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Review

Material selections in asphalt pavement for wet-freeze climate zones: A review

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HIGHLIGHTS

- Identification of wet-freeze climate zones in the United States and parts of Canada.
- Summary of material selections of asphalt pavements in wet-freeze climate zones.
- Introduction of current practices, and the emerging technologies/materials.
- Discussion of asphalt binders and up to mixtures related test/design methods.

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ABSTRACT

The objectives of this review paper are to document current practices in wet-freeze climate zones and introduce emerging technologies that would be largely implemented in wet-freeze climate zones in the near future. A current practice is defined as a procedure that has been shown by research or experience to produce acceptable results and that is established or proposed as a standard suitable for widespread adaptation. An emerging technology is defined as a technique or a material that can improve the asphalt pavement performance, partly replace general materials, and contribute to more sustainable asphalt pavements. This review identified the criteria used to determine locations in the United States and two Canadian provinces with a similar wet-freeze climate. In addition, asphalt binders, asphalt additives/modifiers, asphalt mixture types, reclaimed asphalt mixtures, asphalt mixture test methods, asphalt mixture design methods, and deicers were reviewed. This review concluded with some recommendations in terms of using environmentally friendly materials and selecting cracking and rutting failure criteria to design asphalt mixtures with enhanced performance in wet-freeze climates.

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1. Introduction

Weather conditions affect pavement material selection, design processes, construction procedures, and maintenance strategies. Wet-freeze climates are classified as those that "[experience] long winters with the temperatures below freezing for extended periods" [1]. Such climates leave pavements susceptible to damage due to frost or water retention in the subgrade.

Two of the most important climate parameters of a region are annual precipitation and freezing index. These parameters affect factors such as the pavement's surface temperature, frost penetration depth, and the number of freeze/thaw cycles experienced by the pavement. These factors are necessary considerations for designing, constructing, and maintaining pavements. The freezing index is defined by the area under the temperature curve during the freezing period, represented by the following calculation [2]:

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

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 pavement's freezing index is conservatively assumed to be equal to the freezing temperature of the air.

The Federal Highway Administration (FHWA) uses these two climate parameters to divide the United States into four climate regions (Fig. 1). In wet-freeze climates, the annual rainfall is higher than 28 in. (71 cm) and the freezing index is greater than 100°F-Days. According to the 2016 Highway Performance Monitoring System (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 [3].

Two Canadian provinces—Ontario and Quebec—are considered to be wet-freeze climates because the predominant climate in these provinces is similar to the wet-freeze characteristics defined by the HPMS. Table 1 shows the wet-freeze climate zones of selected five U.S. states, two Canadian provinces.

The wet-freeze climate makes the requirements for pavement system different from many other regions. Building and maintaining roads requires a particular consideration of design and construction procedures that are compatible with climate conditions. These considerations need to result in a pavement 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 need to be selected for withstanding high precipitation and cold winter temperatures. Failure to take into account the weather conditions when selecting the pavement materials, design, and construction techniques may lead to inadequate pavement performance during its service life.

This review will document and introduce material selections of asphalt pavement in wet-freeze climate zones. The strategies can

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

Note: 1 inch = 2.54 cm;
Temperature (unit in °F) = Temperature (unit in °C) × 1.8 + 32.

Fig. 1. Four US Climate Regions based on FHWA (Adapted from [3]).

Table 1
Wet-freeze climate zones of selected five U.S. states, two Canadian provinces.

State [4]/Province [5]	Annual Precipitation		Freezing Index (°F-Days)	Number of days with temperature of 32°F or less	Annual Snowfall		Average annual temperature (°F) [6,7]		
	(inch)	Days			(inch)	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

Note: 1 in. = 2.54 cm; Temperature (unit in °F) = Temperature (unit in °C) × 1.8 + 32.

be current practices or emerging technologies. A current practice is a procedure that has been shown by research or experience to produce acceptable results and has been established or proposed as a standard suitable for widespread adaptation. An emerging technology is a technique or a material that can improve asphalt pavement performance, partly replace natural materials, and contribute to more sustainable asphalt pavements.

2. Objectives and scope

The objectives of this review are the following:

- Document current practices in wet-freeze climate zones.
- Introduce the emerging technologies that will be largely implemented in wet-freeze climate zones in the coming future.

The review will limit its discussion to pavement materials of asphalt pavement.

3. Asphalt binder types

3.1. Neat asphalt binder

Neat asphalt binder (NAB) is refined from crude oil and is directly used in paving. NAB is a visco-elastic material, which means it has both viscous and elastic properties. The properties are dramatically affected by temperature. For example, NAB becomes soft as it is heated and becomes close to an elastic solid as it is cooled. It is the visco-elastic properties that allow asphalt binder to be a critical paving material.

When choosing NAB for given climatic and traffic conditions, the performance of the NAB should be considered, including permanent deformation at high temperatures, fatigue cracking at the intermediate temperatures, and thermal cracking at cold temperatures. In addition, NAB stiffens as it ages (mainly due to volatilization and oxidation).

In the Superpave™ performance-grade (PG) binder specification, the visco-elastic and aging properties of NAB are considered. The viscosity of the NAB at high temperature is measured by a Rotational Viscometer (RV) to determine mixing and compaction temperature of asphalt mixtures. The viscous and elastic behaviors of the NAB at the high-end of in-service temperatures are measured by a Dynamic Shear Rheometer (DSR) to evaluate the rutting potential under traffic loading. Testing is conducted before aging and after short-term aging using the Rolling Thin-Film Oven (RTFO) test, which is used to simulate oxidative aging during construction [8]. In addition, the DSR can be used to evaluate the potential of fatigue cracking at intermediate temperatures. In this test, the binder has already experienced the RTFO test and the Pressure Aging Vessel (PAV) test that is used to simulate five to ten years of in-service aging. The susceptibility of NAB to thermal cracking is measured by a Bending Beam Rheometer (BBR), in which the binder has already undergone short-term RTFO and long-term PAV aging. Fig. 2 shows the flow chart for performance grading tests.

The use of NAB is a current practice in wet-freeze climate zones. Based on the performance grading tests, the different asphalt bin-

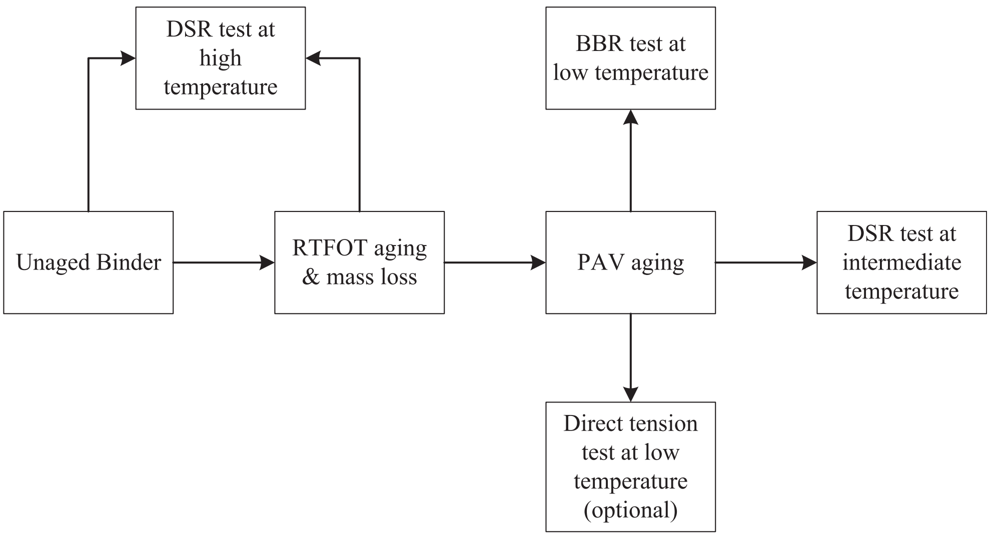

Fig. 2. Flow chart for performance grading tests.

ders have varying minimum and maximum temperatures that affect pavement design. For example, a binder categorized as PG 58-28 will meet the physical properties requirement of a maximum temperature up to 136.4°F (58 °C) and a minimum temperature as low as −18.4°F (−28 °C) [9]. Table 2 shows an example of the binder grades used in Michigan [10].

3.2. Emulsified asphalt

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 an 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 reason for 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 take up to 90 days depending on the type of emulsion. Emulsions are safer than cut-back asphalt and are a best practice that is not unique to wet-freeze climates but is 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.

3.3. Cut-back asphalt

Cut-back is produced "when asphalt binder is dissolved in a petroleum-based solvent". The cut-back 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 [11]. Cut-back asphalt is no longer commonly used because of the volatility of the solvents used and obvious environmental concerns.

3.4. Tack coat

A tack coat consists of neat asphalt binder, cut-back asphalt or emulsified asphalt (asphalt binder diluted with water and an emulsifying agent). The goal of a tack coat is to increase the bonding strength between layers to improve the performance of the pavement structure. It is applied to a road surface in order to aid the bonding between the existing layer and forthcoming overlays, and increase the effectiveness of the pavement for both the short term and the long term performance [12]. Tack coat is a cost-effective bonding method, costing 0.1–0.2% of the total project cost for new or reconstruction work and 1.0–2.0% of total project costs for mill and overlay work [13]. However, if a tack coat's bond fails, correcting the problem could run as high as 30–100% of the original total project costs [13].

Trackless tack coats are designed to serve the same purpose as standard tack coats [14], 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 [15]. Various contractors in Ohio, Missouri, Tennessee, and around the southeast region of the U.S. all offer trackless tack coat products [16–18]; the Virginia Department of Transportation (DOT) and Illinois Center for Transportation have also performed studies into the performance and implementation of trackless tack coats, respectively [15,19,20]. In 2016, Michigan Department of Transportation (MDOT) released a special provision for the permissive use of low-tracking bond coat (trackless tack coat) emulsified asphalt instead of standard tack coats [21].

Table 2
Binder grades used in Michigan (Adapted from [10]).

High Temperature Grades (°C)	Low Temperature Grades (°C)
PG 58	−22, −28, −34
PG 64	−22, −28
PG 70	−22P*, −28P*

* PG 70-22P and PG 70-28P are polymer modified binder.

