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PAVEMENT SURFACE TREATMENTS FOR ICE-PRONE LOCATIONS IN THE ILLINOIS HIGHWAY SYSTEM

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16. Abstract

This project aims to identify and evaluate effective and durable pavement surface treatments (PSTs) suitable for implementation at Illinois Department of Transportation (IDOT) ice-prone locations. A user-friendly questionnaire of northern states and international transportation agencies was developed to capture practitioner insights and collect more detailed information about the current practices of using PSTs for ice prevention. A comprehensive review of existing research and agency practices both nationally and internationally in using PSTs for icy/slippery pavement condition prevention was conducted. The review focused on built-in technologies such as the use of highly rough surface texture, slow-release freezing point depressant, or superhydrophobic additive in asphalt pavement, to identify candidate technologies for the project. PSTs have not been widely adopted by state or local agencies, even for select ice-prone locations. None of the PSTs identified and reviewed have demonstrated long-term success or significant enough potential for the Illinois Center for Transportation (ICT) Technical Review Panel to be comfortable with; as such, the project was wrapped up without further laboratory tests and life-cycle analyses. Some of these built-in PST technologies are promising but all of them, other than high friction surface treatment (HFST), are premature at this stage for any field deployment by Illinois. The major concerns stem from their high cost of implementation and potential lack of long-term durability as an effective anti-icing tool. IDOT should consider conducting traffic safety analyses of their high friction surface treatment (HFST) sites, including winter maintenance operations data and winter crash statistics.

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EXECUTIVE SUMMARY

To ensure the safety, mobility, and productivity of highways during winter season, chemicals and abrasives are usually applied for winter maintenance operations. However, the use of chemicals and abrasives have brought out increasing concerns such as environmental pollutions, motor vehicle corrosions and transportation infrastructure damages; even if deicing, sanding, and anti-icing strategies are adopted. Pavement surface treatments (PSTs) used alone or in combination with other strategies have promising potential as alternatives of chemicals for snow and ice control as they may improve pavement surface friction and decrease the water freezing point or weaken the bond of snow/ice to pavement surface, especially when used for critical highway locations.

The Illinois Department of Transportation (IDOT) is continuously looking for innovative methods to keep the travelling public safe on more than 43,000 lane-miles covered by the IDOT snow/ice removal program. Three types of PSTs including high friction surface treatment (HFST), slow-release freezing point depressant storage pavement (SRFPDSP), and superhydrophobic coating (SHC) were considered as candidate methods for the program. A survey and literature review about these three types of PSTs were carried out to assess current implementation and identify candidate options for laboratory testing and life cycle analyses.

A user-friendly questionnaire of northern states and international transportation agencies was developed to capture practitioner insights and collect more detailed information about the current practices of using PSTs for ice prevention. Some of the information included technical and deployment data as well as the solicited feedback on what works well, what does not, and the limits of PSTs. A few of the twenty respondents from the US, Ontario, and Sweden indicated they have tried HFST and SRFPD, respectively. Other feedback included 14–23°F as the most common temperature range during a typical winter storm. Generally, 16–30 snow events occurred in a typical season with 30–60 inches of total snow accumulation during an average snow season. It was also mentioned that PSTs were primarily used on bridge decks, interstates, curves, and steep grades. The performance of the PSTs with respect to winter conditions and pavement durability was considerably variable for both HFST and SRFPD pavements.

A comprehensive review of existing research and agency practices both nationally and internationally in using PSTs for icy/slippery pavement condition prevention was conducted. The review focused on built-in technologies such as the use of surface texture, slow-release freezing point depressant, or superhydrophobic additive in asphalt pavement, to identify candidate technologies for further investigation. The review also covered the most common practices, innovative practices, and trends related to PSTs; specifically, the materials and mix designs used, the appropriate methodology and equipment to use, as well as the existing experimental design for testing the effectiveness and longevity of PSTs.

An HFST is a thin overlay of calcined bauxite aggregate (a mined and heat-treated manufactured product) bonded to a road that is in good condition with epoxy or polymer resin. HFST is a well-established and increasingly used type of surface treatment for critical locations, such as curves or steep grades with excessive braking, high accident rates, and/or frequent wet-weather conditions.

There is a significant body of literature on HFST, from laboratory testing, field-testing, safety studies, cost-benefit analyses, alternative aggregates, and comparisons to other friction enhancing and pavement preservation treatments (e.g., chip seals, microsurfacing, open graded friction course, and ultrathin friction course). Case studies from South Dakota, North Dakota, Vermont, Virginia, Minnesota and Colorado indicate that it can reduce accidents during winter storms. Two durability issues with SafeLane were evident in multiple field evaluations. SafeLane relies on structurally sound, distress-limited existing pavement (or bridge) conditions. The durability of the SafeLane aggregate with respect to polishing and abrasion resistance in the presence of vehicle traffic, studded tires, and snowplows is concerning.

Slow-release freezing point depressant storage pavements are typically thin surface overlays or wearing course applications with proprietary-formulated pellets with anti-icing properties blended into a standard asphalt mix during batching, and then paved and compacted following conventional methods. The anti-icing chemicals are slowly released from the inside pavements under traffic action to prevent or limit snow or ice from bonding to the pavement surface. Different experimental and commercial salty chemicals as anti-icing additives in asphalt pavement have been studied for decades, and calcium chloride ($CaCl_2$)-based and sodium chloride (NaCl)-based chemicals are dominant. The commercialized additives include Verglimit, Mafilon, IceBane, IceGuard, and WinterPave; while the experimental additives include sodium formate (NaFm), sodium silicate, magnesium-aluminum/chloride layered double hydroxide (Mg-Al/Cl^- LDH), magnesium-aluminum/acetate layered double hydroxide (Mg_2/Al-Ac^- LDH), etc.

Superhydrophobic coatings (SHCs) are very thin layers of water-repellent chemicals sprayed on a pavement surface to prevent or minimize ice and snow adhesion. Laboratory tests of different SHCs have been conducted by Iowa State University, University of Wisconsin-Madison, Suleyman Demirel University (Turkey), and China University of Geosciences. The results showed that SHCs had anti-icing function to a certain degree. However, the high cost and low durability of these coatings are still the main issues for their applications. The case study about a commercially available product developed by China Academy of Transportation Sciences and Highway Engineering Technology (Beijing) Co., Ltd. showed the product presented highly effective and efficient anti-icing/de-icing performances at low temperatures from 0 to -40°C, more than 2-year anti-icing/de-icing durability and preventive maintenance functions, with low construction cost.

PSTs have not been widely adopted by state or local agencies, even for select ice-prone locations. None of the PSTs identified and reviewed have demonstrated long-term success or have significant enough potential for the IDOT Technical Review Panel to believe worth investigating; as such, the project was wrapped up without further laboratory tests and life-cycle analyses. Some of these built-in PST technologies are promising but all of them (other than HFST) are premature at this stage for any field deployment by Illinois. The major concerns stem from their high cost of implementation and potential lack of long-term durability as an effective anti-icing tool. IDOT should consider conducting traffic safety analyses of their HFST sites, including winter maintenance operations data and winter crash statistics.

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CHAPTER 1: STATE OF THE PRACTICE

1.1 INTRODUCTION

Winter maintenance operations play a crucial role in assuring the safety, mobility and productivity of highways enduring winter weather (Shahdah and Fu, 2010; Usman et al., 2010; Ye et al., 2013a). The operators and maintainers of highway networks are facing increasing demands and customer expectations during inclement weather, while confronting unprecedented budget and staffing constraints and a growing awareness of environmental challenges related to the use of chemicals and abrasives for snow and ice control. More sustainable pavement treatments are thus highly desirable.

The Illinois Department of Transportation (IDOT) is continuously looking for innovative methods to keep the travelling public safe on more than 43,000 lane-miles covered by the IDOT snow/ice removal program. Relative to deicing and sanding, anti-icing (typically with liquids) leads to improved level of service (LOS), reduced need for chemicals, and associated cost savings and safety/mobility benefits (Boselly, 2001; Cui and Shi, 2015). Yet, the use of chemicals for snow and ice control has raised concerns over their negative impacts on motor vehicles (Li et al., 2013), transportation infrastructure (Farnam et al., 2015; Shi et al., 2011, 2010), and the environment (Fay and Shi, 2012; Godwin et al., 2003).

