JOURNAL OF TRAFFIC AND TRANSPORTATION ENGINEERING (ENGLISH EDITION) 2019; 6 (3): 245–255

Available online at www.sciencedirect.com

ScienceDirect

journal homepage: www.keaipublishing.com/jtte

Review Article

A review on the best practices in concrete pavement design and materials in wet-freeze climates similar to Michigan

Naser P. Sharifi [a], *Siyu Chen* [a,1], *Zhanping You* [a,*], *Thomas Van Dam* [b], *Christopher Gilbertson* [a]

[a] Department of Civil and Environmental Engineering, Michigan Technological University, Houghton, MI 49931, USA
[b] Nichols Consulting Engineers, Chtd., Reno, NV 89509, USA

HIGHLIGHTS

- Identify the best practices of design and materials for concrete pavements.
- Identify three design methods and five materials.
- Provide examples of their successful performance in wet-freeze climates.

ARTICLE INFO

Article history:
Received 23 July 2018
Received in revised form
4 December 2018
Accepted 5 December 2018
Available online 17 April 2019

Keywords:
Concrete pavements
Pavement design
Pavement materials
Best practice
Wet-freeze climate

ABSTRACT

The research presented in this paper aims to identify best practices of design and materials for concrete pavements in wet-freeze climates similar to the Michigan State. For the purposes of this paper, a best practice is a procedure that has been shown by field-validated research or experience to produce improved results and that is established or proposed as a standard suitable for widespread implementation. The local wet-freeze climate makes the requirements for Michigan's pavement system different from many other regions. Wet-freeze climates can result in various concrete pavement distress mechanisms such as thermally-induced cracking, freeze-thaw deterioration, accelerated cracking due to loss of support, frost heave, and material degradation. Therefore, appropriate procedures for design and material selection need to be selected to withstand high precipitation and freezing winter temperatures. Failure to take into account the climatic conditions may lead to inadequate or reduced pavement performance. However, utilizing appropriate techniques and materials could potentially improve the quality and increase the service life of the concrete pavement. Three design methods and five materials have been identified, and examples of their successful performance in wet-freeze climates are provided. In addition, the reasons that give them the superior performance in wet-freeze climates are discussed in detail.

* *Corresponding author*. Tel.: +1 906 487 1059; fax: +1 906 487 1796.
[1] Co-first author.
E-mail addresses: npourakb@mtu.edu (N.P. Sharifi), siychen@mtu.edu (S. Chen), zyou@mtu.edu (Z. You).
Peer review under responsibility of Periodical Offices of Chang'an University.
https://doi.org/10.1016/j.jtte.2018.12.003

1. Introduction

The American Association of State Highway and Transportation Officials (AASHTO) 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—are also considered to be wet-freeze climates by the research team, because the pre-dominate climate in these provinces is similar to the wet-freeze characteristics defined by the HPMS Field Guide and AASHTO.

Two identifying climate parameters used to classify a region are the freezing index and the annual precipitation. These climate parameters can help to predict such factors as the depth of frost penetration and the number of freeze-thaw cycles experienced by the pavement during its service life. 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 mid-latitude regions, which is useful for determining the depth of shallow foundation construction" (Bilotta et al., 2015). The freezing index is defined by the area under the temperature curve during the freezing period, represented by the following calculation.

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

where T is the average daily temperature for a day i (°F), and N is the number of days during the freezing period. Eq. (1) is developed in the US-Customary units, thus the unit for temperature must be in the US-Customary system, and not in the SI system.

The freezing period begins when T is less than or equal to 0 °C or 32 °F for several days and ends when T becomes greater than −2 °C or 29 °F for several days. The pavement temperature is conservatively assumed to be equal to the air temperature.

The Michigan State is located in the wet-freeze zone as defined by AASHTO and FHWA. The Michigan State has an annual average precipitation of 83.6 cm or 32.9 in., and a freezing index of 1400 °F·d to 2200 °F·d (National Climatic Data Center, 2017; National Oceanic and Atmospheric Administration, 2010). For these two climate parameters, Michigan is higher than the FHWA baseline of a wet-freeze climate zone (71 cm or 28 in. and 100 °F·d, respectively). Thus, the high levels of precipitation and the very low temperatures are parameters that influence pavement performance, which can drastically affect the design, construction, and maintenance practices of the roads in Michigan. By using these two parameters, it is possible to determine locations within the United States, Canada, Europe and Asia with conditions similar to Michigan's climate.

The wet-freeze climate makes the requirements for Michigan's pavement system different from other regions that do not share similar climatic conditions. This influences the design, construction, and maintenance of pavements, which requires consideration of the harsh local climatic condition. Since a wet-freeze climate can lead to pavement distresses such as accelerated cracking due to loss of support, frost heave, and material degradation due to freezing and thawing in the presence of chemical deicers, 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 these climatic conditions when selecting the pavement's materials, design, and construction techniques may lead to inadequate pavement performance and reduced service life (Chen et al., 2019).