3.5. Bio-derived binder

Bio-derived binders are generated from bio-mass materials such as vegetable oils (i.e., soybean, corn, sunflower, and canola), swine waste, and waste wood [22–24]. The bio-derived binders can be used to replace partially the asphalt binder in asphalt pavement [23–31]. Vegetable-oil-based modifiers are considered as renewable resources, and products made from them include rejuvenators (extender oils), bio-polymers, and resin-like synthetic binders [22]. MDOT has sponsored research on using Michigan wood bio-asphalt as an alternative material [32]. 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 [33]. Commercially available bio-derived binders, such as Vegecol and Ecopave, are also available in Europe and Australia. However, it is still an emerging material; therefore, it is recommended to review this material again as more research becomes available.

4. Asphalt additives/modifiers

4.1. Anti-stripping agents

Anti-stripping agents are usually classified into two groups—slurries and liquids. Slurries often make use of hydrated lime, also known as calcium oxide, that has been hydrated with water [34]. Liquids are surfactants that modify asphalt by enabling "the asphalt to coat the aggregate surface more evenly by reducing surface tension" while also "displacing adsorbed water on or near the aggregate surface" [34].

The tensile strength ratio (TSR) test is the standard test for evaluating moisture susceptibility of the asphalt mixture. According to AASHTO T 283, the threshold for TSR is a minimum of 80%. The Hamburg wheel-track testing (HWTT) is an alternative for evaluating moisture susceptibility, but there are no national HWTT threshold specifications; in a study by Martin, Arambula [35], 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 [35].

The use of anti-stripping agents is a current practice in wet-freeze climate zones. 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. Fig. 3 shows wet-freeze climate states that treat Hot Mixture Asphalt (HMA) for moisture damage [36]. Most of the states use liquids anti-stripping agents to prevent HMA moisture damage, such as Minnesota, Michigan, Wisconsin, and Illinois.

4.2. Polymer-modified binder

Early polymer-modified asphalts were designed to accommodate different climatic areas and exhibited such traits as

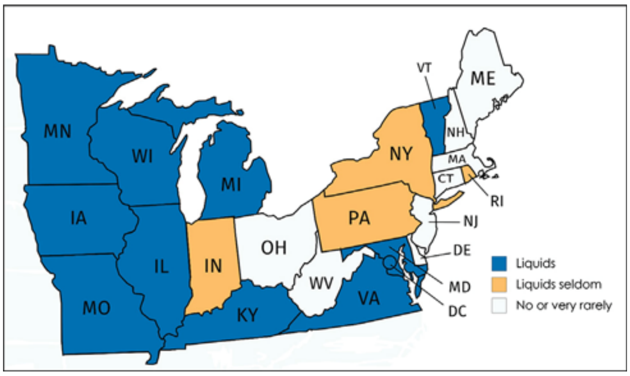

Fig. 3. Wet-freeze climate states that treat HMA for moisture damage (Adapted from [36]).

"decreased temperature susceptibility, increased cohesion and modified rheological characteristics" [37]. These features 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 use of polymer-modified asphalts is a current practice in wet-freeze climate zones. The performance-modifying effects of various polymers on asphalt pavements were investigated by MDOT in the 1990s; the comprehensive list of tests included DSR, BBR, viscosity, Differential Scanning Calorimeter (DSC), Fourier Transform Infrared (FTIR) spectroscopy, Thermal Mechanical Analysis (TMA), and Gel Permeation Chromatography (GPC) [38]. It is 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) [38]. For bonding 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 [39]. For more information on the advances and challenges of polymer modified asphalt can refer to Zhu et al. [40].

SBS is a block copolymer, and its strength and elasticity is derived from its physical cross-linking of its molecules that can create durable pavement even in cold climates [37]. To modify asphalt with SBS, no specific equipment is needed either in the laboratory or the field [41]. 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 [39]. 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 [38]. Furthermore, the indirect tensile test 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 [42]. Presently, SBS is a widely used polymer that can enhance pavement durability in wet-freeze climates.

SBR is another common polymer for modifying asphalt binders and mixtures [38]. SBR polymer increases the adhesion and cohesion between the asphalt and aggregates, as well as the crack resistance at low temperatures [43]. When SBR is incorporated into asphalt at higher amounts, it forms 'a network' that improves the rutting resistance [38]. Modifying asphalt with SBR improves its low-temperature ductility, elastic recovery, and viscosity [39,43].

4.3. Rubber-modified binder

Crumb rubber—primarily from recycled tires—can be used to modify asphalt, thus creating a crumb rubber modified asphalt (CRMA) [44]. CRMA can be used in structural-layer asphalt, surface-layer asphalt, and even chip seals. According to Papagiannakis and Lougheed [45], 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. There are different methods of adding crumb rubber into the asphalt mixtures. In the dry process, crumb rubber is added to the aggregate before mixing with the asphalt binder. In the wet process, the crumb rubber is added to the asphalt binder before mixing with aggregate. It seems like little difference between the two methods, but the selected process dramatically affects the interaction between the crumb rubber and asphalt binder, resulting in a significant difference in the final product. Due to construction and performance issues, the dry process has limited usage. Therefore, the wet process is far more common and will be focused on here.

There are currently two kinds of wet-process crumb rubber modified asphalt used in asphalt pavement in the wet-freeze climate zone of the United States. A Field blend means that crumb rubber particles are blended with asphalt binder at a hot-mix plant [46]. 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 [46]. This technique, which uses a finer size of crumb rubber, makes CRMA similar to other types of polymer-modified asphalt [46].

The Ontario Tire Stewardship and the Ministry of Transportation of Ontario (MTO) surveyed the performance of rubber-modified asphalt in cold regions: United States, Canada, China, and Scandinavia (Sweden, Denmark, and Finland) [47]. The survey showed that 16 agencies use CRMA, 13 agencies use terminal blend, and several agencies use asphalt rubber chip seals or asphalt rubber interlayers. In wet-freeze climate, New Jersey DOT used 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 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 improved the resistance to reflection cracking by using rubberized asphalt in dense-graded and gap-graded mix [47]. At the same time, the agencies noted several drawbacks: limited amount 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 cost [47].

In a 2015 Michigan trial conducted by Michigan Technological University, two pavement sections were paved with rubber-modified asphalt in the terminal blend. One section was in Keweenaw County and the other was in Muskegon County. After the 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 [48]. In addition, crumb rubber has been used to modify warm-mix asphalt. Their environmental and mechanical performance are evaluated using laboratory and field compacted samples [49].

CRMA is a routinely used material in some areas of wet-freeze climate zones, including Maine, Massachusetts, Michigan, New Hampshire, and Pennsylvania. Table 3 displays the quantities and states where asphalt mixture reported using CRMA in 2013 [50].

Table 3
2013 Reported Tons Crumb Rubber (Adapted from [50]).

State	Crumb Rubber Mix (Tons)	Crumb Rubber Used (Tons)
Illinois	4,500	20
Indiana	13,000	30
Maine	14,000	219
Massachusetts	24,897	324
Michigan	12,000	71
New Hampshire	28,000	358
New York	10	–
Ohio	1,500	8
Pennsylvania	18,000	140
Total	**115,907**	**1,170**

The barriers to using rubber-modified asphalt products include high costs related to processing finer crumb sizes, higher construction temperatures required for paving, difficulty with compacting CMRA, and the unknown environmental implications of recycling CRMA [45]. Warm-mix asphalt technology is now being combined with CRMA to reduce the temperatures required for paving and emissions.

The limited research into rubber-modified 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 [51]), 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 [46]).

4.4. Polyphosphoric acid extender

Polyphosphoric Acid (PPA) can improve the high-temperature performance of resisting 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 [52,53].

The MTO conducted a survey in 2007 to gain insights into the poor performance of PPA-modified binder [54]. The task group established to investigate the issue identified an upper limit of PPA usage: for high-volume roads, the polymer could be added to the asphalt binder at quantity lower than 0.5% PPA, while for low-volume roads, PPA could account for up to 1% [54].

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. Fig. 4 illustrates survey responses (Data from [55]). 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 was a "preference for polymers; possible adverse reaction with other additives such [as] hydrated lime; unknown long term performance; and negative reports by others" [52,54–56].

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 Facility (MnROAD) low-volume road in 2007 [52,57]. The five sections of road that used PPA-modified binder experienced rutting depth that was less than 0.12 in. (3 mm) and no signs of moisture damage after 18 months

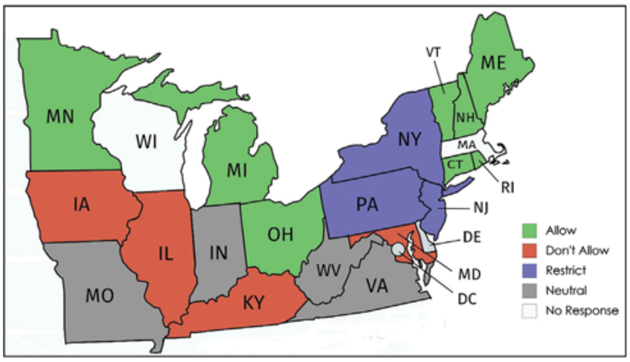

Fig. 4. Map showing responses of wet-freeze state DOTs to their use of PPA as a modifier for asphalt binder (Adapted from [55]).

(summary of the project by D'Angelo [54]). As of March 2016, the average rutting depth of a section using 0.75% PPA was 0.27 in. (6.8 mm) and 0.07 in. (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 in. (8.0 mm) and 0.09 in. (2.3 mm) for inside and outside lanes, respectively [58].

Other wet-freeze states, namely Pennsylvania, New Hampshire, and Maine, have conducted PPA field trials and found the condition of PPA modified segments similar to control segments [59]. Michigan conducted a rehabilitation project along US-31 north of Muskegon in 2005. The project included placing an 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 eight years in service found similar surface conditions and performance between the PPA-modified asphalt and the control segments [59]. However, it is still an emerging material. Therefore it is recommended to review this material again as more research becomes available.

4.5. Fiber-modified asphalt

Fibers have become a common modifier to reinforce asphalt pavements and improve their performance. There are many kinds of fiber used 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 [60], fiber reinforcement of asphalt pavement principally intends to offer extra tensile strength, which can increase the strain energy absorbed when deformation occurs in asphalt pavements [60]. Reinforcing asphalt pavements with fibers also enhances the cohesive and tensile strength of mixtures [60]. While no extra equipment is required for the field construction of fiber-modified pavements, life-cycle costs have been problematic [60,61].

Using fibers to reinforce asphalt pavements was first recorded in the 1960s [62]. Polypropylene-fiber-reinforced asphalt pavement on I-74 in Indiana, was found to have reduced transverse cracking, improved rutting resistance, and decreased overall cracking in its base and binder layers [63]. Polypropylene fibers as well as polyester fibers are useful for preventing reflection cracking in asphalt overlays [61,64].