An alternative to chemicals used to prevent icy pavement conditions is pavement surface treatments (PSTs) built in to enhance friction, to reduce the bond of ice to pavement, or to prevent or treat winter precipitation (Arabzadeh et al., 2016; Lu et al., 2009; Takeichi et al., 2001; Zheng et al., 2015). These range from antifreezing pavements that rely on physical action (through customized texture) or super-hydrophobicity, in situ anti-icing polymer overlays that slowly release freezing point depressants, or heated pavements. PSTs may be used alone or in combination with other strategies for snow/ice control. In light of cost constraints, they are most suitable for critical highway locations such as bridge decks, mountain passes, steep grades, sections adjacent to water or prone to frost and/or sensitive to chemicals, and locations featuring sharp changes in road conditions. Relative to the fixed automated spray technology systems, FAST, (Ye et al., 2013b), PSTs generally feature more versatility, higher reliability and lower capital and maintenance costs. For instance, textured seal coats for pavements (e.g., polymer chip seal and ultra-bounded wear courses) have the potential to prevent dangerous icy or slippery conditions and there are products available on the market (e.g., Safelane™). Preliminary studies have shown the benefits of such high friction polymer overlay surface treatment in accident prevention, but there are also concerns over their lack of long-term effectiveness (Nixon, 2007, 2006).

More effective snow and ice control methods for select ice-prone locations in the Illinois highway system could result in significant economic, environmental, and social benefits. It is thus desirable to evaluate and improve the use of PSTs as a passive yet sustainable snow/ice control measure. There is an urgent need to validate PSTs for their potential implementation in Illinois highway environments, as they promise to prevent dangerous road and bridge icing while minimizing the detrimental effects of deicing chemicals to vehicles, infrastructure, etc.

In this context, the objective of this project is to identify and evaluate “effective and durable pavement surface treatments suitable for implementation at IDOT ice-prone locations”. A few types of PSTs have been developed, including high friction surface treatment (HFST), slow-release freezing point depressant storage pavement (SRFPDSP), superhydrophobic coating (SHC), heated pavement technologies, thermochromic asphalt pavements, and flexible/physical bending pavements, etc. In consultation with the Technical Review Panel (TRP) during a project kick-off teleconference, the scope of this project was limited to HFST, SRFPDSP, and SHC types of PSTs.

1.2 METHODOLOGY

First of all, the research team conducted an online survey of northern states and international transportation agencies, in order to capture practitioner insights and collect more detailed information about the current practices of using PSTs for ice prevention. To ensure a high response rate and usability of survey results, a user-friendly questionnaire was developed and submitted to an IDOT TRP for review before distribution. In addition to technical and deployment data, the survey solicited feedback on what works well, what doesn’t, and the limits of PSTs. International highway agencies responsible for winter maintenance were contacted through organizations such as Transportation Association of Canada’s Summer and Winter Maintenance Subcommittee and Aurora Consortium. It was also helpful to distribute the survey to the Clear Roads, AASHTO SICOP Snow/Ice List Serve, and Winter Maintenance & Effects Linkedin Group to gather relevant information. A few follow-up phone conversations were conducted for select responses for clarification pursposes.

Secondly, the research team conducted a comprehensive review of existing research and agency practices both nationally and internationally in using PSTs for icy/slippery pavement condition prevention, with a focus on built-in technologies such as the use of surface texture, slow-release freezing point depressant, or superhydrophobic additive in asphalt pavement, to identify candidate technologies for further investigation. The literature review covered the most common practices, innovative practices, and trends related to PSTs, materials and mix designs used, the appropriate methodology and equipment to use, as well as the existing experimental design for testing the effectiveness and longevity of PSTs. The literature search started with a detailed search of articles, reports, and other publications using keyword search of databases including but not limited to: TRB’s TRID online (http://trid.trb.org/); Google Scholar; ISI Web of Science; Canada Institute for Scientific and Technical Information; Transport Research Laboratory in UK; National Winter Service Research Group in UK (http://www.nwsrg.org/); and Washington State University (WSU) libraries. Research conducted in Canada, Europe, Japan, China and other international sources during the last three decades have been examined and reviewed, along with the ongoing research and existing documents published by the DOTs, Clear Roads, university transportation centers, Federal Highway Administration (FHWA), National Cooperative Highway Research Program (NCHRP), Airport Cooperative Research Program (ACRP), American Public Works Association (APWA), American Association of State Highway and Transportation Officials (AASHTO), etc.

1.3 SURVEY OF PAVEMENT SURFACE TREATMENTS IMPLEMENTATION

A survey was distributed nationwide to capture practitioner insights and collect detailed information about the current practices of using PSTs for ice prevention (see Appendix A for the survey form). Basic information on typical winter weather (number of storms, typical temperature ranges and total snow accumulation) was solicited, followed by asking respondents if they have used any of the following types of PSTs:

- HFST: anti-skid treatment made of tough aggregate bonded to pavement with epoxy or polymer binder.
- SRFPD: slow-release freezing point depressant: examples include Verglimit with calcium chloride; Mafilon with sodium chloride; Cargill's SafeLane.
- SHC: thin layer of Teflon-like coating on pavement to reduce bond strength of ice to pavement.

The survey was completed by 20 respondents from the US, Ontario, and Sweden (Figure 1), although only five indicated they have used HFST or SRFPD for snow and ice control benefits.

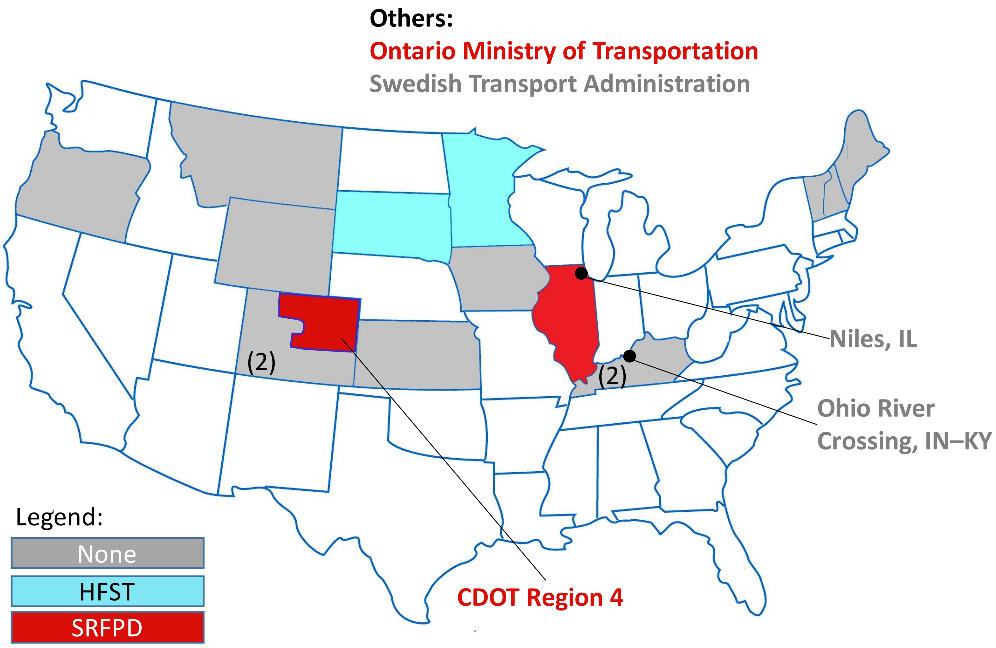

Figure 1. Distribution of survey responses throughout the US, color-coded based on use of PST type.

The question of whether any PSTs were used was answered by nineteen of twenty respondents (one person skipped this question), and the number of responses were gathered for each option and shown below:

- None – 13
- HFST – 2 (in MN, SD)
- SRFPD – 3 (in CO, IL, Ontario)
- SHC – 0
- Other – 1 (Novachip in WY)

Of the five respondents that have used HFST or SRFPD pavements, all chose 14–23°F as the most common temperature range during a typical winter storm. Three indicated generally 16–20 snow events occurred in a typical season, and two typically experience 26–30 storms. Total snow accumulation during an average snow season was 30–45 in. for 3 responses and 45–60 in. for two responses.