The research reported in this paper examines current and emerging practices for pavement design and material selection in wet-freeze climates. For the purposes of this research, 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. It should be mentioned that this study does not aim to introduce a novel design method or a new material that is developed to be used in wet-freeze climates; rather, it tries to identify current practices that have been proven to yield superior performances in wet-freeze climates.

The recommendations in this paper for implementing best practices in pavement design and material selection 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 address both the short- and long-term expectations of the quality of Michigan's road network.

2. Design methods

The process of pavement design is used to select pavement type, the materials used, and the various thicknesses of each layer, which has a profound impact on the 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. Concrete pavement design has shifted from an empirical pavement design approach to a mechanistic-empirical pavement design approach in the United States. Recently, many state Departments of Transportation (DOTs) have performed calibration of the performance models embedded within the AASHTOWare Pavement ME software using long-term pavement performance (LTPP) data and additional local pavement test sections to improve the predictability of the software within their states, MDOT being one of them.

Prior to 2007, road agencies throughout the U.S., as well as internationally (such as the Quebec Ministry of Transportation), followed AASHTO's 1986 and 1993 editions of the Guide for Design of Pavement Structures, which is an empirical approach to concrete pavement design (Hall, 2000). The design method was an extension of the results obtained from the AASHO Road Test conducted in Ottawa, Illinois in the late 1950's (Hall, 2000). It should be mentioned that the empirical basis of the design method remains empirical rooted in the original AASHO Road Test. Therefore, the method can only address “limited pavement types, loads and load applications, age, and environment” (American Association of State Highway and Transportation Officials, 1993).

In 2008, AASHTO released the first version of the Mechanistic-Empirical Pavement Design Guide (MEPDG), providing guidance on applying mechanistic-empirical design principles to a variety of concrete pavement types including jointed plain concrete pavement (JPCP) and continuously reinforced concrete pavement (CRCP) for new pavements and JPCP overlays (greater than 15.25 cm or 6 in.), CRCP overlays (greater than 17.75 cm or 7 in.) and JPCP restoration (American Association of State Highway and Transportation Officials, 2008). In addition, based on AASHTO T 97, the modulus of rupture (MOR) of the concrete should be considered to be greater than 4.5 MPa or 653 psi. The JPCP performance prediction models are for transverse cracking, mean joint faulting, spalling, and international roughness index (IRI), whereas the CRCP performance prediction models are for punchouts and IRI (American Association of State Highway and Transportation Officials, 2008). For the implementation of the mechanistic-empirical design in Michigan and other wet-freeze climates, agencies can refer to AASHTO's Mechanistic-Empirical Pavement Design Guide. In the following sections, three of the design methods that have been successfully used in wet-freeze climates are listed, and their performance in such climate condition are discussed.

2.1. *Continuously reinforced concrete pavement (CRCP)*

As the name implies, CRCP uses continuous longitudinal reinforcement (typically 0.6%–0.7% cross-sectional area) to eliminate transverse contraction joints, instead of allowing the pavement to randomly crack transversely, with a typical crack spacing of 46–183 cm or 1.5–6 ft. The steel reinforcement holds the cracks tight, allowing aggregate interlock to transfer load across the crack interface. Typically, Grade 60 bars, which offer a minimum yield strength of 420 MPa or 60,000 psi, are used for the longitudinal steel reinforcement. The transverse steel is on chairs and is designed to support the longitudinal steel as well as restrain any longitudinal cracks that may form (Fig. 1). The main attractions of CRCP, if constructed properly, is its excellent ride quality (because it has no joint faulting), ability to be overlaid with asphalt without the risk of reflection cracking, and long life. Concrete pavements which are constructed in wet-freeze climates are subjected to harsh thermal stresses in addition to the traffic load-induced stresses. Furthermore, they are subjected to freeze-thaw deterioration mechanism. Thus, they are more vulnerable to initiation and propagation of different types of cracks in different directions. CRCP are equipped with rebar in two directions. The provided rebar could effectively control the propagation of both the longitudinal and transverse cracks; therefore, CRCPs seem to have promising performance in wet-freeze climates.

Major drawbacks of CRCP are its high initial construction cost, it is difficult to construct and it is costlier to repair than

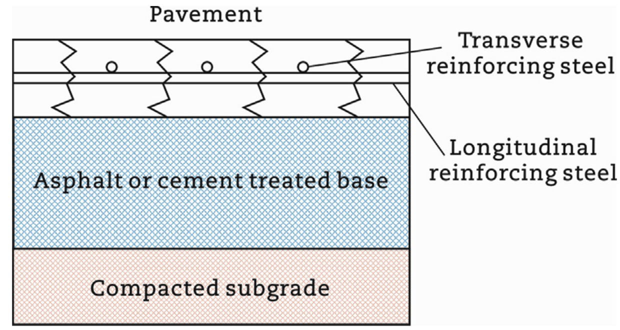

Fig. 1 – Continuously reinforced concrete pavement (not to scale) (Van Dam et al., 2015).