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" [60,65]. 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 [60]. 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 [60].

Life-cycle costs related to paving fabrics and fibrous treatments have, thus far, made these technologies prohibitive in 1989, according to Maurer and Malasheskie [61]. However, recent research into cellulose-fiber, carbon-fiber, and glass-fiber reinforcement of asphalt pavements have yielded test sections with attributes such as 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 without the use of cellulose fibers than the pavements with fibers over a six-month period [60]. For asphalt roads containing carbon fibers, the pavement demonstrates improved resistance to cracks and mechanical properties and increased electrical conductivity, which can facilitate the 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 [60,66]. Finally, the crack propagation of asphalt pavements containing glass fibers decreased, and the stability and deformability improved [60].

The use of fiber-modified asphalt is both a current practice and an emerging technology in wet-freeze climate zones. Some kinds of fibers are used in current practices (e.g. cellulose fiber), and some kinds of fibers are mainly used in research projects (e.g., carbon fibers).

4.6. Nanomaterials

Nanomaterials, a completely new set of materials with various characteristics, have a size range from 1 nm–100 nm. Researchers used nanomaterials to modify asphalt materials to improve certain properties as discussed in an early paper by You and Dai in 2007 [67]. Nanomaterials such as nanoclay, nanosilica, nano hydrated lime, carbon nanotubes, and graphite nanoplatelets have been utilized in asphalt binders and asphalt mixtures [68–79]. Nano-modified materials have shown significant enhancements in mechanical and thermal properties. It was observed that 2% nanoclay (by mass of the binder) in the asphalt binder may increase the shear complex modulus by 184% [70]. Using nano hydrated lime may reduce 75% usage of conventional hydrated lime to improve the resistance to the moisture damage of asphalt mixtures [80]. The addition of 2–4% nanomaterials (by mass of the asphalt binder) can significantly improve rutting resistance in asphalt mixtures. For example, the average rut depth was reduced by almost half when 4% nanoclay (nanoclay modified asphalt and especially the polymer modified nanocaly modified asphalt) was applied in a modified asphalt mixture as compared to the control asphalt mixture [75]. The effects of moisture susceptibility and chloride-based deicers on asphalt mixtures were also investigated in studies [68,69]. Nanoclay modification improved the moisture susceptibility of asphalt mixtures. The mixture with 1.5% nanoclay (by mass of the binder) appeared to exhibit high tensile strengths when water or deicers were present. The addition of nanosilica and nanotubes also enhanced the resistance to permanent deformation [78], and the graphite nanoplatelets improved the thermal performance of asphalt binders and mixtures [81]. It is worth further research to explore the potential application of graphite nanoplatelets in asphalt binders and mixtures.

Even though using nanomaterials in asphalt pavement is still in the research stage, it may be a promising material to extend the service life of pavements in wet-freeze climates. Further research efforts may investigate the implementation of nano-modified mixtures in construction. A few examples of such efforts could be the production of a uniform nano-modified binder, improvement of the low temperature performance of nano-modified mixtures, or the economic and environmental assessments of nano-modified binder and mixtures.

5. Asphalt mixture types

5.1. Conventional hot-mix asphalt

Hot-mix asphalt (HMA) is a type of asphalt pavement construction that is widely used and not exclusive to wet-freeze climates. HMA consists of asphalt binder that has been 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 and the surface layer of asphalt or composite pavements [11]. However, HMA experiences decreased stiffness and fatigue life when subjected to multiple freeze-thaw cycles [82]. States such as Michigan have various guidance documents on HMA mixture requirements, such as minimum and maximum specifications for crushed aggregate, fine aggregate angularity, sand equivalent, and aggregate gradation [83].

5.2. Warm-mix asphalt

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 25–80°F (14–25 °C). The variability of this temperature reduction depends on such things like "mix, plant, climate, lift thickness, and hauling distance" [11]. Making WMA relies on the incorporation of additives into the asphalt mixture, and the cost of WMA largely depends upon the availability of the warm-mix additives. 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 [84]:

- 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" [84].
- A few additives in the non-foaming 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 [84]. Sulfur-extended asphalt is the use of sulfur to replace, in part, the asphalt binder and to increase the stiffness of the mixture [22]. 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" [22]. The Thiopave®-modified asphalt has been field tested in Canada. Sulfur-extended asphalt is an emerging technology. Harmful levels of hydrogen sulfide and sulfur dioxide have been known to occur at elevated temperatures. Therefore, future recycling of sulfur-extended pavement should be performed at reduced temperatures [84]. 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 [85,86]. 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 [87], Missouri used 2100 tons of Sasobit®-WMA mixture during a 10-day road construction project. Their HMA sections had approximately 0.02 in. (0.45 mm) of rutting while the Sasobit®-WMA mixtures had 0.03 in. (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 in. (0.8 mm) of rutting while the HMA increased from 0.015 in. (0.4 mm) to 0.02 in. (0.5 mm); nonetheless, Hurley, Prowell [87] did not decisively declare either material as superior. Similarly, a Wisconsin field investigation found the Sasobit®-WMA mixtures have less than 0.04 in. (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 [88].

- 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 in fluid content improves coating and compaction. Some foaming process techniques 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 [84]. 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 [84]. 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 [84]. 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 and $3.50 per ton to the mixture costs [89]. In addition, the theory, development, and application of the foaming process were reviewed by Mohd Hasan et al. [90] and foaming processes and agents have been studied in recent years [91–95].

WMA has been evaluated and is being increasingly used by agencies in the United States (see Fig. 5, data from Hansen and Copeland [50]). National Cooperative Highway Research Program (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 [96]. It concluded that HMA and WMA pavements have similar performance at a service life between 4 and 10 years [96]. 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 [22,97]. It was found that WMA may be workable—or compactable—for as much as 27 min longer than HMA [97].

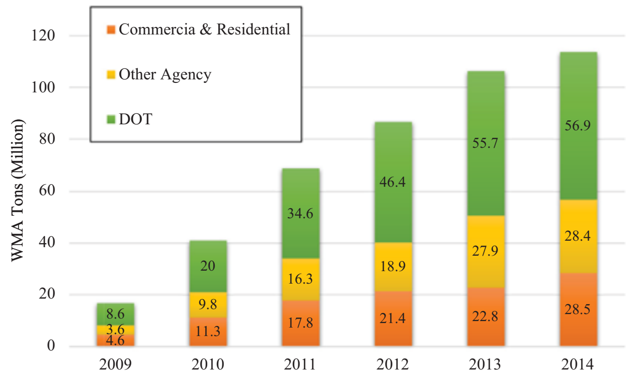

Fig. 5. Estimated tons of WMA usage by industry sector 2009–2014 in the United States (Adapted from [50]).

The main potential drawback of WMA is its vulnerability to rutting and moisture retention [98,99]. However, WMA may be beneficial in wet-freeze climates for its extended paving window. A study by Kristjansdottir [98] showed that WMA can have better results for cold-weather paving when WMA processes are used with regular HMA production temperatures [98]. 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 [100]. 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 [98]. The recent NCHRP report surmised that the addition of anti-stripping agents can likely alleviate the potential for moisture susceptibility of WMA pavement [35]. To control the temperature when placing WMA, MDOT has temperature limits for when the water-foaming method can be used or when using a chemical additive can be used [101]. In wet-freeze environments, compaction, moisture susceptibility, and binder grade may play critical roles during the paving process. WMA is itself an innovative outgrowth of HMA; since it is still in various stages of experimentation, WMA innovative applications require more experimentation and field trials.

5.3. Reclaimed asphalt pavement

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 [102–105]. RAP is usually produced by cold-milling the existing asphalt pavement surface, and then experiencing additional crushing.

In 2009, the North Carolina Department of Transportation (NCDOT) conducted a survey to collect the RAP use in the United States [102]. As shown in Fig. 6, most of the wet-freeze climate states permit more than 25 percent RAP in HMA layers; however, fewer than half of the wet-freeze climate states use more than 20 percent RAP in HMA layers (see Fig. 7). For example, Illinois, Kentucky, Missouri, New Hampshire, Pennsylvania, Vermont, and West Virginia permit more than 25 percent RAP in HMA layers,

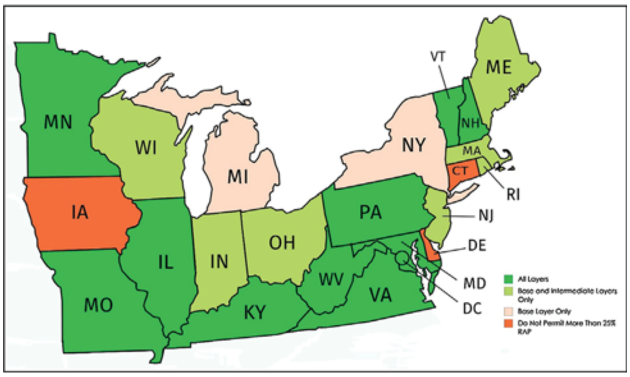

Fig. 6. Wet-freeze States that Permit More Than 25 Percent RAP in HMA Layers (Adapted from [102]).

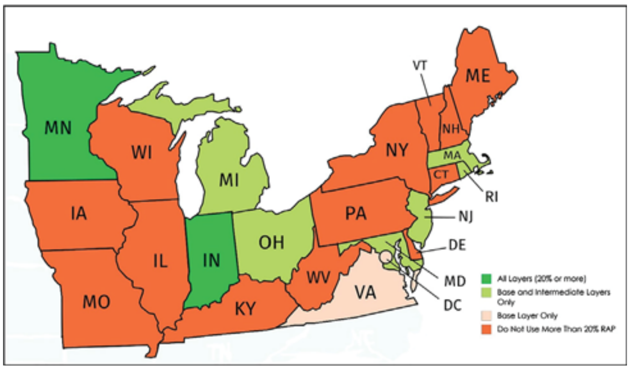

Fig. 7. Wet-freeze States that Use More Than 20 Percent RAP in HMA Layers (Adapted from [102]).

but they do not actually use more than 20 percent RAP in HMA layers.

From a recent report, Fig. 8 shows the estimated percent RAP usage by wet-freeze climate states in 2014 [50]. The estimated percent RAP usage is different among the wet-freeze climate states, ranging from less than 3% to 32%. For example, average percent RAP in Michigan is 32%, while in Vermont is less than 3% as reported. Nearly half of the wet-freeze climate states use more than 20% RAP in HMA/WMA.