PSTs were primarily used on bridge decks, although interstates, curves, and steep grades were also mentioned, as shown in Figure 2. Some states have used PSTs in multiple locations, thus there were more than five responses to this question.

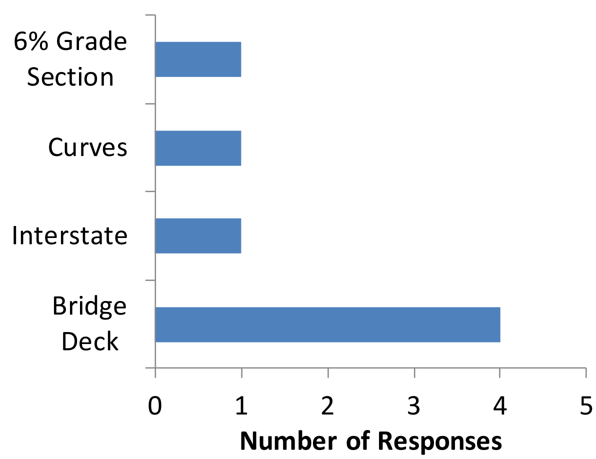

Figure 2. Location of PST application.

The performance of the PSTs with respect to winter conditions and pavement durability was considerably variable for both HFST and SRFPD pavements, as shown in Figure 3, likely deriving from the low number of responses.

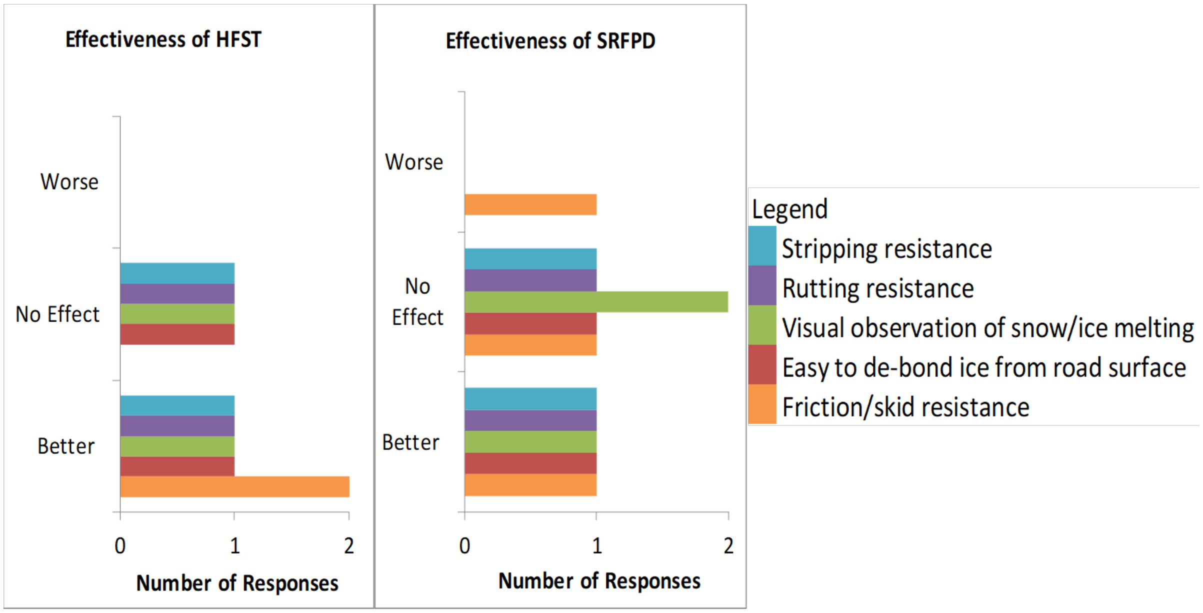

Figure 3. Effectiveness of HFST or SRFPD pavements compared to adjacent pavements.

A few follow-up questions were asked about the use of PSTs. From these, the following information was collected:

- Pavement markings are compatible with the PST: all 5 responded "yes".
- Conventional snow and ice control method was still needed: plowing, anti-icing with salt brine, salting.
- HFST:
  - South Dakota is the only state that indicated satisfactory performance with HFST. They have observed reduced raveling and ice buildup on bridge decks and reduced slide-offs on curves.
  - Minnesota observed better friction on a bridge deck, although the snow and ice control operations were the same (not reduced).
- SRFPD:
  - Cargill SafeLane was constructed at Region 4 in Colorado as shown in Figure 1. Even though mechanical plowing and salt application were still necessary for snow and ice control, they noticed that "Cargill safe lane holds the liquid longer."
  - Ontario used Verglimit at two trial locations in the 1980s and observed deicer leakage from the pavement throughout the year, and the pavement appeared slippery in the summer. The anti-icing performance was less effective during the second winter season.

- Cargill SafeLane constructed on a few bridge decks in Illinois did not show benefit for snow and ice control.

1.4 PAVEMENT SURFACE TREATMENTS

1.4.1 High Friction Surface Treatments

An HFST is a thin overlay of calcined bauxite aggregate (a mined and heat-treated manufactured product) bonded to a road that is in good condition with epoxy or polymer resin. The treatment has a high cost, but it is extremely durable and after factoring in longevity and accident-reductions, may be an economical cost for critical locations (Cheung, 2018). Durability of HFST to snowplowing operations has mostly been very positive, whereas tire chains and studded tires have contributed to notable wear (CTC & Associates LLC, 2018).

1.4.1.1 Summary of field tests

There is a significant body of literature on HFST, from laboratory testing, field-testing, safety studies, cost-benefit analyses, alternative aggregates, and comparisons to other friction enhancing and pavement preservation treatments (e.g., chip seals, microsurfacing, open graded friction course, and ultrathin friction course). The goal of this literature review was to gather information related specifically to the performance and durability of HFST during winter storms or icy conditions, rather than conducting an extensive review of all HFST literature. A summary of all field test reports about HFST reviewed is shown in Table 1, followed by more details about each project. It should be noted that Cargill's SafeLane is not officially a HFST. Briefly, it is a frictional overlay with dolomitic limestone aggregate epoxied to structurally sound, good condition pavement (Cargill Deicing Technology, 2011; Cargill Salt, 2010). The manufacturer claims that the aggregate acts like a rigid sponge to retain deicing chemicals for a longer time. Cargill supplies the epoxy and aggregate, and the overlay can now only be installed by Cargill-licensed installation contractors.

Table 1. Summary of HFST Field Tests

Project Location & Year	**Project information**	**Performance**	**Reference**
Standard HFST			
South Dakota, Deadwood, US14A, 2014	• Asphalt highway, horizontal curve • ADT 5,000 • pre-install winter road condition crashes 2011-14 = 7	• post-install winter road condition crashes 2014-17 = 1	(SDDOT, 2017)
South Dakota, Lead, US14A, 2014	• Asphalt highway, horizontal curve • ADT 2,800 • pre-install winter road condition crashes 2011-14 = 3	• post-install winter road condition crashes 2014-17 = 0	(SDDOT, 2017)
South Dakota, Sioux Falls, I-229, 2014	• Concrete interstate, horizontal curve • ADT 18,000 • pre-install winter road condition crashes 2011-14=20	• post-install winter road condition crashes 2014-17 = 5	(SDDOT, 2017)