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; Michigan Department of Transportation, 2017a, b; Roesler et al., 2016). MDOT has performed but does not currently use CRCP, although they did some CRCP projects in the past. After reviewing the current state-of-the-practice, the research team recommends that MDOT reviews this practice and considers implementing this in the future. 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). Michigan is considering the use of CRCP for a short section of pavement in Jackson to bridge over subsidence caused by a collapse of abandoned underground coal mines.

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). 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 and Tayabji, 2012). 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 et al. (1999) provided a review of the design and performance of CRCP pavements in Illinois. The majority of the sections constructed between 1955 and 1994 were 18–25.5 cm or 7–10 in. 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 18 cm or 7 in. thick sections whereas the best performance was found in the 25.5 cm or 10 in. thick sections.

Recently, CRCP has been considered for use on the Illinois tollway (Tayabji et al., 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 an 8-cm or 3-in. thick flexible HMA base on granular subbase.

Due to the presence of the reinforcement (commonly 0.06%–0.07% 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 costlier and require more specialization (Michigan Department of Transportation, 2017a, b). Overall, CRCP is a considered a cost-effective pavement type due to improved performance, longevity, and reduced life-cycle costs. Additionally, it has a superior performance in wet-freeze climates. Degradation because of repetitive freeze-thaw cycles is one of the main deterioration mechanisms of concrete pavements in wet-freeze climates. The expansion of penetrated water when it turns to ice makes the cracks bigger, and provides more room for extra water for the next freezing cycle. These cycles eventually cause the pavement to fail. However, CRCP takes the advantage of continuous rebar that prevents the cracking to expand.

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 for using CRCP is an expected service life in excess of 50 years.

2.2. *Precast concrete pavement*

Precast concrete pavement (PCP) is most often used as a repair method that allows rapid replacement of damaged concrete pavement while taking advantage of the ability to extend a construction season (Tayabji et al., 2012). PCP relies on concrete panels cast at a precast plant and subsequently installed on-site (Federal Highway Administration, 2017). This method reduces the on-site time needed for construction and curing, making well-designed and well-constructed PCP a rapidly-deployable solution for either new construction or rehabilitation on high-volume sections of the road network (Federal Highway Administration, 2017). PCP falls into two general categories: precast jointed concrete pavement (PJCP) and precast post-tensioned concrete pavement (PTCP).

The recommended design flexural strength of precast concrete pavement is 4.5 MPa or 650 psi, and the minimum compressive strength at time of panel shipment to the project site is 27.5 MPa or 4000 psi (Tayabji et al., 2013). 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 justify 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). 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).

States including Michigan, Indiana, Virginia, Louisiana, 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 found that five of the nine panels that were installed still had good performance (Tayabji et al., 2012; Tayabji and Brink, 2015). Additional sections have been constructed by MDOT on US-131 and 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 (Burnham, 2007).

PCP uses similar materials to cast-in-place concrete pavements although the mixture has been optimized for the precast operation. Proprietary components are also used in many PCP systems; these components include the joint load transfer systems of the PCP, the pre-stressing hardware, the expansion joint components (Tayabji et al., 2012), and most recently, proprietary leveling devices installed at the slab corners. 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). 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).

PCP panels are cast in a plant and stored (typically for 14 days) prior to being 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). 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 precast slab, leveling and grouting of the slabs to ensure the slabs are properly supported, backfilling load transfer slots, and joint sealing. 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, 2017). 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 this increases early-age strength allowing for the beds to be flipped more quickly, facilitating a 24-h production cycle.

The initial cost of precast panels can be substantially higher than typical DOT repair strategies and, thus, their 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 (Burnham, 2007). Additionally, the performance of PCP is influenced by construction techniques; improper installation can damage the surrounding concrete pavement, not adequately install load transfer, or result in non-uniform slab support resulting in the poorer-than-expected service life of the precast slabs.

Since PCP slabs are cast at a production plant, 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). As it was explained in Section 2.1, cracks on the surface of the pavement provide the path for water to penetrate into the depth of the pavement, and accelerate the freeze-thaw failure. The better control of the production of PCP minimizes the number and the width of the cracks on the pavement. This causes the PCP pavements to show superior performance in wet-freeze climates. 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). Finally, in some studies, PCP has demonstrated effectiveness in eliminating early age failures related to construction (Tayabji et al., 2012).