As shown in Fig. 7, allowing a high RAP content in the state specifications does not indicate that a high percentage of RAP will be used in practice. The most common challenges to the use of RAP are specification limits of state transportation department, inconsistent RAP, lack of RAP availability, and lack of experiences. In addition, in terms of mixture performance for high RAP mixes, the quality of the blended virgin and RAP binders as well as cracking performance due to mix stiffening from high RAP quantities are the two most common concerns.

To increase the use of RAP and ensure asphalt mixture quality, it is recommended to utilize proper techniques for obtaining, stockpiling, and processing RAP: take random samples and conduct RAP composition tests of the RAP materials, assess RAP mixture performance, and document RAP use during production, construction, and long-term performance.

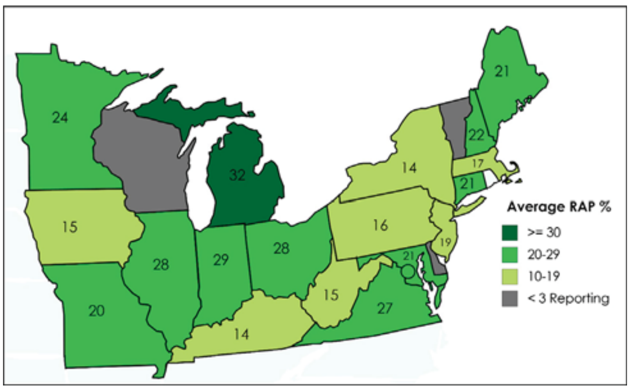

Fig. 8. Estimated Average Percent of RAP in Asphalt Mixtures by Wet-freeze States for 2014 (Adapted from [50]).

5.4. Recycled asphalt Shingles

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 material, which can promote environmental control while reduce project costs [106]. The IDOT allows up to 5 percent RAS by weight of total mix in its special provision, named *Special Provision for Reclaimed Asphalt Pavement (RAP) and Reclaimed Asphalt Shingles (RAS)* [107]. The MDOT permits that up to 17 percent RAS by weight of total binder as cited in its special provision, titled *Special Provision for Recycled Hot Mix Asphalt and Recycled Asphalt Shingles in Superpave Mixtures* [108]. Table 4 presents a summary of specifications on the RAS allowable percentage in wet-freeze climates.

To increase the usage of the RAS, there are obstacles to overcome, including lack of documented performance, lack of material specification, lack of practical experience, and additional required tests when using tear-offs RAS [109].

6. Asphalt mixture test methods

A number of mechanical tests are utilized to determine whether or not an asphalt mixture will be satisfactory for a specific application. For wet-freeze climate zones, the resistances to low temperature cracking, moisture damage, fatigue cracking, and rutting play important roles in producing asphalt mixtures. The following

Table 4
Summary of specifications on RAS allowable percentage in wet-freeze climates.

State	Maximum Amount	Equivalent Amount* (By weight of total mix)
Illinois [107]	5% RAS by weight of total mix	5%
Indiana [110]	3.0% RAS by weight of total mixture and 15.0% binder replacement	3%
Iowa [111]	5% RAS by weight of total aggregate	4.8%
Michigan [108]	17% RAS by weight of total binder	0.8%
Minnesota [112]	5% RAS by weight of total aggregate	4.8%
Ohio [113]	5% RAS by dry weight of mix	5%
Pennsylvania [114]	5% RAS by weight of total mixture	5%

* Assume that binder content is 4.5% and aggregate content is 95.5% in the traditional HMA mixture design.

subsections introduce several experimental methods for assessing the asphalt mixture. Table 5 shows the related asphalt mixture test methods for wet-freeze climate zones.

6.1. Short- and long-term oven conditioning

When evaluating the performance of HMA in the laboratory, it is vital to simulate the effects of short-term and long-term aging in the field. The short-term aging occurs during plant mixing and construction. During the production and paving process, some of the asphalt binders are absorbed by the aggregate, lowering the effective binder content, and the binders are aged by the high temperature that occur in the overall construction process. Long-term aging occurs during the service life of the pavement, where the binder experiences oxidative aging.

The procedures for short-term and long-term oven conditioning of asphalt mixtures have been developed and standardized in AASHTO R 30 [115]. The short-term oven conditioning includes evenly spread loose mixture in a forced draft oven at 275°F (135 °C) for 4 h. The mixture is spread evenly with a thickness between 0.98 and 1.97 in. (25 and 50 mm) in a pan and stirred every 1 h. The long-term oven conditioning is conducted after the short-term oven conditioning. This conditioning consists of conditioning the loose mixture at 185°F (85 °C) for 120 h.

Because rutting distress occurs in the early life of a pavement, evaluation of the rutting resistance should be conducted on samples with short-term conditioned. Fatigue and low temperature cracking tests should be performed on samples with long-term conditioned. In terms of moisture sensitivity test, AASHTO T 283 has different conditioning procedures that conditioning loose mixtures in a forced draft oven at 140°F (60 °C) for 16 h.

6.2. Low temperature cracking tests

Assessment of an asphalt mixture resistance to low temperature cracking can be evaluated by using the Disk-Shaped Compact Tension (DCT) test, Semicircular Bend Geometry (SCB) test at low temperature, or Indirect Tensile Test (IDT) creep compliance. The DCT test is conducted in accordance with ASTM D 7313 [116] and the sample for this test procedure is a circular specimen with a single edge notch loaded in tension. The SCB test at low temperature determines the fracture energy of asphalt mixture following AASHTO TP 105 [117]. The IDT creep compliance is determined by three measurements at 18°F (10 °C) intervals in accordance with AASHTO T 322 [118].

To protect the asphalt mixture from the thermal cracking, a low-temperature cracking specification is recommended by Marasteanu et al. [119], as shown in Table 6. In terms of DCT test, a minimum fracture energy of 400 J/m^2 is proposed for a low traffic volume road. For a high traffic volume road, a minimum fracture energy of 690 J/m^2 is suggested. In terms of SCB test as the low temperature, a minimum fracture energy of 350 J/m^2 and a minimum fracture toughness of 800 kPa·m$^{1/2}$ are recommended.

In addition, rubber modified asphalt mixtures possessed excellent low temperature cracking resistance in terms of the fracture energy. Buttlar et al. tested different crumb rubber modified asphalt mixtures at −18 °C and the fracture energy ranges from 691 J/m^2 to 1554 J/m^2 [120].

At Michigan Technological University, researchers found that rubber modified asphalt mixtures performed much better than the control HMA since the fracture resistance gained by nearly 25% [49]. In this study, the fracture energies at −24 °C for control HMA, crumb rubber modified HMA, and crumb rubber modified WMA were 467 J/m^2, 578 J/m^2, and 579 J/m^2, respectively based upon laboratory compacted plant mixture. The base asphalt used in this study was PG58-34, and the Evotherm additive was at 0.3% by weight of the asphalt binder for the WMA. The rubber asphalt was terminal blended asphalt to meet the specification of PG58-34. The performance grade of both the control asphalt and the CR modified asphalt are PG58-34.

6.3. Moisture sensitivity tests

The moisture sensitivity can be assessed using the modified Lottman test in accordance with AASHTO T 283 [121] and/or the Hamburg Wheel Tracking (HWT) test in accordance with AASHTO T 324 [122]. For the modified Lottman test, the moisture sensitivity is determined by a tensile strength ratio (TSR). The TSR is defined as the ratio of the average split tensile strength of the unconditioned sample to the conditioned sample. The conditioned sample is partially saturated with water and with freeze-thaw cycle. It is widely accepted that the TSR should be greater than 0.80 for a moisture damage resistant sample. It is noted that moisture conditioning can also be obtained by Moisture Induced Sensitivity Test (MIST™) following ASTM D 7870 [123,124]. For the HWT test, samples are tested underwater. The moisture sensitivity is based on the stripping inflection point, at which a slop intersection of the creep and stripping portions of the rut depth versus the number of wheel passes.

Table 5
Asphalt Mixture Test Methods for wet-freeze climate zones.

Test		Reference	Evaluation Indexes
Short- and long-term oven conditioning		AASHTO R 30	–
Low Temperature Cracking Tests	Disk-shape Compact Tension Test	ASTM D 7313	Fracture energy, fracture strength
	Semicircular Bend Geometry Test at Low Temperature	AASHTO TP 105	Fracture energy, fracture toughness
	Indirect Tensile Test	AASHTO T 322	Creep compliance, indirect tensile strength
Moisture Sensitivity tests	Modified Lottman Test	AASHTO T 283	Indirect tensile strength, tensile strength ratio
	Hamburg Wheel Tracking Test	AASHTO T 324	Stripping inflection point
Fatigue Tests	Flexural Fatigue Test	AASHTO T 321	Cycles to failure, flexural stiffness
	Flexibility Index Test	AASHTO TP 124	Flexibility index, fracture energy
	Direct Tension Cyclic Fatigue Test	AASHTO TP 107	Damage characteristic curve
Rut Resistance Tests	Asphalt Pavement Analyzer	AASHTO T 340	Rut depth
	Hamburg Wheel Tracking Test	AASHTO T 324	Rut depth, number of passes
	Incremental Repeated Load Permanent Deformation Test	AASHTO TP 116	Minimum strain rate
	Flow Number Test	AASHTO T 378	Flow number, dynamic modulus
	Superpave™ Shear Tester	AASHTO T 320	Permanent shear strain and stiffness

Table 6
Recommended Low-temperature Cracking Specification for Loose Mixture.

Test	Test Temperature	Test Criteria	Comment
DCT Test	PGLT + 10 °C	Fracture Energy, >400 J/m^2	Traffic Volume <10 million EASLs
		Fracture Energy, >460 J/m^2	Traffic Volume between 10 and 30 million EASLs
		Fracture Energy, >690 J/m^2	Traffic Volume >30 million EASLs
SCB Test	PGLT + 10 °C	Fracture Energy, >350 J/m^2 Fracture Toughness, >800 kPa·m$^{1/2}$	

Note: PGLT is Performance Grade Low Temperature; EASLs are Equivalent Single Axle Loads. The proposed specification is from Marasteanu et al. [119].

6.4. Fatigue tests

A durable asphalt pavement requires an excellent performance of fatigue cracking resistance [125–127]. The fatigue life of asphalt mixture can be determined by flexural fatigue test, Flexibility Index Test (FIT), or direct tension cyclic fatigue test. For the flexural fatigue test, asphalt mixture beams fabricated using a kneading or rolling wheel compaction equipment is tested for fatigue resistance in accordance with AASHTO T 321 [128–130]. FIT is developed by Illinois researchers to predict the cracking resistance of asphalt concrete mixtures using RAP and RAS [131]. For this test, a provisional standard method AASHTO TP 124 [132] is available. AASHTO TP 107 [133] shows test procedures and calculation processes for the damage characteristic curve using the direct tension cyclic fatigue test.