Project Location & Year	Project information	Performance	Reference
Cargill SafeLane			
Vermont, Searsburg, Rte 9, 2007	• Steep grade, 13.5% climb • 273-ft SafeLane installed • AADT 2,150 per lane • pre-install winter crashes 2005-07 = 13 with 30 complaints • SafeLane pre-charged with $CaCl_2$ after each storm • SafeLane lanes same plowing/salting during storm as non-SafeLane downhill lanes	• post-install crashes 2007-08 = 0 with 0 complaints • SafeLane had less snow accumulation than non-SafeLane downhill lanes • severe cracking, rutting and popouts (attributed to pre-existing conditions) • SafeLane removed in 2009	(Kipp et al., 2014)
Vermont, Burlington, North Prospect St, 2008	• Downhill lane • SafeLane chosen to improve traction and reduce crashes • ADT not reported	• post-install crashes 2008-12 = 0 • Considerable cracking and popouts by 2012	(Kipp et al., 2014)
Vermont, Jericho, Rte 15, Bridge #7, 2008	• Curve before bridge, many crashes and "close-call" incidents • ADT not reported	• In 2010 wheelpaths had exposed epoxy and very little aggregate; Cargill milled and reapplied SafeLane to the wheelpaths with harder, more studded-tire resistant aggregate	(Kipp et al., 2014)
Virginia, I-81 bridge decks, 2005	• Compared 2-layer SafeLane (limestone aggregate) to modified VDOT's 1-layer epoxy/silica-basalt aggregate overlay • ADT not reported	• SafeLane is a thicker overlay and aggregate is coarser with higher absorption and greater freeze/thaw weight loss than VDOT overlay	(Sprinkel et al., 2009)
Virginia, smart road, CRCP road, 2006	• Compared 2-layer SafeLane (limestone aggregate) to VDOT's standard 2-layer epoxy/silica-basalt aggregate overlay • Research road, not open to public traffic (ADT not applicable)	• SafeLane had greatest initial friction improvement, but also fastest decline in friction number • 5 artificial snow events, although snow production was not uniform. Ultimately both SafeLane and VDOT overlays provide improved friction at the beginning of the storm before winter operations are deployed	(Sprinkel et al., 2009)

Project Location & Year	Project information	Performance	Reference
North Dakota, Willison, US 2, Sand Creek Bridge, 2008	• SafeLane installed on eastbound bridge, two lanes, and a portion of exit ramp on asphalt pavement • ADT not reported	• post-install winter accidents due to ice on bridge 2008-13=2 • Inspected in 2010, 2012, 2013 epoxy and aggregate still in place on bridge, although wheelpaths showed considerable polishing and reduced friction • Winter performance inconclusive, bridge receives same treatment as other bridges (better safe than sorry), though maintenance personnel do think SafeLane helps retain deicers and reduces accidents	(Loegering and Mastel, 2013)
North Dakota, Mandan, I-94, BNRR & Missouri Rd Bridge, 2008	• SafeLane installed on westbound bridge (eastbound bridge was control)	• post-install winter accidents due to ice on bridge 2008-13=1; also 1 due to water on bridge • Same aggregate polishing and winter operations treatment/anecdotes as ND Sand Creek Bridge (above)	(Loegering and Mastel, 2013)
Minnesota, Hibbing, Mitchell bridges, 2006	• SafeLane installed on southbound lanes (untreated northbound was control)	• SafeLane skid numbers dropped from 80 after installation to 34 within 3 years • Sheared aggregate from vehicle traffic and plow operations • No consistent differences between SafeLane and control decks during 3 winters of plow operator surveys • SafeLane protects bridge deck from chloride intrusion • Winter accidents significantly lower after SafeLane installed • Service life too short (3.5-5 yrs) to justify	(Evans, 2010)

Project Location & Year	Project information	Performance	Reference
Colorado, Keenesburg, I-76, 2010	• SafeLane installed on eastbound concrete bridge deck on existing asphalt overlay (westbound bridge was control) • Pre-existing cracks in asphalt overlay, filled with SafeLane aggregate • AADT 13,000	• Cracks reflected by 2011 • 40% drop in texture according to sand patch test • British pendulum tester showed drop from 80 to 75 after 1 year • If SafeLane isn't pre-charged with liquid deicer seems to perform worse than control; with deicer seems better • Winter crashes seem to have reduced, though not statistically valid	(Young et al., 2014)
Colorado, Denver/Aurora, I-225 flyover ramp, 2009 and 2010	• SafeLane installed first in right lane (2009), then left lane (2010) • AADT 123,000	• Texture depth via sand patch tests 2010 – 2013 showed significant one-year drop during "break in" period • Existing concrete surface had good skid resistance; SafeLane improved skid resistance only for the first year • No formal winter performance data collected, but Aurora Police Department thinks SafeLane has made the bridge safer	(Young et al., 2014)

1.4.1.2 Case studies

HFST is a well-established and increasingly used type of surface treatment for critical locations, such as curves or steep grades with excessive braking, high accident rates, and/or frequent wet-weather conditions. Roadway departure and wet pavement crashes are frequently cited as reasons to consider HFST at a specific location. However, some case studies indicate that it can reduce accidents during winter storms.

South Dakota

The South Dakota Department of Transportation installed HFST in 2014 on four horizontal curves with two to four times higher than average accident rates, most notably during snow-packed or icy road conditions. The sections were located on US14A near Deadwood with 5,000 ADT asphalt-paved highway and Lead with 2,800 ADT asphalt-paved highway, and I-229 in Sioux Fall with 18,000 ADT concrete paved interstate. Their standard practice would have been costly geometric improvements, but FHWA Accelerated Innovation Deployment (AID) funds were used to test HFST for winter weather run-off-the-road safety improvements in 2014. Comparing winter road condition, crashes in the three winter seasons prior to HFST installation between October 2011 and April 2014 and three years after HFST installation between October 2014 and April 2017 showed a reduction from an average of 10 crashes/year to only 2 crashes/year, which was a much larger than anticipated reduction in accident rates. As soon as just one year of monitoring, SDDOT was so pleased with the results they proposed adopting HFST as a standard operating procedure for horizontal curves with higher-than-average run-off-the-road winter condition crash rates (SDDOT, 2017). Even after adjusting for winter severity for the specific years before and after HFST installation, crash reduction was 77%.

North Dakota

At the Sand Creek Bridge on the US Hwy 2 near City of Williston, SafeLane was installed on the eastbound bridge in 2008, and an untreated westbound bridge was used as control. The evaluation in Fall 2010 showed all epoxy and most of the aggregate remained in place on the bridge deck, whereas the overlay portion that extended to the asphalt pavement after the bridge has been sheared by plows in the crowned portion because of ruts that have developed in the underlying asphalt pavement. Overall the aggregate angularity and surface friction have reduced due to polishing by vehicle traffic. The evaluations in Fall 2012 and Spring 2013 showed continued loss in surface friction in the wheel paths due to polishing by vehicle traffic. The deicing capabilities of SafeLane could not be conclusively quantified as district maintenance personnel treated the SafeLane bridges with the same chemicals as other bridges in the district. In 2010, maintenance personnel concluded that SafeLane helped retain deicing chemicals and the treatment has reduced accidents, but also made it harder to collect sand during spring clean-up. Pre-install accident rates are not reported. As of December 2013, there were four total accidents near the bridge. Two of the accidents were due to ice on the bridge, and others derived from ice on the highway before the bridge (Loegering and Mastel, 2013).

At the BNRR and Missouri Road Bridge on Interstate 94 near City of Mandan, SafeLane was installed on the westbound bridge in 2008, and the untreated eastbound bridge was used as control. The evaluations in Fall 2010, Fall 2012 and Spring 2013 for this bridge showed similar polishing and loss in traction as the Sand Creek Bridge. This bridge also received the same deicing operations by district maintenance staff as other district bridges. In 2010, winter maintenance personnel suggested that even when frost was present on the SafeLane bridge, it did not seem as slippery as other decks without SafeLane. Pre-install accident rates are not reported. As of December 2013, there were four accidents near the bridge. One of the accidents resulted from ice on the bridge, and two of the accidents were due to ice on the road before the bridge, and the rest was due to standing water on the bridge (Loegering and Mastel, 2013).