2.3. *Self-consolidating concrete pavement*

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

Self-consolidating concrete (SCC) pavement uses a concrete mix that consolidates under its weight (Wang et al., 2005). It is made up of cementitious material, aggregate, and other additives 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 (Petersen and Peterson, 2006; Wang et al., 2005). Self-consolidating concrete mixtures normally have a flexural strength of approximately 4.55 MPa or 658 psi, and a compressive strength between 32.5 and 52.5 MPa or 4640 to 7540 psi (Busari et al., 2017).

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 et al., 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 (Wang et al., 2005). However, laboratory testing performed by 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 (Wang et al., 2005).

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 do 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. 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. Materials

Selecting materials for the construction of good-performing and long-lasting pavement is dependent on in-service weather conditions as well as the 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 more stringent 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, plays an essential role in achieving the desired service life for a pavement. This section focuses on some opportunities that are available in the material selection that can result in improved concrete pavement performance. The following is a list of five materials that enhance the performance of concrete pavements in wet-freeze climates.

3.1. Portland limestone cement

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% (Plei and Tayabji, 2012; Shannon et al., 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 the practical maximum to ensure the limit is not exceeded.

PLC has been used in Europe for over three decades. However, only a limited amount of PLC pavements, approximately 332 km or 200 miles, has been constructed in the United States (Shannon et al., 2014). An I-94 project in Wisconsin used 30,600 cubic meters or 40,000 cubic yards 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).

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 for 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 the inter-grinding 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. It 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 form. This results in a decreased pore space and reduces the permeability (Barrett et al., 2014). This phenomenon improves the resistance of the pavement against the freeze-thaw deterioration. Minimizing the pore space and reducing the permeability decreases the potential of water penetration, and consequently reduces the potential of the creation of extra cracks due to the expansion of water when it turns to ice.

3.2. Highly corrosion resistant steel dowel and tie bars

The use of smooth round dowel bars has 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. The yield strength of dowel and tie bars can reach to 690 MPa or 100 ksi. Typically, 46 cm or 18 in. long and varying in diameter from 2.54–3.8 cm or 1–1.5 in., dowels are commonly placed 30 cm or 12 in. 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 to 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 the 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 1.3–1.59 cm or 0.5–0.625 in. in diameter), longer (typically 76 cm or 30 in.), spaced further apart (commonly 61–91 cm or 24–36 in.), 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.

It is an MDOT current practice to use embedded steel dowels and tie bars that have been treated with an epoxy coating to resist corrosion. It is not current MDOT practice to use other coating systems or non-corroding materials. It is recommended by the research team that MDOT monitors the performance of current practice to see if a change to a more robust coating system on non-corroding materials is warranted.

Commonly made of solid steel, dowel bars and tie bars used in freeze-thaw environments are commonly coated with the 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 U.S. (Tayabji et al., 2010; Washington State Department of Transportation, 2013). Epoxy coatings can provide corrosion resistance to dowels and tie bars by providing a barrier to prevent moisture and chloride ions from reaching the steel surface, which is a crucial benefit in wet-freeze climate conditions 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 rapidly corrode at the joint resulting in joint lockup, spalling, and necking down of the dowel. The standard corrosion resistant coating for dowels and tie bars is an A934 epoxy.

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. It has been shown that epoxies can prevent loss of cross-sectional area in steel and, consequently, lead to a longer pavement lifespan (Kahhaleh et al., 1998).

In Michigan, bridge decks made with epoxy-coated rebar (ECR) demonstrated a potential service life of approximately 70 years in one study (Boatman, 2010), and of approximately 86 years in an update to that study (Valentine, 2015). Michigan has had only one ECR bridge deck that receive an inspection rating of “poor” after 35 years of ECR use (Valentine, 2015). Recently, MDOT has moved to the use of more robust ASTM A1078 Type 2 dowels coated with ASTM A934 epoxy (specified as being purple or gray) to provide a tougher coating to resist damage during handling and construction and provide added corrosion resistance (MDOT 12SP-602I-01 2017).

As an alternative to epoxy coating, Tayabji et al. (2010) discussed laboratory studies and field trials in Minnesota, Pennsylvania, and Ohio that evaluated zinc-alloy cladding to provide corrosion resistance for Grade 60 carbon steel bars. 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 (Tayabji et al., 2010). Michigan has approved of the use of zinc cladding III HS on MDOT projects (Michigan Department of Transportation, 2017a, b).

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 other alternative corrosion-resistant dowel bars in lieu of epoxy-coated steel. These include stainless steel, stainless steel clad, basalt, glass-fiber reinforced polymer, and corrosion-resistant steel (such as MMFX), as well as zinc clad. The Washington State, 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 on a mountain pass that would be exposed to higher amounts of corrosive deicing salts would need a dowel bar with higher corrosion resistance (Uhlmeyer and Russell, 2013). The recent MDOT move to the use of a more robust Type 2 epoxy coating (specified as being purple or gray) for ASTM A1078 dowels to provide a tougher coating to resist damage during handling and construction is expected to provide added corrosion resistance (MDOT 12SP-602I-01 2017).