6.5. Rut resistance tests

The rut resistance can be assessed using an asphalt pavement analyzer in accordance with AASHTO T 340 [134]. This test consists of a load exerted through a rubber hose that is inflated at a given pressure. Samples for this test is commonly fabricated by the Superpave™ gyratory compactor. Besides that, the HWT test following AASHTO T 324, incremental repeated load permanent deformation test following AASHTO TP 116 [135], flow number test following AASHTO T 378 [136], or Superpave™ shear tester following AASHTO T 320 [137] can also be used to evaluate the rut resistance of asphalt mixtures.

Based on a national survey on the use of the HWT test, seven states in wet-freeze climates are currently utilizing HWT for research purposes or the state specifications. These seven states are Illinois, Iowa, Maine, Massachusetts, New York, Pennsylvania, and Wisconsin. Table 7 presents the performance criteria for HWT test for Illinois DOT and Wisconsin DOT, for both of which the minimum number of cycles at 0.5 in. (12.5 mm) rut depth is based on the asphalt binder grade. In addition, six states in wet-freeze climates (Connecticut, Minnesota, New Jersey, Ohio, Virginia, and West Virginia) use the asphalt pavement analyzer to evaluate rut resistance of asphalt mixture [138].

Table 7
Performance Criteria for HWT Test.

Agency	Asphalt Binder Grade	Minimum Number of Cycles at 0.5 in. (12.5 mm) Rut Depth*
Illinois DOT [139]	PG 58 or lower	5,000
	PG 64	7,500
	PG 70	15,000
	PG 76 or higher	20,000
Wisconsin DOT [140]	PG 58	5,000
	PG 64	10,000
	PG 70	15,000
	PG 76	20,000

* Test performed at 122°F (50 °C).

7. Asphalt mixture design methods

7.1. Superpave™

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. Superpave™ is a new system for mix design and performance-testing of hot mix asphalt and aims to deal with extreme temperature and heavy loads. Superpave™ system could be divided into three parts: (1) a PG asphalt binder specification and tests, which is based on the range of temperatures experienced by pavement; (2) aggregate criteria and tests; (3) a mixture design system using both a volumetric mixture design with SGC and analysis/performance prediction element [141].

In wet-freeze climates, Iowa DOT assessed the current asphalt mix design gyratory levels in Iowa state [142]. They evaluated the post-construction compaction effect and analyzed if 4% target airs were being obtained. It was found that the current design compaction levels produce mixes that have higher than 4% air voids after 4-year traffic densification. It is suggested to find the optimum gyration level in Iowa in the future work.

Wisconsin and Michigan are currently using regressing air voids method on HMA pavements. 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 applied this to address the issue of dry mixes, with a published special provision (12SP-501J) [143]. Wisconsin DOT is conducting a study for its specifications relating air void regression.

7.2. Balanced mix design

Balanced mix design (BMD) is "asphalt mix design using performance tests on appropriately conditioned specimens that addresses multiple models of distress taking into consideration mix aging, traffic, climate and location within the pavement structure". It involves of design the mixture to meet an intended application and service need [144].

In the volumetric design method, the volumetric parameters (such as air voids, voids in the mineral aggregate, voids filled with asphalt) cannot adequately evaluate mixture variables, such as recycled materials, warm-mix additives, polymer modifiers, rejuvenators, and fibers. However, the BMD balances mix performance with acceptable binder content. The mix performance consists of rutting resistance, fatigue cracking resistance, low temperature cracking resistance, reflection cracking resistance, and moisture susceptibility. In wet-freeze climate zones, tests for low temperature cracking, rutting and moisture sensitivity are the measure of performance that are most important. Fig. 9 displays the balanced mix design between cracking performance and rutting performance.

There are three main BMD approaches with different innovation potentials. From low to high innovation potential, they are Volumetric Design with Performance Verification, Performance Modified Volumetric Design, and Performance Design. (1) The

Fig. 9. Balance Mix Design.

Table 8
BMD practice in wet-freeze climate zones [144].

State	Design Approach	Stability Test	Durability/Cracking Test
Illinois	Volumetric Design with Performance Verification	Hamburg Wheel Tracking	Semi Circular Bend (IFIT)
New Jersey	Volumetric Design with Performance Verification	Asphalt Pavement Analyzer	Texas Overlay Test
Wisconsin	Volumetric Design with Performance Verification	Hamburg Wheel Tracking	Disk-Shaped Compact Tension & Semi Circular Bend (IFIT)

Volumetric Design with Performance Verification follows the Superpave™ design method to verify performance properties; if the mixes fail to meet the performance requirement, the mixes will be redesigned. Volumetric parameters would have to in the design range of AASHTO M323. For example, Illinois, New Jersey, and Wisconsin are exploring and developing this approach, as shown in Table 8. (2) The Performance Modified Volumetric Design first selects the initial binder content using AASHTO M323/R35. After the performance tests, the mixture proportions and/or binder content could be modified to meet the performance requirement. The final volumetric parameters may differ from the existing AASHTO M323 limit. For example, California (not in wet-freeze climates zone) is exploring this approach. (3) The Performance Design consists of conducting a series of performance tests with different binder contents and selecting the design binder content based on the performance result. The determined volumetric parameters do not require to fit with the existing AASHTO M323 limits. Table 8 presents the BMD practice in wet-freeze climate zones.

Currently, state departments of transportation are conducting BMD related research activities. For example, Minnesota DOT has a research project titled "Balanced Design of Asphalt Mixture" [145]. Indiana DOT has an active research project titles "Performance Balanced Mix Design for Indiana's Asphalt Pavements". Wisconsin DOT has two active research project titled "Analysis and Feasibility of Asphalt Pavement Performance-Based Testing Specifications" and "Regressing Air Voids for Balanced HMA Mix Design". In wet-freeze climate zones, DOTs with similar pavement distress considerations are selecting different performance tests and different BMD approaches, because they have different mix applications (e.g. overlays) or mix components (e.g. high recycled mixes). Therefore, BMD approaches differ and will probably continue to differ in the future.

8. Deicers for winter maintenance

Winter road maintenance is a significant consideration in wet-freeze climates. According to research by the Roadway Safety Foundation, winter road conditions lead to 115,000 injuries and 1000 deaths in the United States each year [146]. It is reported that deicing operations have reduced the crash frequency by 88.3 percent [146].

In a wet-freeze climate, snow and ice dramatically affect the quality of the pavement surface and, consequently, road safety. Therefore, effective methods of de-icing and anti-icing are critical for maintaining pavements in the winter. Strategies for controlling snow and ice can be divided into two categories, de-icing and anti-icing. De-icing includes methods of using either mechanical means (i.e., plowing) or chemical substances to road surfaces during or after a storm in order to break the bonds that have formed between the snow or ice and the pavement surface. Anti-icing, on the other hand, is the application of chemical substances to road surfaces before a winter storm occurs. For simplicity, this paper utilizes the term deicer to refer to all chemical materials used for anti-icing and de-icing practices. Common deicers are categorized as chloride-based, acetate-based, and agro-based deicers [147,148]. Common chloride-based deicers are sodium chloride (NaCl), calcium chloride ($CaCl_2$), and magnesium chloride ($MgCl_2$). Other than chlorides, acetate-based deicers such as potassium acetate (KAc) and calcium magnesium acetate (CMA) are also used. A recent study suggested that rock salt had a statistically-significant faster clearing speed on asphalt pavements than on concrete pavements [149]. Western Transportation Institute compared the costs and benefits of different deicers and found that, when used in conjunction with plowing, both salt brine (liquid NaCl) and $CaCl_2$ had the highest benefit-cost ratio. Other de-icing materials analyzed were $MgCl_2$, solid rock salt (solid NaCl), and abrasives [146,150].

With an increasing use of deicers, it is important to understand the effects of deicers on asphalt pavements [151]. Chloride-based deicers have little influence on the asphalt pavement, since asphalt binder has a relatively high chemical resistance to chloride-based deicers. However, using different road salts (sodium chloride) decreases the skid resistance of asphalt pavement. Current studies focus on how to improve skid resistance of different mixture types when chloride-based deicers are used [151]. Opposed to chloride-based deicers, the acetate- and formate-based deicers affect the durability of asphalt pavement. The damage mechanism seems to involve chemical reactions, emulsifications, distillations, and additional stress in the asphalt mixture. To enhance the resistance of asphalt pavements to acetate-based deicers, it is recommended to use polymer-modified binders, use high quality aggregates, test the compatibility between the mixture and the deicers, and compact the asphalt pavement to a low void content [151,152].

9. Summary

Twenty-two states in the United States and two Canadian provinces are considered as wet-freeze climate zones in this review, based on annual precipitation and freezing index.

This review documented and introduced materials selections of asphalt pavement in wet-freeze climate zones. The strategies include both current practices and emerging technologies. A current practice is a procedure that has been shown by research or experience to produce acceptable results and that is established or proposed as a standard suitable for widespread adaptation. An emerging technology is a technique or a material that can improve asphalt pavement performance, (partly) replace natural materials, and contribute to more sustainable asphalt pavements. The current practices and emerging technologies in wet-freeze climates are listed in Table 9 and a few key technologies are summarized as following:

(1) In terms of asphalt binders, neat asphalt binder, emulsified asphalt, and tack coat are current practices in wet-freeze climate, while bio-derived binder is still an emerging material which needs more research efforts.

Table 9
Summary of Materials and Design Methods in Wet-freeze Climate Zones.