Vermont

The 273-ft long SafeLane overlay was installed on the Route 9 with two westbound lanes (AADT 2,150 for both lanes) and steep uphill grade 13.5% in the town of Searsburg in July 2007. In the two winters prior, there were 13 crashes and 30 complaints and many instances of insufficient traction for multi-axle trucks to make it up the steep grade. Heavy rain occurred in the evening at the first day after installation, likely affecting bonding durability. Two lifts were installed with mechanical sweepers, leaf blowers, and compressed air to remove any loose aggregate after the first lift. For each lift, the passing lane was installed first, then the travel lane. In the first winter after installation, there were no accidents and all trucks that made it to the overlay section successfully reached the top of the grade, although some trucks got stuck at the base of the hill where the overlay did not extend. After each storm, $CaCl_2$ liquid was applied to the overlay in preparation for the next storm. During storms, plowing and salting remained the same on the westbound SafeLane lanes and untreated eastbound lanes, although the SafeLane had less snow accumulation. Cracking, rutting, and popouts were so severe that in 2009 the SafeLane was removed as part of a larger pavement maintenance project. The durability problems are mostly attributed to pre-existing site conditions as the popouts extended to the underlying pavement. Since its removal in 2009, there have been many reports of multi-axle trucks again not able to navigate to the top of the hill (Kipp et al., 2014).

At the North Prospect Street in City of Burlington, SafeLane was installed on downhill lane by Parent Construction in August 2008 to improve traction and reduce crashes. Considerable cracking and popout were noticed in 2012, but it has not required maintenance. No information about winter performance was found. No crashes or incidents occurred as of 2012 since the SafeLane was installed (Kipp et al., 2014).

At the Bridge #7 of Route 15 in City of Jericho, SafeLane was installed by Parent Construction in August 2008 because of many crashes and “close-call” incidents. In summer 2010, research personnel monitored the site noticed slippery wheelpaths with exposed epoxy and very little aggregate. In September 2010, the cores were collected and examined by Cargill. Cargill repaired the wheelpaths of the overlay by milling and replacing with harder aggregate, which was better able to withstand studded tires (Kipp et al., 2014).

Virginia

At the bridge decks of Interstate 81, two SafeLane overlays and 2 VDOT overlays were installed. They included MP 219 Structure 2037 southbound 2-layer SafeLane in 2005, MP 219 Structure 2036 northbound 1-layer VDOT modified EP-5 overlay in 2004, MP 240 Structure 2024 northbound 2-layer SafeLane in 2005, and MP 240 Structure 2025 southbound 1-layer VDOT modified EP-5 overlay in 2005. Research involved lab tests on aggregate samples and cores to assess aggregate abrasion resistance, absorption and soundness, bond strength, permeability, and chloride content and field tests, to evaluate skid resistance and effectiveness in preventing snow accumulation and ice formation. When comparing SafeLane with limestone aggregate to VDOT EP-5 overlay with silica–basalt aggregate; SafeLane is thicker, the aggregate gradation is coarser, the absorption is higher, and the weight loss after freezing and thawing is much higher. Too few winter storms occurred during the 2005-2006 winter season to use friction tests to determine differences between the two types of overlays. According to the researchers’ communications with Cargill, the specific aggregate used on these test sections is not the one currently used in installations (Sprinkel et al., 2009).

Virginia Smart Road, two 100-ft long 2-layer Safelane overlays and two 100-ft long 2-layer standard VDOT epoxy overlays were constructed in September 2006. The existing bare-tined continuous reinforced concrete pavement between the epoxy overlays was used as control. Skid tests with an ASTM E274 trailer 52, 74 and 102 days after installation showed the SafeLane overlay to have the greatest initial friction number, but also the fastest decline in friction number. SafeLane averaged FN 78 at 52 days and FN 70 after 102 days; EP-5 averaged FN 62 for 52 and 102 days; bare-tined concrete controls had average FN 52 for all measurements. The snowmaking facility at Virginia Smart Road was used for five snow-making events between January 18 and February 23, 2007. Friction was measured with a Halliday RGT Road Grip Tester installed on a plow truck. Measurements were taken before and during snowmaking and after plowing. Inconsistencies with snow accumulation on the test sections limited the comparisons that could be made. Sometime SafeLane outperformed the bare-tined concrete control, sometimes it performed worse. The same is true for the VDOT EP-5 overlay. The researchers ultimately concluded that both overlays are most beneficial in improving friction compared to bare-tined concrete pavements "in the early stages of a storm before snow-fighting crews can get to the location to start the winter maintenance operation" (Sprinkel et al., 2009).

Minnesota

At the Mitchell bridges (structures 69002 and 69003) in City of Hibbing, SafeLane was installed in July 2006 on southbound lanes, and untreated northbound lanes was used as control. Skid numbers decreased dramatically within 3 years after installation. In September 2006, no skidding was generated and the operators estimated the skid number to be 80, measuring by a Dynatest skid trailer. After 1, 2, and 3 years in service, the skid numbers were 53, 42, and 34, and qualitative observations were consistent with skid reduction data in which aggregate shearing (but not popping out of epoxy) was observed during normal traffic and plowing (which does use considerable down-force on the plow blades). Cores were collected for chloride analyses, and the result showed "the SafeLane overlay has provided significant protection against chloride intrusion on the southbound decks" (Evans, 2010). Plow operators filled out surveys for both the SafeLane southbound decks and control northbound decks during three winter seasons after installation, but no consistent differences were evident between the SafeLane or control sections with respect to traction or snow/ice control. Winter accident rate was significantly lower after installation of SafeLane at this site and also 3 other sites in MN (Alexandria, Barnsville, and Bemidji). The researcher recommended continuing long-term evaluation of SafeLane to confirm its short service life prediction based on skid number loss, but did recommended overlays in general for their ability to increase traction, reduce accidents, and reduce chloride ingress.

Colorado

The concrete bridge deck over Weld County Road 53, West of Keenesburg on Interstate 76 already had an asphalt overlay with underlying impermeable membrane. The SafeLane was installed on the eastbound bridge with 13,000 AADT in June 2010. The westbound bridge was left untreated as control. Cracks in the asphalt overlay near the abutments were filled with SafeLane aggregate before installing the epoxy/aggregate overlay. By 2011, the cracks had reflected through the SafeLane overlay. Sand patch tests showed SafeLane had a drop in texture depth of 40% after one year in service, but still had greater texture compared to the control asphalt overlay. This bridge was too short to use the locked wheel skid trailer, THUS CDOT purchased a British Pendulum Tester for friction tests. The control asphalt overlay has BPN 79. The SafeLane after installation was BPN 80 and after one year was BPN 75. RWIS, cameras and in-deck sensors for temperature, moisture, chemical presence and condition were used to evaluate the anti-icing properties. SafeLane will absorb moisture so it's best to pre-treat with liquid chemicals by pre-charging and recharging with deicers.

"Sensor data shows that if no deicing chemical is applied to SafeLane, then it seems to perform worse than a traditional asphalt surface" (Young et al., 2014). Weather-related crashes seem to have reduced, but insufficient data is available to make statistically-valid conclusions.

At the Parker Road to southbound Interstate 225 flyover ramp in Denver/Aurora metropolitan area, the SafeLane was installed on the right lane with 123,000 AADT in October 2009, and the left lane was installed in May 2010 because of weather-related delay. Sand patch tests in May 2010, March 2011, October 2012, and June 2013 showed that SafeLane had a high drop in texture depth during the first year, but then levels off after this "break-in" period, and the texture was significantly greater than concrete surface before the overlay was installed. Ribbed tire, locked wheel skid trailer tests showed the concrete deck had good skid numbers prior to the overlay and the increase in skid number due to SafeLane only lasted one year; at which point skid numbers dropped to that of pre-existing conditions. All skid numbers were above 50 though and any value over 35 is deemed acceptable. Only anecdotal anti-icing performance was obtained for this site, but the Aurora Police Department suggested that SafeLane has made the bridge safer.

Summary of SafeLane Field Tests

Two durability issues with SafeLane were evident in multiple field evaluations. One is dependent on the structural condition of underlying pavement. SafeLane is not a structural overlay, but merely a frictional wearing surface. Therefore, it relies on structurally sound, distress-limited existing pavement (or bridge) conditions. However, the durability of the SafeLane aggregate with respect to polishing and abrasion resistance in the presence of vehicle traffic, studded tires, and snowplows is concerning. Cargill Deicing Technology has changed the product over the years thus it's possible newer versions have better performance.

