numerous cycles of freezing and thawing along with higher than average precipitation when compared to many areas of the United States. The research team selected twenty-two states in the United States that have at least some regions with wet-freeze climates as classified by the Federal Highway Administration, two Canadian provinces, and eight international cities as wet-freeze zones based on annual precipitation, number of days with temperature of 32 °F or less, annual snowfall, and average annual temperature.

For the purposes of this report, a best practice is a procedure shown by research and experience to produce optimal results and that is established or proposed as a standard suitable for widespread adaptation. Given the evolving nature of pavement technologies and, hence, the fluidity that necessarily occurs with adopting, modifying, or replacing best practices, the researchers identified best practices that are currently used by the Michigan Department of Transportation (MDOT) and practices that are not fully adopted for use by MDOT but merit greater consideration. This research made it clear that MDOT is a pioneer for developing and adopting best practices in wet-freeze climates and thus the research team did not find many practices recognized by other agencies as best practices but are not currently used by MDOT. However, there are a few recommendations that do merit consideration of further review once additional research and experience becomes available. The section below lists the most promising practices being recommended for implementation after field trials, as well as recommendations for further research for both asphalt and concrete pavements.

4.1 RECOMMENDATIONS FOR FURTHER RESEARCH

4.1.1 Further Research for Asphalt Concrete Pavement

For asphalt concrete pavement, recommendations for promising technologies that may be advanced through further research are as follows:

1. Warm-Mix Asphalt – Although MDOT’s current practice allows for the use of some warm-mix asphalt (WMA) technologies, the research team suggests that MDOT conduct a review of selected available technologies and conduct field trials on those that are not currently used but have shown great promise in use by other agencies located in freeze-thaw climates. For example, the cost and performance of WMA based on foaming technologies (such as Advera WMA and

Astec Green System) should be compared to the performance of WMA based on chemical additives (such as Cecabase RT and Evotherm) and non-foaming additives (such as Thiopave and Sasobit®). There are no obvious barriers to conducting this type of investigation short of the costs incurred to conduct the study,

2. AASHTOWare Pavement ME Design – Elements of the AASHTOWare Pavement ME Design software has been implemented to some degree by MDOT as a result of previous research studies. The design approach used by this software includes parameters to improve resistance to thermal cracking, fatigue cracking, and rutting. It is recommended that MDOT consider a more complete implementation of design method, which should entail revisiting the development of the calibrations used to predict pavement performance. There are no obvious barriers to more fully utilizing the AASHTOWare Pavement ME Design software other than the efforts to validate the current calibration through studying of MDOT's recent pavement performance experience and in training a larger number of MDOT personnel in the effective use of the software.

3. Perpetual Pavement – Perpetual pavement is a variation on full-depth HMA, with three distinct layers designed to address specific stress states and environments. It is recommended that perpetual pavements be investigated culminating in field sites and monitoring for 5 to 10 years to develop performance models and a standard design. As part of this effort, pavement layer bonding and high-modulus asphalt mixtures should be studied.

4. Innovative Materials – A number of new construction materials, including bio-derived binder, half warm-mix asphalt, sulfur-extended asphalt, PPA extenders, and fiber-modified asphalt as described in Section 3, hold promise for improving pavement performance but require additional research. Continued laboratory and field research is recommended with the aim of implementation. As an example, bio- derived binder has very promising applications only if the materials are consistent from one manufacture to the other and meet storability requirements. This is a long term effort and may require considerable resources. Further, not all technologies will likely be implementable due to reasons like lacking of industry interest, familiarity of the technologies, cost effectiveness, and availability of the materials. Success would be beneficial in the long-term if one or more of these technologies were to be adopted for use by MDOT.