Materials/Methods	Status	
	Current Practices	Emerging Materials/ Technologies
Asphalt Binder Types		
Neat Asphalt Binder	X	
Emulsified Asphalt	X	
Tack Coat	X	
Bio-derived Binder		X
Asphalt Additives/Modifiers		
Anti-stripping Agents	X	
Polymer-modified Binder	X	
Rubber-modified Binder	X	
Polyphosphoric Acid Extender		X
Fiber-modified Asphalt	X	X
Nanomaterials		X
Asphalt Mixture Types		
Conventional HMA	X	
Warm-mix Asphalt	X	
Reclaimed Asphalt Pavement	X	
Recycled Asphalt Shingles	X	
Asphalt Mixture Test Methods		
Short- and Long-term Oven Conditioning	X	
Low Temperature Cracking Test	X	
Moisture Sensitivity Test	X	
Beam Fatigue Test	X	
Rut Resistance Test	X	
Asphalt Mixture Design		
Superpave™	X	
Balance Mix Design		X

(2) In terms of asphalt additives/modifiers, anti-stripping agents, polymer-modified binder (SBR or SBB modifier), rubber-modified binder, and fiber-modified asphalt are current practices and still developing in wet-freeze climate, while polyphosphoric acid extender and nanomaterials could be an alternative modifier for asphalt binder.
(3) In terms of asphalt mixture types, conventional HMA mixtures, warm-mix asphalt mixtures, and reclaimed asphalt mixtures are current practices in wet-freeze climates.
(4) In terms of asphalt mixture test methods, short- and long-term oven conditioning, low temperature cracking test, moisture sensitivity test, beam fatigue test, and rut resistant test are current testing methods for asphalt mixtures.
(5) In terms of mixture design method, Superpave™ is a current practice in wet-freeze climate, while many state department of transportations are conducting balanced mix design related research projects.
(6) The chloride-based deicers have little influence on the asphalt pavement, while the acetate- and formate-based deicers affect the durability of asphalt pavement.

10. Recommendations

In wet-freeze climates, the presence of pavement distresses such as cracking, frost damage, material degradation, and thaw weakening, requires careful material selection for withstanding high precipitation and cold winter temperatures. In the future, it is highly suggested to conduct research on a number of potential materials, such as bio-derived binders, PPA extenders, fiber-modified asphalt, nanomaterials, and rubber modified binders. For example, bio-derived binders have shown the potential to improve the thermal cracking performance of petroleum-based asphalt binder [23]. However, the uncertainties of bio-derived binder, including diverse supplies, storability, and long term performance provide the challenges for a large scale application.

Using environmentally friendly materials provides a method to achieve a sustainable future and reduce the effect of human activities. Recently, asphalt-related materials have made significant progress by using an increasing amount of RAP, RAS, or crumb rubbers to partly replace virgin binder. In addition, WMA mixtures can reduce energy consumption and gas emissions. The challenge lies in how to maintain or even enhance the performance of asphalt mixture as well as use greater amounts of recycled materials. Therefore, applications with recycled materials require more experiments and field trials.

Good properties of cracking resistance and moisture damage resistance are vital requirements for asphalt pavements in wet-freeze climates. The current Superpave™ design method presents improvements in material selection with enhanced low temperature performance and moisture damage resistance. However, this approach is limited to volumetric testing and cannot adequately evaluate mixture variables, such as recycled materials, warm-mix additives, polymer modifiers, rejuvenators, and fibers. It is highly suggested to develop a balanced mix design approach for different applications. Future research work will include the cracking and rutting failure criteria for different applications, such as climates, mixtures, traffic levels, and pavement structures [119,145].

Conflict of interest

The authors claim no conflict of interest.

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References

[1] Federal Highway Administration, Appendix I: Climate Zone Definitions, Highway Pavement Monitoring System Field Manual, U.S. Department of Transportation Federal Highway Administration, 2000. p. I-1–I-2.
[2] J. Mahoney, M. Rutherford, R. Hicks, Guidelines for Spring Highway Use Restrictions, 1987.
[3] Federal Highway Administration, Highway Performance Monitoring System Field Manual, 2014.
[4] National Climatic Data Center. Air Freezing Index-USA Method, National Climatic Data Center [cited 2017 April 1st]; Available from: https://www.ncdc.noaa.gov/sites/default/files/attachments/Air-Freezing-Index-Return-Periods-and-Associated-Probabilities.pdf.
[5] Calculating insulation needs to fight frost heave by comparing freezing index and frost depth. In: Tech Solutions 605.0. DOW Chemical Canada-Building Solutions. Available from: http://msdssearch.dow.com/PublishedLiteratureDOWCOM/dh_01f6/0901b803801f6296.pdf?filepath=styrofoam/pdfs/noreg/178-00754.pdf&fromPage=GetDoc.
[6] Average Annual State Temperatures, Current Results, Weather and Science Fact. Available from: https://www.currentresults.com/Weather/US/average-annual-state-temperatures.php.
[7] Canada Cities Annual Temperature, Current Results, Weather and Science Facts. Available from: https://www.currentresults.com/Weather/Canada/Cities/temperature-annual-average.php.

[8] B. Hofko et al., Effect of short-term ageing temperature on bitumen properties, Road Mater. Pavement Des. 18 (sup2) (2017) 108–117.
[9] Asphalt Institute, SP-1 Superpave Performance Graded Asphalt Binder Specifications and Testing, 2001, Lexington, Kentucky.
[10] Michigan Department of Transportation, Local Agency Programs Hot Mix Asphalt (HMA) Selection Guidelines, Michigan Department of Transportation, Lansing, Michigan, 2016, p. 1.
[11] T.J. Van Dam et al., Towards Sustainable Pavement Systems: A Reference Document, U.S. Department of Transportation Federal Highway Administration, Washington, DC, 2015, p. 61801.
[12] K.I.Q. Hasiba, Development of a Testing Approach for Tack Coat Application Rate at Pavement Layer Interfaces, in: Civil Engineering, University of Illinois at Urbana-Champaign, Urbana, Illinois, 2012, p. 62.
[13] Federal Highway Administration, Tack Coat Best Practices, TechBrief, U.S. Department of Transportation Federal Highway Administration, Washington, DC, 2016.
[14] Ohio Department of Transportation, Construction Administration Manual of Procedures, Ohio Department of Transportation, Columbus, Ohio, 2013, p. 1190.
[15] T.M. Clark, T.M. Rorrer, K.K. McGhee, Trackless Tack Coat Materials: A Laboratory Evaluation for Performance Acceptance, Virginia Department of Transportation, Richmond, Virginia, 2012, p. 18.
[16] Jurgensen Companies, Trackless Tack, 2017 [cited 2017 October 19]; Available from: http://www.jrjnet.com/product/asphalt/trackless-tack/.
[17] Heartland Asphalt Materials, Trackless Tack, 2011 [cited 2017 October 20]; Available from: http://www.heartlandasphaltmaterials.com/Trackless%20Tack.aspx.
[18] Blacklidge, UltraTack®. 2017 [cited 2017 October 17]; Available from: http://blacklidgeemulsions.com/himod-technology/#ultratack.
[19] I. Al-Qadi et al., Best Practices for Implementation of Tack Coat: Part 1 – Laboratory Study, Illinois Department of Transportation, Springfield, IL, 2012, p. 26.
[20] I.L. Al-Qadi et al., Best Practices for Implementation of Tack Coat: Field Study (Part 2), Illinois Department of Transportation, Spingfield, Illinois, 2012, p. 59.
[21] Michigan Department of Transportation, Special Provision for Low-Tracking Bond Coat Emulsified Asphalt, Permissive Use, in: Michigan Department of Transportation, Michigan, Lansing, 2016, p. 6.
[22] S. Tayabji, K.D. Smith, T. Van Dam, Advanced High-Performance Materials for Highway Applications: A Report on the State of Technology, U.S. Department of Transportation Federal Highway Administration—Office of Pavement Technology, Washington, DC, 2010.
[23] J. Mills-Beale et al., Aging influence on rheology properties of petroleum-based asphalt modified with biobinder, J. Mater. Civil Eng. 26 (2) (2014) 358–366.
[24] E.H. Fini et al., Partial replacement of asphalt binder with bio-binder: characterisation and modification, Int. J. Pavement Eng. 13 (6) (2012) 515–522.
[25] X. Yang, Z. You, High temperature performance evaluation of bio-oil modified asphalt binders using the DSR and MSCR tests, Constr. Build. Mater. 76 (2015) 380–387.
[26] R. Zhang et al., High temperature performance of SBS modified bio-asphalt, Constr. Build. Mater. 144 (2017) 99–105.
[27] X. Yang, Z. You, J. Mills-Beale, Asphalt binders blended with a high percentage of biobinders: aging mechanism using FTIR and rheology, J. Mater. Civ. Eng. 27 (4) (2014) 04014157.
[28] X. Yang, J. Mills-Beale, Z. You, Chemical characterization and oxidative aging of bio-asphalt and its compatibility with petroleum asphalt, J. Cleaner Prod. 142 (2017) 1837–1847.
[29] R. Zhang et al., Optimization of bio-asphalt using bio-oil and distilled water, J. Cleaner Prod. 165 (2017) 281–289.
[30] R. Zhang et al., Thermal storage stability of bio-oil modified asphalt, J. Mater. Civ. Eng. 30 (4) (2018) 04018054.
[31] R. Zhang et al., Using bio-based rejuvenator derived from waste wood to recycle old asphalt, Constr. Build. Mater. 189 (2018) 568–575.
[32] X. Yang et al., Mechanical performance of asphalt mixtures modified by bio-oils derived from waste wood resources, Constr. Build. Mater. 51 (2014) 424–431.
[33] H.L. Von Quintus, Effectiveness of asphalt penetrating sealers in extending new asphalt pavement, Life (2017).
[34] D. Watson, J.R. Moore, A.J. Taylor, Effectiveness of Anti-Strip Agents in Asphalt Mixtures, Georgia Department of Transportation Office of Research, Forest Park, Georgia, 2012, p. 83.
[35] A.E. Martin et al., Evaluation of the Moisture Susceptibility of WMA Technologies, in: NCHRP Report 763, Transportation Research Board of the National Academies, Washington DC, 2014, p. 108.
[36] R.G. Hicks, L. Santucci, T. Aschenbrener, Topic 1: Inroduction and Seminar Objectives, Moisture Sensitivity of Asphalt Pavements, Transportation Research Board, Washington, D.C., 2003.
[37] G.D. Airey, Rheological properties of styrene butadiene styrene polymer modified road bitumens, Fuel 82 (2003) 11.
[38] M. Hawley, L. Drzal, G. Baladi, Polymers in Bituminous Mixtures – Phase II, Michigan Department of Transportation, Lansing, Michigan, 1997.
[39] Y. Becker, M.P. Mendez, Y. Rodriguez, Polymer modified asphalt, Vision Tecnol. 9 (1) (2001) 12.
[40] J. Zhu, B. Birgisson, N. Kringos, Polymer modification of bitumen: advances and challenges, Eur. Polymer J. 54 (Supplement C) (2014) 18–38.
[41] G.R. Woolley, J.J.J.M. Goumans, P.J. Wainwright, Waste Materials in Construction: Science and Engineering of Recycling for Environmental Protection, Elsevier Science, 2000.
[42] A.I. Al-Hadidy, T. Yi-qiu, Effect of styrene-butadiene-styrene on the properties of asphalt and stone-matrix-asphalt mixture, J. Mater. Civ. Eng. 23 (4) (2011) 7.
[43] Y. Yildirim, Polymer modified asphalt binders, Constr. Build. Mater. 21 (2007) 66–72.
[44] D. Ge et al., Modification mechanism of asphalt binder with waste tire rubber and recycled polyethylene, Constr. Build. Mater. 126 (2016) 66–76.
[45] A.T. Papagiannakis, T.J. Lougheed, A Review of Crumb-Rubber Modified Asphalt Concrete Technology, Washington State Transportation Commission & U.S. Department of Transportation Federal Highway Administration, 1995, p. 97.
[46] R.G. Hicks, D. Cheng, T. Duffy, Terminal Blend Rubberized Asphalt, California Pavement Preservation Center for California Integrated Waste Management Board, Sacramento, California, 2010.
[47] D. Cheng, R.G. Hicks, Survey on the Use of Rubber Modified Asphalt Pavements in Cold Regions, Ontario Tire Stewardship, Toronto, Canada, 2012.
[48] Z. You, X. Yang, Q. Dai, Low Emission Asphalt with Crumb Rubber, 2016: Reported to Michigan Department of Environmental Qualify.
[49] X. Yang et al., Environmental and mechanical performance of crumb rubber modified warm mix asphalt using Evotherm, J. Cleaner Prod. 159 (2017) 346–358.
[50] K.R. Hansen, A. Copeland, Asphalt Pavement Industry Survey on Recycled Materials and Warm-mix Asphalt Usage: 2014, 2015: Washington, DC.
[51] J.T. Harvey et al., Fatigue Performance of Asphalt Concrete Mixes and Its Relationship to Asphalt Concrete Pavement Performance in California, Division of New Technology and Research, Sacramento, California, 1995.
[52] M. Buncher, J. D'Angelo, Establishing a baseline of knowledge through 2005 by reviewing AI IS-220, Transportation Research Circular: Polyphosphoric Acid Modification of Asphalt Binders: A Workshop, Transportation Research Board, Minneapolis, Minnesota, 2009.
[53] D. Ge et al., Modification mechanism of asphalt modified with Sasobit and Polyphosphoric acid (PPA), Constr. Build. Mater. 143 (2017) 419–428.
[54] J.A. D'Angelo, Workshop summary, Transportation Research Circular: Polyphosphoric Acid Modification of Asphalt Binders: A Workshop, Transportation Research Board, Minneapolis, Minnesota, 2009.
[55] D. Maurer, J.A. D'Angelo, Department of transportation perspective: a survey on polyphosphoric acid use and issues, Transportation Research Circular: Polyphosphoric Acid Modification of Asphalt Binders: A Workshop, Transportation Research Board, Minneapolis, Minnesota, 2009.
[56] Federal Highway Administration, Tech Brief: The Use and Performance of Asphalt Binder Modified with Polyphosphoric Acid (PPA), U.S. Department of Transportation Office of Pavement Technology, 2012, p. 13.
[57] Minnesota Department of Transportation. Asphalt Binder Modification-MnROAD Field Investigation of Polyphosphoric Acid Modified Asphalt. Road Research 2017; Available from: http://www.dot.state.mn.us/mnroad/projects/Polyphosphoric_Acid_Mod_Asphalt/index.html.
[58] Minnesota Department of Transportation, Road Research: MnRoad – Field Monitoring, 2016.
[59] H.L. Von Quintus, Performance of Asphalt Mixtures Containing Polyphosphoric Acid, Asphalt Institute, Lexington, Kentucky, 2014.
[60] S.M. Abtahi, M. Sheikhzadeh, S.M. Hejazi, Fiber-reinforced asphalt-concrete – a review, Constr. Build. Mater. 24 (2010) 7.
[61] D.A. Maurer, G.J. Malasheskie, Field performance of fabrics and fibers to retard reflective cracking, Geotext. Geomembr. 8 (1989) 239–267.
[62] A. Mahrez, M. Karim, H. Katman, Prospect of using glass fiber reinforced bituminous mixes, J. Eastern Asia Soc. Transp. Stud. 5 (2003) 794–807.
[63] Y. Jiang, R.S. McDaniel, Application of cracking and seating and use of fibers to control reflective cracking, Transp. Res. Record: J. Transp. Res. Board 1388 (1993) 150–159.
[64] S. Tapkin, The effect of polypropylene fibers on asphalt performance, Build. Environ. 43 (2008) 1065–1071.
[65] H.L. Von Quintus, J. Mallela, R.L. Lytton, Techniques for Mitigation of Reflective Cracks, in 2010 FAA Worldwide Airport Technology Transfer Conference. 2010: Atlantic City, New Jersey.
[66] S. Wu et al., Investigation of the conductivity of asphalt concrete containing conductive fillers, Carbon 43 (2005) 1358–1363.
[67] Z. You, Q. Dai, Review of advances in micromechanical modeling of aggregate–aggregate interactions in asphalt mixtures, Can. J. Civ. Eng. 34 (2) (2007) 239–252.
[68] S.W. Goh et al., Effect of deicing solutions on the tensile strength of micro-or nano-modified asphalt mixture, Constr. Build. Mater. 25 (1) (2011) 195–200.
[69] X. Shi et al., Exploring the interactions of chloride deicer solutions with nanomodified and micromodified asphalt mixtures using artificial neural networks, J. Mater. Civ. Eng. 24 (7) (2011) 805–815.
[70] Z. You et al., Nanoclay-modified asphalt materials: preparation and characterization, Constr. Build. Mater. 25 (2) (2011) 1072–1078.
[71] R. Li et al., Developments of nano materials and technologies on asphalt materials–a review, Constr. Build. Mater. 143 (2017) 633–648.
[72] A. Diab et al., Moisture susceptibility evaluation of nanosize hydrated lime-modified asphalt-aggregate systems based on surface free energy concept, Transp. Res. Rec. 2446 (1) (2014) 52–59.
[73] H. Yao, Q. Dai, Z. You, Fourier transform infrared spectroscopy characterization of aging-related properties of original and nano-modified asphalt binders, Constr. Build. Mater. 101 (2015) 1078–1087.