The dowel bars' corrosion resistance appears to be directly proportional to the cost of the bars, with dowel bars with higher corrosion resistance having a 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.

3.3. *Optimized aggregate grading*

Optimizing aggregate gradations has 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 et al. (2012), is based on a modification to the typical 8–18 chart. Wet-freeze states such as Minnesota and Iowa have been able to obtain aggregate gradations that fall within the Tarantula curve specifications. Texas has demonstrated that mixtures with an aggregate gradation falling within the Tarantula curve had excellent responses to vibration with very low cementitious materials content (approximately 267 kg/m^3 or 450 lb/yd^3) (Taylor and Fick, 2015).

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). Furthermore, 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, and mineralogy are others), and thus an aggregate grading that works in one location might not necessarily work at another 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. Following the Tarantula curve makes the concrete denser, and reduces the porosity of the material; thus makes it more durable against freeze-thaw deterioration.

3.4. *Nanomaterials*

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 et al., 2012). 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 and Sobolev, 2010).

Utilizing nanomaterials 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.

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 et al., 2017; Shah et al., 2015). Nanomaterials also reduce a pavement's permeability, which mitigates its vulnerability to freeze-thaw deterioration (Birgisson et al., 2012; Norhasri et al., 2017).

3.5. *Phase change materials*

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 et al., 1977; Sharifi, 2016; Sharifi and Mahboub, 2018; Sharma et al., 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 and Bentz, 2011). Based on this idea, the PCM which is incorporated in the concrete pavement, absorbs the heat energy during the day. The stored energy will be used during the night time to keep the concrete warmer. This technique significantly decreases the number of freeze-thaw cycles experienced by the pavement, and effectively increases the service life of the concrete pavement by controlling the freeze-thaw deterioration mechanism. 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 (Fig. 2) (Sakulich and Bentz, 2011; Sharifi and Sakulich, 2013).

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”. 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 and Turpin, 2007). Alpena of Michigan experienced a 24% decrease (the control pavement experienced 107 freeze-thaw cycles in a year 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 and Turpin, 2007; Sharifi et al., 2015). It should be mentioned that utilizing PCMs in concrete pavements 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.

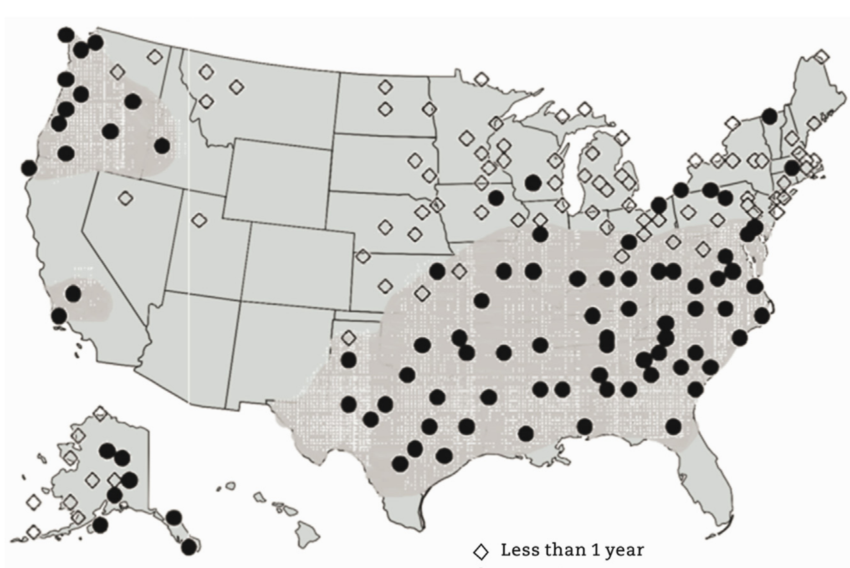

Fig. 2 – Locations in which incorporation of the maximum 120 kg/m^3 of PCM increases bridge deck service life (Sakulich and Bentz, 2011).

4. Conclusions

This research gathered information on innovative engineering "best practices" in concrete pavement materials selection and design methodologies 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. Technologies such as continuously reinforced concrete pavement, precast concrete pavement, and self-consolidating concrete pavements were provided, and some emerging technologies such as Portland limestone cement, nanomaterials, and phase change materials were introduced. Continuously reinforced concrete pavement is a considered a cost-effective pavement type due to improved performance, longevity, and reduced life-cycle costs. Precast concrete pavement is most often used as a repair method that allows rapid replacement of damaged concrete pavement while taking advantage of the ability to extend a construction season. In addition, phase change materials may help to extend a pavement's service life in Michigan's wet-freeze climate. The discussed technologies showed promise in wet-freeze climates, and using them in such climates improves the quality and increases the service life of concrete pavements. This study can be expanded by discussing the technologies and materials that have been successfully used in other parts of the world, such as Europe and Asia, to confront the deterioration mechanisms in concrete pavements in wet-freeze climates.