5. Intelligent Compaction – It is well documented that the performance of asphalt pavements is strongly linked to the density achieved during construction. Intelligent compaction has continued to evolve with today's technologies providing valuable real-time information that can be used to ensure improved compaction in the field. It is recommended that the most recent generation of intelligent compaction technologies be field evaluated and data management-related problems solved. If successful, a guide specification should be developed. This technology is readily implementable and no barriers to implementation are anticipated.

7. HMA Patching -- MDOT experiment with alternative means for HMA patching including investigation of the microwave method for pothole repair. Implementation could be conducted through small scale demonstration projects, and if successful, rapid adoption could be realized.

4.1.2 Further Research for Concrete Pavement

For concrete pavement, recommendations for promising technologies to be advanced through further research are as following:

1. Two-Lift Concrete Pavement – Although MDOT did not have great success with the two-lift European pavement constructed in the early 1990's, the technique has been applied experimentally and in practice (Illinois Tollway) by a number of agencies in the last 15 years. For certain applications, the use of this technique might be cost effective, particularly if high volumes of recycled material are incorporated into the bottom lift. A review of modern two-lift concrete pavements should be conducted and recommendations regarding future implementation made. The technology is readily implementable and MDOT has used it in the past. Barriers to implementation include having the right project so that both cost and environmental benefits can be derived compare to traditional JPCP construction.

2. Roller-Compacted Concrete Pavement – Roller-compacted concrete (RCC) has been used for decades for hydraulic structures and heavily loaded industrial pavements. Within the last decade, improvements in constructability and finishing have made it an attractive material for certain pavement applications (local roads, shoulders, parking areas, etc.), supported by various guide and specification documents. For high-speed pavements where ride quality is critical, RCC can be overlaid with HMA or diamond ground to provide a relatively smooth riding surface. It is recommended that a review of RCC pavement applications be conducted and design and specification documents be prepared to support RCC pavement implementation. Implementation would entail a demonstration project for suitable applications, which initially would be low speed, low traffic volume pavements. In time, as contractor experience develops and MDOT gains comfort in the technology, implementation could be extended to other applications. Implementation requires a long-term commitment to advancing the technology through demonstration projects and the training of MDOT personnel.

3. Alternative Cementitious Binders – Review current literature and conduct laboratory and field research to support further implementation of ASTM C595 blended cements, alkali-activated cements, and geopolymer cements. The implementation of each should advance as the research resolves barriers. There are no obvious barriers to promoting implementation of ASTM C595 blended cements as these are already in the MDOT standard specification. The barriers are local availability. With regards to other binders, research should be considered on viability in Michigan, both from a cost and availability perspective.

4. Innovative Materials – There are a number of innovative construction materials, including nanomaterials and phase change materials that may offer promising opportunities in the near future. MDOT should continue laboratory and field research to evaluate potential implementation. Implementation is uncertain until basic research is completed.

4.1.3 Additional Research Opportunities

In addition, the following should be evaluated for pavement applications in general:

1. Outlet Diffusers – Study the design of outlet diffusers to increase pipe capacity in highway applications. This will require the use of field demonstrations as part of the implementation process.

2. Drainage Management Systems – Development of a fully integrated drainage management system, similar to the drainage information analysis and mapping system, for the evaluation of underground drainage infrastructure assets is a practice being advanced at MDOT. In addition, field research of drainage retrofits could be conducted. The main barrier to implementation is cost and acceptance of the need to do this at the regional level in lieu of putting the money into pavement surface improvements.

3. Permeable Base – In areas where subdrainage is required, the use of permeable bases should be investigated as an alternative. MDOT should develop standard of permeable base and monitor the long-term performance.

4. Construction Demolition Waste (Building rubble) **–** Conduct research to support increased use of construction demolition waste (CDW) including recycled concrete aggregates. Although recycling and reusing CDW or recycled concrete aggregates can have economic and environmental benefits and reduce the amount of virgin materials needed for new construction, applications should consider life cycle impacts including impacts on performance. The use of these materials are well established, thus the barriers to implementation are the need to demonstrate the viability of these materials in pavement applications requiring demonstration projects and documentation.