[74] H. Yao et al., Rheological properties, low-temperature cracking resistance, and optical performance of exfoliated graphite nanoplatelets modified asphalt binder, Constr. Build. Mater. 113 (2016) 988–996.
[75] H. Yao, Z. You, Effectiveness of micro-and nanomaterials in asphalt mixtures through dynamic modulus and rutting tests, J. Nanomater. 2016 (2016) 10.
[76] H. Yao, Z. You, Performance of micro-and nano-modified asphalt mixtures through flow number and moisture susceptibility evaluations, J. Test. Eval. 45 (6) (2017) 2009–2019.
[77] H. Yao et al., Rheological properties and chemical analysis of nanoclay and carbon microfiber modified asphalt with Fourier transform infrared spectroscopy, Constr. Build. Mater. 38 (2013) 327–337.
[78] H. Yao et al., Rheological properties and chemical bonding of asphalt modified with nanosilica, J. Mater. Civ. Eng. 25 (11) (2012) 1619–1630.
[79] H. Yao et al., Performance of asphalt binder blended with non-modified and polymer-modified nanoclay, Constr. Build. Mater. 35 (2012) 159–170.
[80] A. Diab et al., Effects of regular-sized and nanosized hydrated lime on binder rheology and surface free energy of adhesion of foamed warm mix asphalt, J. Mater. Civ. Eng. 27 (9) (2014) 04014254.
[81] H. Yao et al., Property analysis of exfoliated graphite nanoplatelets modified asphalt model using molecular dynamics (MD) method, Appl. Sci. 7 (1) (2017) 43.
[82] G. Barlas, Material Characteristics of Hot Mix Asphalt and Binder Using Freeze-Thawing Condition, in: Civil Engineering, University of New Mexico: University of New Mexico UNM Digital Repository, 2013, p. 78.
[83] Michigan Department of Transportation, Special Provision for Superpave HMA Mixtures, 2007: michiganltap.org.
[84] B.D. Prowell, G.C. Hurley, B. Frank, Warm-mix Asphalt: Best Practices, third ed., National Asphalt Pavement Association Lanham, Md, USA, 2012.
[85] A. Jamshidi, M.O. Hamzah, Z. You, Performance of warm mix asphalt containing Sasobit®: state-of-the-art, Constr. Build. Mater. 38 (2013) 530–553.
[86] X. Li et al., Gradation segregation analysis of warm mix asphalt mixture, J. Mater. Civ. Eng. 30 (4) (2018) 04018027.
[87] G.C. Hurley, B.D. Prowell, A.N. Kvasnak, Missouri Field Trial of Warm Mix Asphalt Technologies: Construction Summary, U.S. Department of Transportation Federal Highway Administration, 2010, p. 73.
[88] V. Aurilio, Meeting Difficult Hot Mix Asphalt Challenges with Warm Mix Asphalt Solutions, Transportation Association of Canada, Vancouver, British Columbia, 2009.
[89] R. West et al., Field Performance of Warm Mix Asphalt Technologies, in: National Cooperative Highway Research Program (NCHRP) Reports, National Academies of Sciences, Engineering, Medicine, Washington, DC, 2014, p. 240.
[90] M.R. Mohd Hasan, Z. You, X. Yang, A comprehensive review of theory, development, and implementation of warm mix asphalt using foaming techniques, Constr. Build. Mater. 152 (2017) 115–133.
[91] M.R. Mohd Hasan, S.W. Goh, Z. You, Comparative study on the properties of WMA mixture using foamed admixture and free water system, Constr. Build. Mater. 48 (2013) 45–50.
[92] M.R. Mohd Hasan et al., Quantification of physicochemical properties, activation energy, and temperature susceptibility of foamed asphalt binders, Constr. Build. Mater. 153 (2017) 557–568.
[93] Z.P. You et al., Preliminary laboratory evaluation of methanol foamed warm mix asphalt binders and mixtures, J. Mater. Civ. Eng. 29 (11) (2017) 7.
[94] L. You et al., Characteristics of water-foamed asphalt mixture under multiple freeze-thaw cycles: laboratory evaluation, J. Mater. Civ. Eng. 30 (11) (2018) 04018270.
[95] L. You et al., Laboratory testing of rheological behavior of water-foamed bitumen, J. Mater. Civ. Eng. 30 (8) (2018) 04018153.
[96] Washington State University, Long-term Field Performance of Warm Mix Asphalt Technologies, Transportation Research Board, 2017.
[97] S.W. Goh, Z. You, Warm mix asphalt using sasobit® in cold region, 14th Conference on Cold Regions Engineering, ASCE, Duluth, Minnesota, 2009.
[98] O. Kristjansdottir, Warm Mix Asphalt for Cold Weather Paving, Washington State Department of Transportation, Olympia, Washington, 2006, p. 92.
[99] M.R. Mohd Hasan et al., Laboratory moisture susceptibility evaluation of WMA under possible field conditions, Constr. Build. Mater. 101 (2015) 57–64.
[100] G.C. Hurley, B.D. Prowell, A.N. Kvasnak, Michigan Field Trial of Warm Mix Asphalt Technologies: Construction Summary, U.S. Department of Transportation Federal Highway Administration, 2009, p. 40.
[101] Michigan Department of Transportation, Special Provision for Warm-Mix Asphalt Permissive Use for Local Agency Projects, Michigan Department of Transportation, Lansing, Michigan, 2016, p. 1.
[102] A. Copeland, Reclaimed Asphalt Pavement in Asphalt Mixtures: State of the Practice, U.S. Department of Transportation Federal Highway Administration, 2011.
[103] S.W. Goh, Z. You, Mechanical properties of porous asphalt pavement materials with warm mix asphalt and RAP, J. Transp. Eng. 138 (1) (2011) 90–97.
[104] Z. You et al., Evaluation of low-temperature binder properties of warm-mix asphalt, extracted and recovered RAP and RAS, and bioasphalt, J. Mater. Civ. Eng. 23 (11) (2011) 1569–1574.
[105] B. Colbert, Z. You, The determination of mechanical performance of laboratory produced hot mix asphalt mixtures using controlled RAP and virgin aggregate size fractions, Constr. Build. Mater. 26 (1) (2012) 655–662.
[106] Illinois Department of Transportation, Use of Reclaimed Asphalt Shingles in Illinois, 2013.
[107] Illinois Department of Transportation, Special Provision for Reclaimed Asphalt Pavement (RAP) and Reclaimed Asphalt Shingles (RAS) 2017.
[108] Michigan Department of Transportation, Special Provision for Recycled Hot Mix Asphalt and Recycled Asphalt Shingles in Superpave Mixtures, Michigan Department of Transportation, Lansing, Michigan, 2016, p. 1.
[109] M. Stroup-Gardiner, Recycled Materials and Byproducts in Highway Applications—Manufacturing and Construction Byproducts, Transportation Research Board, 2013. vol. 8.
[110] Indiana Department of Transportation, Standard Specifications, Indiana Department of Transportation, Indianapolis, Indiana, 2018, p. 1118.
[111] Iowa Department of Transportation, Standard Specifications for Highway and Bridge Construction, Iowa Department of Transportation, Ames, Iowa, 2012, p. 1270.
[112] Minnesota Department of Transportation, Standard Specifications for Construction, Minnesota Department of Transportation, 2018 ed.St. Paul, Minnesota, 2018, p. 725.
[113] Ohio Department of Transportation, Construction and Material Specifications, Ohio Department of Transportation, Columbus, Ohio, 2016, p. 906.
[114] Pennsylvania Department of Transportation, Specifications, Pennsylvania Department of Transportation, Harrisburg, Pennsylvania, 2016, p. 1204.
[115] AASHTO R 30, Standard Practice for Mixture Conditioning of Hot Mix Asphalt (HMA), American Association of State Highway and Transportation Officials, 2015.
[116] ASTM, Standard Test Method for Determining Fracture Energy of Asphalt-Aggregate Mixtures Using the Disk-Shaped Compact Tension Geometry, ASTM D7313, ASTM International, West Conshohocken, PA, 2007.
[117] AASHTO, Standard Method of Test for Determining the Fracture Energy of Asphalt Mixtures Using the Semicircular Bend Geometry (SCB), AASHTO TP105, American Association of State Highway and Transportation Officials, 2015.
[118] AASHTO, Standard Method of Test for Determining the Creep Compliance and Strength of Hot Mix Asphalt (HMA) Using the Indirect Tensile Test Device, AASHTO T322, American Association of State Highway and Transportation Officials, 2011.
[119] Marasteanu, M., et al., Investigation of Low Temperature Cracking in Asphalt Pavements National Pooled Fund study–Phase II, 2012: St. Paul, MN.
[120] W.G. Buttlar, P. Rath, Illinois Tollway I-88 Ground Tire Rubber Test Sections: Laboratory Mix Designs & Performance Testing, University of Missouri-Columbia, 2017.
[121] AASHTO, Standard Method of Test for Resistance of Compacted Asphalt Mixtures to Moisture-Induced Damage, AASHTO T283, American Association of State Highway and Transportation Officials, 2014.
[122] AASHTO, Standard Method of Test for Hamburg Wheel-Track Testing of Compacted Hot Mix Asphalt (HMA), AASHTO T324, American Association of State Highway and Transportation Officials, 2014.
[123] ASTM, Standard Practice for Moisture Conditioning Compacted Asphalt Mixture Specimens by Using Hydrostatic Pore Pressure, ASTM D7870, ASTM International: West, Conshohocken, PA, 2013.
[124] S. Chen, S. Adhikari, Z. You, Relationship of coefficient of permeability, porosity, and air voids in fine-graded HMA, J. Mater. Civ. Eng. 31 (1) (2018) 04018359.
[125] S. Lv et al., Normalization of fatigue characteristics for asphalt mixtures under different stress states, Constr. Build. Mater. 177 (2018) 33–42.
[126] S. Lv et al., Viscoelastic fatigue damage properties of asphalt mixture with different aging degrees, KSCE J. Civ. Eng. 22 (6) (2018) 2073–2081.
[127] S. Lv et al., Fatigue damage characteristics considering the difference of tensile-compression modulus for asphalt mixture, J. Test. Eval. (2018) 46.
[128] AASHTO, Standard Method of Test for Determining the Fatigue Life of Compacted Asphalt Mixtures Subjected to Repeated Flexural Bending, AASHTO T321, American Association of State Highway and Transportation Officials, 2014.
[129] S. Adhikari, S. Shen, Z. You, Evaluation of fatigue models of hot-mix asphalt through laboratory testing, Transp. Res. Record: J. Transp. Res. Board 2127 (2009) 36–42.
[130] S. Lv et al., Comparisons of synchronous measurement methods on various moduli of asphalt mixtures, Constr. Build. Mater. 158 (2018) 1035–1045.
[131] I.L. Al-Qadi et al., Testing protocols to ensure performance of high asphalt binder replacement mixes using RAP and RAS, Illinois Center for Transportation/Illinois Department of Transportation, 2015.
[132] AASHTO, Standard Method of Test for Determining the Fracture Potential of Asphalt Mixtures Using Semicircular Bend Geometry (SCB) at Intermediate Temperature, AASHTO TP124, American Association of State Highway and Transportation Officials, 2016.
[133] AASHTO, Standard Method of Test for Determining the Damage Characteristic Curve of Asphalt Mixtures from Direct Tension Cyclic Fatigue Tests, AASHTO TP107, American Association of State Highway and Transportation Officials, 2014.
[134] AASHTO, Standard Method of Test for Determining Rutting Susceptibility of Hot Mix Asphalt (HMA) Using the Asphalt Pavement Analyzer (APA), AASHTO T340, American Association of State Highway and Transportation Officials, 2015.
[135] AASHTO, Standard Method of Test for Rutting Resistance of Asphalt Mixtures Using Incremental Repeated Load Permanent Deformation (iRLPD), AASHTO TP116, American Association of State Highway and Transportation Officials, 2015.