Conflict of interest

The authors declare no conflict of interest.

Acknowledgments

Parts of this review are from Michigan Department of Transportation (MDOT) published report, titled "Identifying Best Practices in Pavement Design, Materials, Construction, and Maintenance in Wet-Freeze Climates Similar to Michigan". The research work was sponsored by Michigan Department of Transportation (MDOT) and Federal Highway Administration (FHWA). The research team appreciated the guidance and involvement of Curtis Bleech of MDOT as project manager, Andre Clover as project engineer, Michael Eacker, Kevin Kennedy, James Siler, John Staton, and Curtis Bleech in the Research Advisory Panel (RAP). The authors also acknowledge the contribution from John Velat, Vicki Sage, and Pete Torola of MTU, and Jeff Stempihar, James Signore, Nicole Dufalla, and Linda Pierce of NCE. This document is disseminated under the sponsorship of the Michigan Department of Transportation (MDOT) and Federal Highway Administration (FHWA) in the interest of information exchange. MDOT/FHWA assumes no liability for its content or use thereof. The contents of this report reflect the views of the contracting organization, which is responsible for the accuracy of the information presented herein. The contents may not necessarily reflect the views of MDOT/FHWA and do not constitute standards, specifications, or regulations.

REFERENCES

American Association of State Highway and Transportation Officials (AASHTO), 2008. Mechanistic-Empirical Pavement Design Guide: A Manual of Practice. AASHTO, Washington DC.

American Association of State Highway and Transportation Officials (AASHTO), 1993. AASHTO Guide for Design of Pavement Structures. AASHTO, Washington DC.

Barrett, T.J., Sun, H., Nantung, T., et al., 2014. Performance of Portland limestone cements. Journal of the Transportation Research Board 2441, 112–120.

Bentz, D.P., Turpin, R., 2007. Potential applications of phase change materials in concrete technology. Cement and Concrete Composites 29, 527–532.

Bilotta, R., Bell, J.E., Shepherd, E., et al., 2015. Calculation and evaluation of an air-freezing index for the 1981–2010 climate normals period in the coterminous United States. Journal of Applied Meteorology and Climatology 54 (1), 69–76.

Birgisson, B., Mukhopadhyay, A.K., Geary, G., et al., 2012. Nanotechnology in Concrete Materials: A Synopsis. Transportation Research Board, Washington DC.

Boatman, B., 2010. Epoxy Coated Rebar Bridge Decks: Expected Service Life. Michigan Department of Transportation, Lansing.

Burnham, T.R., 2007. Precast Concrete Pavement Panels on Minnesota Trunk Highway 62 - First Year Performance Report. Minnesota Department of Transportation, St. Paul.

Busari, A.A., Akinmusuru, J.O., Dahunsi, B.I.O., et al., 2017. Self-compacting concrete in pavement construction: strength grouping of some selected brands of cements. Energy Procedia 119, 863–869.

Chen, S.Y., You, Z.P., Sharifi, N.P., et al., 2019. Material selections in asphalt pavement for wet-freeze climate zones: a review. Construction and Building Materials 201, 510–525.

Concrete Reinforcing Steel Institute (CRSI), 2004. Performance Observed: CRCP in Louisiana—Then and Now. CRSI Case History Report. Concrete Reinforcing Steel Institute, Schaumburg.

Federal Highway Administration (FHWA), 2007. Take a Look at Two-Lift Concrete Paving. FHWA-HRT-07-016. FHWA, Washington DC.

George, A., 1989. Handbook of Thermal Design. McGraw Hill Book Co., New York.

Gharaibeh, N., Darter, M., Heckel, L., 1999. Field Performance of Continuously Reinforced Concrete Pavement in Illinois. Illinois Department of Transportation, Springfield.

Hall, K.T., 2000. State of the Art and Practce in Rigid Pavement Design-Transportation in the New Millennium. Transportation Research Board, Washington DC.

Federal Highway Administration, 2017. Tools for Using Precast Concrete Pavement (PCP) Systems to Reduce the Duration of Construction Closures on Critical Roadways and to Provide Long-Life Performance. Available at: https://www.fhwa.dot.gov/goshrp2/Solutions/Renewal/R05/Precast_Concrete_Pavement (Accessed 18 October 2017).

Iowa Department of Transportation (IDOT), 2017. Level III: Portland Cement Concrete. IDOT, Ames.

Kahhaleh, K.Z., Vaca-Cortés, E., Jirsa, J.O., et al., 1998. Corrosion Performance of Epoxy-Coated Reinforcement-Beam Tests. Texas Department of Transportation, Austin.