1.4.2 Slow-release freezing point depressant storage pavements

SRFPDSPs are typically thin surface overlays or wearing course applications with proprietary-formulated pellets with anti-icing properties blended into a standard asphalt mix during batching and then paved and compacted following conventional methods. The anti-icing chemicals are slowly released under traffic action to prevent or limit snow or ice from bonding to the pavement. Although most don't claim to melt every snowflake, the chemicals improve the ability of plows to clear the accumulated snow or ice.

1.4.2.1 Summary of lab and field tests

Different salty chemicals as anti-icing additives in asphalt pavement have been studied for decades. Calcium chloride ($CaCl_2$)-based and sodium chloride (NaCl)-based chemicals are two main types of anti-icing additives used for asphalt pavement (Shi and Fu, 2018). There are some other anti-icing additives that have been investigated including sodium formate (NaFm) and sodium silicate (Wright et al., 2016), magnesium-aluminum/chloride layered double hydroxide (Mg-Al/Cl^- LDH) (Peng et al., 2015b) and magnesium-aluminum/acetate layered double hydroxide (Mg_2/Al-Ac^- LDH) (Peng et al., 2015a). Other experimental or lab-produced mixes have been prepared by mixing cementitious materials (CMs), water resistant modifier and NaCl powders, with the particle size between 0.075 mm and 4.75 mm (Wang et al., 2017).

Some anti-icing additives have been commercialized for many years, with laboratory and field test reports available, including Verglimit, Mafilon, IceBane, IceGuard and WinterPave. Verglimit is a $CaCl_2$-based chemical packaged in linseed oil or polyvinyl acetate. Mafilon, of which the main component is NaCl with the content of 56%, is another commercial anti-icing additive available (Li and Wang, 2012). IceBane mainly consists of NaCl and $CaCl_2$ which are modified by a special hydrophobe, and 99% of the particles is less than 0.6 mm (Liu et al., 2015a, 2014). The main component of Iceguard is 58.8% $CaCl_2$ with the particle size from 0.1 mm to 4 mm, and the cost of Iceguard is 60% of Verglimit (Zheng et al., 2017). A commercialized anti-icing additive containing 73% NaCl, $CaMg(CO_3)_2$, $MgCO_3$ and SiO_2 has been studied, but the name of the additive was not mentioned in the paper (Giuliani et al., 2012). Another unnamed commercialized anti-icing additive composed of 60% NaCl, $CaCl_2$, SiO_2, CaO, Fe_2O_3, and Al_2O_3 with particle size mostly less than 0.075 mm (Ma et al., 2018). The summary of commercial and experimental anti-icing additives is shown in Table 2.

Table 2. Slow Release Freezing Point Depressant Storage Pavements

Product Name (if applicable)	• **Active Ingredient (Concentration)** • **Other Ingredients** • **Particle Size** • **Commercial or Experimental (C or E)**	• **Test Conducted** ➢ **Significant Findings**	**References**
WinterPave	• $CaCl_2$ (20–<30%) • SiO_2 • N/A • C	• Three low-volume roads (ADT 100 – 2,080) in three different Ohio cities ➢ WinterPave added to OGFC wearing course in summer 2017 failed during first winter, will be replaced summer 2018 ➢ WinterPave at other two locations installed 2012 showed good durability but no discernable difference in winter performance	(Iterchimica, 2016) (Iterchimica, n.d.) (Sargand and Williams, 2016) (Personal Communication)
Verglimit	• $CaCl_2$ (94.6%) • N/A • 0.1-5 mm • C	Field tests mostly in 1980s in NY, PA, MN, CO, IL, Manitoba, Western Europe ➢ No winter benefits below 20°F (possibly even 27°F) ➢ Better product for areas with warmer, wet-snow winters than colder, dry-snow climates ➢ Hygroscopic and may become slippery after absorbing moisture	(Zheng et al., 2017) (Zheng et al., 2015)
Iceguard	• $CaCl_2$ (58.8%) • N/A • 0.1-4 mm • C	• Impact load test for deicing performance, using a hammer impact ice layer on mixture with 5% additive by mass of mixture ➢ 46 impact loads for modified sample and 61 impact loads for control sample, indicating adhesion between ice and mixture can be reduced.	(Zheng et al., 2017)

		• Snow-melting test using a simulated traffic load to evaluate the effects of snowfall intensity, temperature and filler content on snowmelt quality, and the testing data was analyzed using the Regression model ➢ Temperatures should exceed -10 ºC for moderate or light snow conditions and exceed 0 ºC for heavy or blizzard snow conditions. Filler content had limited influence.	
Mafilon	• NaCl (56%) • SiO_2, MgO, CaO, and others • Less than 0.6 mm • C	Fupu and Zhijun 2012 • Lab snow/ice melting test during real snow events ➢ Snow/ice melting performance increased with dosage increase at the temperatures from 3ºC to 8 ºC. The mixture with 100% filler replacement totally melted the accumulated snow after 4 hours, whereas limited snow was melted on control sample. • Field test ➢ The observed result indicated a superior exposure area and limited snow adhered to the ice on modified pavement. • Data collection for the salt residual percentage in Japan from 1990 to 1996 ➢ The salt residual percentage declined to 20% after 6 years, with a certain snow/ice-melting capacity. • Engineering properties ➢ Better anti-rutting performance; slightly affected the low-temperature performance; moisture stability decreased with the increase of MFL content Luo and Yang 2015: • Snowmelt performance test, outdoor snow melting observation at -6 ºC, with 70% filler replacement ➢ MFL can greatly improve the snow melting speed: less snow thickness (reduced from 22 mm to 5 mm, 4 hours after snow started) and the less ice coverage on the slab (50% reduction, 3 hours after snow stopped). • Mixture–ice bond shear strength test at -6 ºC, with 70% filler replacement ➢ The strength of modified sample was 25% of control sample • Engineering properties	(Li and Wang, 2012) (Luo and Yang, 2015)

		➢Mechanical performance degraded, but can be mitigated by adding high-elastic modifiers	
IceBane	• NaCl, and $CaCl_2$ (56%) • CaO, Al2O3, SiO2, Na2O, K2O, Fe2O3 • 99% < 0.6 mm • C	• Salt release test without fresh water replacement ➢The anti-icing durability of dense-grade mixture was better than that of open-grade mixture. More salt content, smaller particle size, more wetting-drying cycles, longer immersion time, higher temperature and dynamic load had more potential to facilitate salt release. The existence of epoxy in the asphalt mixture prepared using a commercial epoxy asphalt binder can slow salt release • Pull-out test at -10 ºC ➢The pull-out strength was reduced from about 0.3 MPa to about 0.05 MPa with the addition of the additive (6-8 wt% filler replacement) • Snow melting observation during real snow event ➢Snow was totally melted on additive modified sample (8 wt% filler replacement) after 2 hours that snow stopped • Engineering properties ➢Rutting resistance and low-temperature cracking resistance of dense-grade asphalt mixture were reduced with the addition of the additive. Moisture resistance was reduced at lower additive content (2% and 4% by mass of mixture) but increased at higher additive content (5% and 6%). With epoxy added to mixture, IceBane did not affect engineering properties.	(Liu et al., 2014) (Liu et al., 2015a) (Liu et al., 2015b) (Min et al., 2017)
Harbin Institute of Technology, ZFSY	• NaCl (34%) • Carrier C, polysiloxane A, ethyl alcohol • N/A • C	Product development tests with different carriers, coatings and comparisons to Mafilon (no bitumen) • Permeability and dissolution tests of compounds ➢Carrier C with polysiloxane A and ethyl alcohol best performer Tests with anti-icing additive in asphalt binder and asphalt mixtures • Soak modified binders in water, change water every 2 hrs, and measure Cl^- concentration over time ➢ZFSY lasts longer than Mafilon • Asphalt mixtures placed outside during real snow events ➢ZFSY has less snow accumulation than typical asphalt pavement down to 14°F. At -4°F ZFSY	(Tan et al., 2014)