[136] AASHTO, Standard Method of Test for Determining the Dynamic Modulus and Flow Number for Asphalt Mixtures Using the Asphalt Mixture Performance Tester (AMPT), AASHTO T378, American Association of State Highway and Transportation Officials, 2017.
[137] AASHTO, Standard Method of Test for Determining the Permanent Shear Strain and Stiffness of Asphalt Mixtures Using the Superpave Shear Tester (SST), AASHTO T320, American Association of State Highway and Transportation Officials, 2011.
[138] L.N. Mohammad et al., Hamburg Wheel-Track Test Equipment Requirements and Improvements to AASHTO T 324. 2015.
[139] Illinois Department of Transportation, Hamburg Wheel-Track Testing of Compacted Hot Mix Asphalt (HMA), in AASHTO T324 (Illinois Modified), 2015.
[140] Wisconsin Department of Transportation, WisDOT Modified Test Procedure for AASHTO T-324, 2014.
[141] Federal Highway Administration, Superpave Fundamentals, in Course No. 131053. Washington, D.C.
[142] R.C. Williams et al., Validation of Gyratory Mix Design in Iowa, 2016.
[143] Michigan Department of Transportation, Special Provision for Acceptance of Hot Mix Asphalt Mixture on Local Agency Projects, in 12SP-501J-05. 2016: Lansing, Michigan.
[144] S. Buchanan, AAPT-AI Webinar Series: Balanced Mix Design Part 1: Balanced Mix Design Need, Approaches, and Implementation. 2017.
[145] D. Newcomb, F. Zhou, Balanced Design of Asphalt Mixtures, Minnesota Department of Transportation, St. Paul, Minnesota, 2018.
[146] L. Fay et al., Benefit-Cost of Various Winter Maintenance Strategies, Clear Roads Pooled Fund, St. Paul, Minnesota, 2015.
[147] Tetra Tech, Emerging Technologies in Winter Road Maintenance—Improving Safety While Minimizing Environmental Impacts, in MDOT Storm Water Management, T. Tech, Editor. 2006: michigan.gov.
[148] X. Shi et al., Use of chloride-based ice control products for sustainable winter maintenance: a balanced perspective, Cold Reg. Sci. Technol. 86 (2013) 104–112.
[149] S.M.K. Hossain et al., Optimum winter road maintenance: effect of pavement types on snow melting performance of road salts, Can. J. Civ. Eng. 43 (2016) 802–811.
[150] Local Road Research Board, Snow and Ice Control Guidebook, 2016.
[151] X. Shi et al., Deicer impacts on pavement materials: introduction and recent developments, Open Civil Eng. J. 3 (2009) 16–27.
[152] T. Pan, X. He, X. Shi, Laboratory investigation of acetate-based deicing/anti-icing agents deteriorating airfield asphalt concrete, Asphalt Paving Technol.-Proceedings 77 (2008) 773.
[153] Z. You, C. Gilbertson, T. Van Dam, Identifying Best Practices in Pavement Design, Materials, Construction, and Maintenance in Wet-Freeze Climates Similar to Michigan, Michigan Technological University, 2018.