Kumari, K., Preetha, R., Ramachandran, D., et al., 2015. Nanoparticles for enhancing mechanical properties of fly ash concrete. Materials Today Proceedings 3 (6), 2387–2393.

Lane, G.A., Kott, A.C., Rossow, H.E., 1977. Macro-encapsulation of PCM. U.S. Energy Research and Development Administration, Oak Ridge.
Ley, T., Cook, D., Fick, G., 2012. Concrete Pavement Mixture Design and Analysis (MDA): Effect of Aggregate Systems on Concrete Properties. Federal Highway Administration, Washington DC.
Lomboy, G., Kejin, W., Ouyang, C., 2011. Shrinkage and fracture properties of semiflowable self-consolidating concrete. Journal of Materials in Civil Engineering 23 (11), 1514−1524.
Michigan Department of Transportation, 2017a. Materials Source Guide − Qualified Products List. Michigan Department of Transportation, Lansing.
Michigan Department of Transportation, 2017b. Road Design Manual. Michigan Department of Transportation, Lansing.
National Climatic Data Center, 2017. Air Freezing Index- USA Method, National Climatic Data Center. Available at: https://www.ncdc.noaa.gov/sites/default/files/attachments/Air-Freezing-Index-Return-Periods-and-Associated-Probabilities.pdf (Accessed 1 April 2017).
National Concrete Pavement Technology Center, 2014. Limestone Cements. https://www.concreteconstruction.net/concrete-production-precast/the-advantages-of-portland-limestone-cement_o (Accessed 1 April 2017).
National Oceanic and Atmospheric Administration, 2010. Statewide Time Series: Annual Precipitation of Michigan from 1981 to 2010. Available at: https://www.ncdc.noaa.gov/cag/statewide/time-series (Accessed 1 April 2017).
National Precast Concrete Association, 2009. Precast Concrete Pavement Slab Systems (Tollway). National Precast Concrete Association, Carmel.
Norhasri, M.S.M., Hamidah, M.S., Fadzil, A.M., 2017. Applications of using nano material in concrete: a review. Construction and Building Materials 133, 91−97.
Petersen, L., Peterson, R., 2006. Intelligent Compaction and In-situ Testing at Mn/DOT TH53. Minnesota Department of Transportation, St. Paul.
Plei, M., Tayabji, S., 2012. Continuously Reinforced Concrete Pavement Performance and Best Practices. FHWA-HIF-12-039. Federal Highway Administration, Washington DC.
Roesler, J.R., Hiller, J.E., Brand, A.S., 2016. Continuously Reinforced Concrete Pavement Manual − Guidelines for Design, Construction, Maintenance, and Rehabilitation. Federal Highway Administration, Washington DC.
Sakulich, A.R., Bentz, D.P., 2011. Increasing the service life of bridge decks by incorporating phase-change materials to reduce freeze-thaw cycles. Journal of Materials in Civil Engineering 24 (8), 1034−1042.
Sanchez, F., Sobolev, K., 2010. Nanotechnology in concrete—a review. Construction and Building Materials 24 (11), 2060−2071.
Shah, S., Hou, P., Konsta-Gdoutos, M.S., 2015. Nano-modification of cementitious material: toward a stronger and durable concrete. Journal of Sustainable Cement-Based Materials 5 (1−2), 1−22.
Shannon, J., Howard, I.L., Cost, V.T., et al., 2014. Benefits of Portland-limestone cement for concrete with rounded gravel aggregates and higher fly ash replacement rates. In: Transportation Research Board 94th Annual Meeting, Washington DC, 2014.
Sharifi, N.P., 2016. Application of Phase Change Materials to Improve the Thermal Performance of Buildings and Pavements. Worcester Polytechnic Institute, Worcester.
Sharifi, N.P., Mahboub, K.C., 2018. Application of a PCM-rich concrete overlay to control thermal induced curling stresses in concrete pavements. Construction and Building Materials 183, 502−512.
Sharifi, N.P., Sakulich, A., 2013. Application of phase change materials in structures and pavements. In: The 2nd International Workshop on Design in Civil and Environmental Engineering, Worcester, 2013.
Sharifi, N.P., Freeman, G.E., Sakulich, A.R., 2015. Using COMSOL modeling to investigate the efficiency of PCMs at modifying temperature changes in cementitious materials−case study. Construction and Building Materials 101, 965−974.
Sharma, A., Tyagi, V.V., Chen, C.R., et al., 2009. Review on thermal energy storage with phase change materials and applications. Renewable and Sustainable Energy Reveiws 13 (2), 318−345.
Tayabji, S., Brink, W., 2015. Precast Concrete Pavement Implementation by U.S. Highway Agencies. FHWA-HIF-16-007. Federal Highway Administration, Washington DC.
Tayabji, S., Smith, K.D., Van Dam, T., 2010. Advanced High-Performance Materials for Highway Applications: A Report on the State of Technology. Federal Highway Administration, Washington DC.
Tayabji, S., Ye, D., Buch, N., 2012. Precast Concrete Pavement Technology. Transportation Research Board, Washington DC.
Tayabji, S., Ye, D., Buch, N., 2013. Model Specifications for Precast Concrete Pavement Systems. Transportation Research Board, Washington DC.
Tayabji, S., Tyson, S., Roesler, J., et al., 2016. Promising Practices for Construction, Repair, and Rehabilitation of Continuously Reinforced Concrete Pavement. Transportation Research Board, Washington DC.
Taylor, P., Fick, G., 2015. Blended Aggregates for Concrete Mixture Optimization. Federal Highway Administration, Washington DC.
Uhlmeyer, J., Russell, M., 2013. Dowel Bars for New and Existing Concrete. Washington State Department of Transportation, Olympia.
Valentine, S., 2015. Expected Service Life of Michigan Department of Transportation Reinforced Concrete Bridge Decks. Michigan Department of Transportation, Lansing.
Van Dam, T.J., Harvey, J.T., Muench, S.J., et al., 2015. Towards Sustainable Pavement Systems: A Reference Document. Federal Highway Administration, Washington DC.
Wang, K., Shah, S., White, D.J., et al., 2005. Self-consolidating Concrete - Applications for Slip-form Paving: Phase I (Feasibility Study). Federal Highway Administration, Washington DC.
Wang, K., Surendra, P.S., Grove, J., et al., 2011. Self-Consolidating Concrete—Applications for Slip-form Paving: Phase II. Federal Highway Administration, Washington DC.
Washington State Department of Transportation, 2013. Dowel Bars for New and Existing Concrete Pavements. Washington State Department of Transportation, Olympia.