		doesn't melt snow but has reduced snow bond strength	
N/A	• NaCl (73%) • CaMg(CO3)2, MgCO3 and SiO2 • Less than 4.75 mm • C	Giuliani et al. 2012: • Frost formation observation on asphalt mastic film with 50 wt.% additives, from RT to -15 ºC with a cooling rate of 15 ºC/min ➢ Frost totally covered on control sample and only covered the edge of modified sample, after 10min cooling • Skid resistance measurements at 5 ºC. ➢ Slightly increased the BPN of dense-graded sample and significantly increased the BPN of open-graded sample after 10 min spreading water on sample surface • Freezing point determination of a thin water film on mixture surface ➢ The freezing temperature of the sample with 5.7 % additive (-2 ºC) was slightly lower than that of the control sample (0 ºC). • Salt release test in water for anti-icing durability, with cycles of washing and mechanical abrasion ➢ NaCl were still releasing from asphalt mixture after two months without washing and abrasion and after one month with washing and abrasion. Ma et al. 2016: • Ice layer rupture test and ice layer pull-out test at -5 ºC ➢ Rupture pressure and pull-out stress of the sample with 6% additive by mass of aggregates were about half of that of control sample • Engineering properties ➢ Mechanical performance degraded, but can be mitigated by adding polyester fibers	(Giuliani et al., 2012) (Ma et al., 2016)
N/A	• NaCl (60%) • CaCl2, SiO2, CaO, Fe2O3, and Al2O3 • 90% < 0.075 mm • C	• Ice-layer rupture test, pull-off test, and interface shear test at -10 ºC ➢ Rupture strength, pull-off strength and shear strength of modified mixture (100% filler replacement) were about half of that of control sample • Engineering properties ➢ Mechanical performance degraded, but can be mitigated by adding high-performance modifiers	(Ma et al., 2018)
N/A	• NaCl (55%) • SiO_2, $CaCl_2$, CaCO3	• Skid resistance test for anti-icing stability, expressed as the decreasing rate of BPN (the	(Xu et al., 2015)

	• Less than 0.3 mm • C	difference of initial and final BPNs during the testing time). ➢ The decreasing rate of BPN reduced by about 40% for the mixture sample with 100% filler replacement. • Salt release test ➢ Salt release increased rapidly at the first 3 h and kept stable after 12 h. The mixtures containing more fillers resulted in more salt release of a unit area at the same time. • Engineering properties ➢ With an increasing additive replacement, rutting resistance, low temperature cracking resistance and water stability were worse compared to control sample.	
N/A	• NaCl and CaCl2 • N/A • N/A • N/A • C	• Anti-icing and deicing tests: simulating the moderate to high snow precipitation during winter on pavement sample ➢ Excellent anti-icing and deicing performances after 10-times tests • Prediction of anti-icing durability ➢ 14 ~ 20 years calculated based on the annual loss of salt in pavement with temperature and rainfall wash simulations	(CATS, 2018a, 2018b)
Salt-Storage Aggregate	• NaCl (N/A) • $MgCl_2$, MgO, silicone powder, glass powder and maifanite powder • 0.075 mm - 4.75 mm • E	• Salt release test without fresh water replacement ➢ Salt release amount per unit area increased and then gradually became stable after a 7-day soaking time. Salt release amount from asphalt mixtures increased with the standing time and the additive content. • Outdoor snow melting observation at -2 ºC ➢ Almost no snow on asphalt mixtures was found after 10 h snowfall, whereas the control samples were totally covered with snow. • Engineering properties ➢ Excellent water stability and high mechanical strengths, which might derive from the additional modifiers in the additive.	(Wang et al., 2017)
NaFm	• NaFm (100%) • N/A • Ave 0.055 mm • C	• Environmental SEM, varying humidity 0-100%, then 100-0%, then repeated again ➢ During wetting (around 60-70% RH) NaFm is present at surface and can influence ice adhesion; at lower humidity NaFm is surrounded by mastic • Theoretical work of adhesion calculations for ice adhesion	(Wright et al., 2016)

		➢NaFm filler provides 70% reduction in ice adhesion relative to limestone filler • Ice bond strength measured with torque-wrench with 1, 3, 5% NaFm solutions frozen on bitumen mastic disc ➢Ice bond strength reduced by 7%, 17%, 46% with 1, 3, 5% NaFm compared to water at 23°F • Stripping test, rolling bottle method ➢NaFm showed similar binder affinity to limestone filler control • Water sensitivity by indirect tensile strength of dry and wet specimens ➢NaFm showed similar water sensitivity as control	
Sodium Silicate	• Sodium Silicate (100%) • N/A • Ave 0.075 mm • C	• Environmental SEM, varying humidity 0-100%, then 100-0%, then repeated again ➢During wetting (around 60-70% RH) NaFm is present at surface and can influence ice adhesion; at lower humidity NaFm is surrounded by mastic • Theoretical work of adhesion calculations for ice adhesion ➢NaFm filler provides 67% reduction in ice adhesion relative to limestone filler • Ice bond strength measured with torque-wrench with 1, 3, 5% NaFm solutions frozen on bitumen mastic disc ➢Ice bond strength reduced by 2%, 14%, 32% with 1, 3, 5% sodium silicate compared to water at 23°F • Stripping test, rolling bottle method ➢Sodium silicate showed significant reduction in binder affinity • Water sensitivity by indirect tensile strength of dry and wet specimens ➢Sodium silicate has highly sensitive to water, expected to be detrimental to asphalt durability	(Wright et al., 2016)
Mg-Al/Cl^- LDH	• Mg-Al/Cl- LDH (100%) • N/A • 98.5% < 0.6 mm • E	• Freezing point of a thin water film on asphalt mixture, with and without immersion in water ➢Freezing point decreased linearly (from -3 ºC to -5 ºC) as additive content increased (from 3 % to 6% by mass of mixture). The freezing point of the sample containing a commercial Cl-based additive was slightly lower (about 1 ºC) than that containing Mg-Al/Cl^- LDH. The freezing point of the sample containing 5% Mg-Al/Cl^- LDH remained at -5 ºC during 12-hour immersion time, whereas the freezing point of the sample	(Peng et al., 2015b)

		containing the commercial additive tended to increase • Horizontal ice-adhesion force test, with and without immersion in water, testing temperature from -6 ºC to -10 ºC ➢ Without immersion, ice-adhesion force for the commercial additive was lower than that for Mg-Al/Cl^- LDH. After immersion ice-adhesion, force for the commercial additive was greater than that for Mg-Al/Cl^- LDH. Indicates asphalt mixtures containing Mg-Al/Cl^- LDH for ice removal would not be weakened by water immersion.	
Mg_2/Al-Ac^- LDH	• Mg_2/Al-Ac- LDH (100%) • N/A • N/A • E	• Similar freezing point test (see above row) ➢ Similar test results (see above row) • Snow melting observations with real snow events at -3 ºC - -5 ºC ➢ In the first snow even, the mixture with commercial Cl-based additive showed more potential to melt snow than that with Mg_2/Al-Ac^- LDH. After several-time wash by melted snow and rain, the mixture with Mg_2/Al-Ac^- LDH showed more potential to melt snow than that with the commercial additive in the second snow event	(Peng et al., 2015a)

1.4.2.2 Case studies

Verglimit – The following contents are directly cited from (Shi and Fu, 2018).

> The calcium chloride chemical Verglimit® has been investigated as a deicing agent in hot mix asphalt since the 1980s (Augeri, 1987; Turgeon, 1989). Verglimit® features an additive of anti-icing chemicals (0.1-5 mm flake particles of 95% $CaCl_2$ and 5% NaOH) encapsulated in linseed oil or polyvinyl acetate and admixed generally at 5-6% by weight of the mixture in the top course of hot mix asphalt pavements. It is intended to provide anti-icing benefits throughout the life of the pavement and works best for bridge decks, steep grades, sharp curves, heavily shaded roads, and roads adjacent to water. Laboratory test results showed that Verglimit increased the resistance of asphalt pavement to rutting at high temperatures, slightly reduced its temperature susceptibility, and decreased its resistance to moisture damage (Stuart and Mogawer, 1991). There are several reports available on the field performance of Verglimit pavements and, in general, the data were somewhat inconclusive (Burnett, 1985; Kiljan, 1989; Lohrey, 1992; Maupin, 1986; Turgeon, 1989). Specifically regarding its performance at extremely cold temperatures, the following are notable:
>
> - Observations by the New York State DOT on a test section installed in Albany, NY in 1978 suggested the overlay performs better during temperatures above

20 °F. At lower temperatures, few or no apparent differences can be discerned relative to an adjacent control section (Burnett, 1985).