5. Chinese and US Pavement Design Comparison – China's pavement design guide has been used in China's expressway system. The equivalent Chinese single-axle loads and control criteria are different than the United States' pavement design, which may result in different designed pavement thickness and affect pavement design, material selection, and overall cost of construction. The research team recommends conducting research to compare the United States' pavement design with China's pavement design.

6. Semi-rigid base for asphalt pavement used in China - Asphalt pavement on semi rigid base has been a dominant pavement structure used in China in the past a few decades. The semi rigid base layers are constructed with cement-treated base or cement-stabilized base in wet-freeze and all other climate regions in China. This type of design has not been widely used in the United States, even though such base will resist heavier traffic loads. It is beneficial for MDOT to study such pavement structure.

4.2 RECOMMENDATIONS FOR IMPLEMENTATION

4.2.1 Implementation Recommendations for Asphalt Concrete Pavement

For asphalt concrete pavement, the following technologies are recommended for implementation after field trials are completed:

1. Subgrade Stabilization – MDOT mainly uses the undercutting process to deal with weak soils. Lime-stabilized, cement-stabilized, and asphalt emulsion (foam asphalt) -stabilized subgrade should be evaluated for the creation of suitable platform for asphalt pavements. Conduct structural evaluation following construction and monitor for long-term performance.

2. Cold in-place recycling – MDOT should evaluate the use of cold in-place recycling of pulverized asphalt pavement that is mixed with new binder and new materials and used as a base layer. Structural evaluation should follow construction and be monitored for long-term performance.

3. Longitudinal Joint Sealer – Longitudinal joint sealer should be investigated to improve the performance of longitudinal joints. Monitoring new field sites around the state and for 5 to 10 years and development of a potential standard or specification should be considered.

4.2.2 Implementation Recommendations for Concrete Pavement

For concrete pavement, the following technologies are recommended for implementation after field trials are completed:

1. Optimized Aggregate Grading – Investigate the status of MDOT's optimized aggregate grading limits and assess whether the current specifications are sufficient or whether they may need adjusting to accommodate recent findings. This includes consideration of minimum cementitious materials content.

2. Continuously Reinforced Concrete Pavement – Continuously reinforced concrete pavement (CRCP) had been found to be an excellent choice as a long-life pavement in highly trafficked urban areas. Consideration should be given to investigating CRCP as an alternative for MDOT as a potential best practice.

3. Precast Concrete Pavements – Precast concrete pavement (PCP) has been effectively used to for rapid repair in highly trafficked urbanized areas. The technology has continued to evolve over the last decade, and the current generation of PCP may offer an attractive alternative for MDOT in some situations.

4. Bonded Concrete Overlays of Asphalt - Bonded concrete overlays of asphalt (BCOAs) are considered a best practice in a number of freeze-thaw states including Iowa, Illinois, and Minnesota. Although Michigan has constructed BCOAs, recent advances and design and materials have increased the attractiveness of this alternative and further implementation efforts may be warranted.

5. Enhanced Corrosion Resistant Dowels – It is well-known that the Type 1 775 epoxy-coating for dowel bars was susceptible to corrosion due to manufacturing imperfections, damage to the coating that occurred due to handling and construction, and wear that occurred in service. This makes dowels having a high level of corrosion resistance attractive for long-life concrete pavement applications. MDOT has recently implemented the use of ASTM A1078 dowel bars featuring ASTM A1078 Type 2 938 epoxy-coatings, which are more robust than the Type 1 775 epoxy coating. It is recommended that field trials be initiated with these newly specified dowel bars as well as with a few other highly corrosion-resistant dowel bars to assess the effectiveness of each system.

6. Real-Time Smoothness – Considerable research has been conducted in the last two years on real-time smoothness techniques. The results of this research should be reviewed and test sites constructed in Michigan to familiarize MDOT and the contracting community with these technologies.

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