Dr. Naser P. Sharifi is a postdoctoral scholar in Department of Civil Engineering at the University of Kentucky. He served as post-doctoral scholar in Department of Civil and Environmental Engineering of Michigan Technological University during the mentioned MDOT project. The main focus of his research is on the application of phase change materials in construction and pavement materials. He has also studied the applicability of different strategies to increase the service life of asphalt and concrete pavements. Dr. Sharifi received his PhD from Worcester Polytechnic Institute, Worcester, MA, in 2017, and was a temporarily research associate in the Department of Civil and Environmental Engineering at Michigan Technological University, Houghton, MI, from March 2017 to June 2017.

Siyu Chen is currently a PhD candidate at Michigan Technological University. He has over six years of research experience with pavement materials and pavement design. His research interests include moisture damage of asphalt mixture, rubber modified asphalt mixture, and modeling of asphalt mixtures. He has taken part in projects with a wide range, such as rubber asphalt, skid resistance performance, and identifying best practice. He has published over seven paper in journals and conference proceedings.

Dr. Zhanping You earned his PhD in civil engineering from the University of Illinois at Urbana-Champaign in 2003. He has over 20 years of practical and research experience with pavements engineering and materials including completed research projects on a wide range of subjects including pavement materials and pavement design, sustainable materials and micromechanics based models for pavement materials. Sponsors of his research program include: National Science Foundation (NSF), U.S. Environmental Protection Agency (U.S. EPA), Michigan Department of Environmental Quality (MDEQ), Federal Highway Administration, Michigan Department of Transportation (MDOT), Minnesota Department of Transportation (MnDOT), and Texas Department of Transportation (TxDOT). Professor You has published over 300 papers in journals and conference proceedings. He has served as an associate editor for the American Society of Civil Engineers' (ASCE) Journal of Materials in Civil Engineering since 2008. He has been involved in professional services for many professional organizations including ASCE (Chair of Mechanics of Pavements Committee and Chair of Bituminous Materials Committee), the Transportation Research Board (TRB), Association of Asphalt Paving Technologists (AAPT), International Society of Asphalt Pavements (ISAP), American Association for the Advancement of Science (AAAS), and International Union of Laboratories and Experts in Construction Materials, Systems and Structures (RILEM).

Dr. Thomas Van Dam has been actively involved in pavement-related issues at the national, regional, and state levels. His areas of expertise include sustainable civil engineering infrastructure, airport and highway pavement performance, durability, and training. With more than 30 years of experience in pavement design and evaluation, concrete, materials assessment and sustainability, he has managed large projects for the FHWA, multiple state departments of transportation and the Innovative Pavement Research Foundation to analyze the effects of concrete properties and durability on pavement performance and has published numerous articles and papers.

Dr. Christopher Gilbertson is an experienced researcher and instructor having developed and delivered instructional materials to pre-college, college, and practitioner-level audiences. Dr. Gilbertson's research interests include design, load rating, and asset management of bridges and pre-college outreach. He is active in the TRAC and NSTI programs which serve to excite middle and high-school students about careers in the STEM (science, technology, engineering, and math) fields specifically in areas related to transportation and civil engineering.