  - Areas such as Western Europe, New York State, and Pennsylvania with relatively warm, wet winters have had positive deicing results; however, areas with colder, drier winters such as Minnesota, Manitoba, and Illinois have not seen deicing benefits (Turgeon, 1989; Xie et al., 2015).
  - In Colorado Verglimit projects, the deicing action was slow and the effects were often masked by normal salting and sanding operations (Stuart and Mogawer, 1991).

Stuart and Mogawer (1991) concluded that Verglimit generally triples the cost of the mixture and thus is used in selected problem areas. The additional cost is not offset by reductions in sanding and salting operations but may be offset if accidents are reduced. In the field, some Verglimit pavements exhibited raveling problems and others did not, which highlights the need for better quality control at the hot mix plant and during pavement construction (especially compaction). Due to their ability to absorb moisture from air, Verglimit pavements may become slippery after construction, which can be mitigated by sand application or water flushing (Stuart and Mogawer, 1991). An article from the Michigan DOT (MDOT, 1993) concluded that Verglimit achieves its effectiveness when the temperature is over 27 °F (−3 °C). Heavy traffic (at least 5,000 ADT) is a must for Verglimit to reach its full deicing potential. The primary advantages include minor environmental risk and remarkable reduction in salt application.

WinterPave

WinterPave was developed in Italy and is currently sold there by Iterchimica and is marketed and sold within the US by Cargill Deicing Technology. The product is added during asphalt pavement mixing with a typical dosage of 4 - 5% of aggregate mass, as a replacement. The following field tests in Ohio were identified:

VIN 50 in Ohio is a part of a large project with many low volume road preventive maintenance test sections, with 2,080 ADT. The 5.4-mile project has multiple test sections. In September 2017, four test sections were constructed with OGFC control surface (2 sections) and OGFC with WinterPave additive surface (2 sections) (Sargand and Williams, 2016). The OGFC control sections have performed satisfactorily. The OGFC WinterPave sections both failed and had to be milled and replaced. They were failing (Figure 4) during the fall and plow operations during the 2017-2018 winter, which caused large sections to be torn up. According to Ohio District 10 engineer John Coen, these sections will be repaved this fall with a new treatment, but Ohio DOT does not want to include WinterPave in any future test sections (personal communication, 8/9/2018).

Figure 4. WinterPave failure Ohio DOT test sections on VIN-50 low-volume road tests (provided by ODOT, 2018, phone and email communication).

Williamsburg-Bantam Rd, Williamsburg Township, Ohio, with very little traffic (<100 ADT), was repaved in 2012 with 1.5” HMA overlay and 0.25 mile length. About half was used as control with traditional asphalt; half was WinterPave. WSU talked to the Clermont County Engineer’s office about the current status and was told no noticeable difference with WinterPave was found. It hasn’t failed and repaved, but also it hasn’t seen any reduced snow/ice control operations (personal communication, 8/8/2018).

WinterPave was constructed on the 1000-ft section of the Barr Rd in Brecksville, Ohio in 2012. Brecksville Service Department was emailed and called for information about the performance. Personal communication by WSU with the foreman: “We are very pleased with the durability of WinterPave. Surface and edge line cracks have been minimal. In fact, just last month small surface cracks began to develop and those were immediately sealed. Unfortunately, results of Winter Pave melting falling snow on contact or preventing snow and ice pack on the surface have been somewhat disappointing. Barr Road was a 3” mill. A binder layer of 2.5” was applied then topped with 0.5” of Winter Pave” (personal communication, 8/10/2018).

An unnamed commercialized additive in China

The product was developed by the China Academy of Transportation Sciences and Highway Engineering Technology (Beijing) Co., Ltd. and commercially available in China. The following information is publicly available from (CATS, 2018a, 2018b). It was pointed out that this product has excellent anti-icing/deicing performances, high anti-icing/deicing (functional) durability, low road maintenance cost, low product cost and lower vehicle accident rate, and the application fields include roads near river and lake, shady and chilly sections of roads, tunnel entrance and exit zones, bridges and culverts, roads at the turning, as well as road slopes. Some successful applications on the roads in China are shown in the following pictures (Figure 5 – Figure 10).

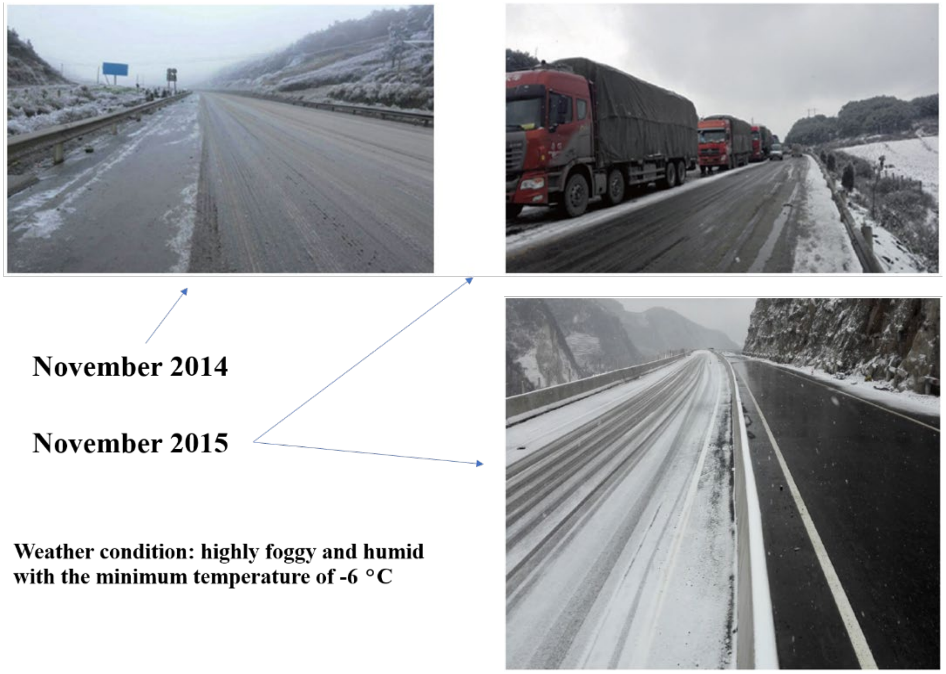

Figure 5. Sections of the G213 road in the Yunnan Province of China.

Figure 6. A section of the road in the Inner Mongolia Municipality of China.

Figure 7. Sections of the road in the Harbin Province of China.

Figure 8. A section of the road in the Liaoning Province of China (-6 ºC).

Figure 9. A section of the road in Beijing of China.

Figure 10. A section of the road in Beijing of China.

1.4.3 Superhydrophobic coatings

SHCs are very thin layers of water-repellent chemicals sprayed on a pavement surface to prevent or minimize ice and snow adhesion. The main problem with these coatings is cost and durability. Interesting coatings and test methods were developed during a four-phase research project in the 1970s. However, season-long durability (once-per-season application) was not achieved (Ahlborn and Poehlmann, 1976). More recently, laboratory tests of SHCs have been conducted.

Iowa State University conducted asphalt pavement lab tests for the samples with various application parameters of SHC, including spray duration and dosage. The samples were from horizontally sliced gyratory pucks and tested for water contact angle, microtexture kinetic coefficient of friction, and the British pendulum tester. The SHC was applied using a layer-by-layer method in which a two-part epoxy dissolved in xylene was first sprayed on the sample surface, followed by PTFE dispersed in acetone sprayed over the epoxy resin. PTFE is polytetrafluoroethylene, a well-known ice-phobic material that has been used on airplane wings, ground wires, telecommunication antennas and other plastic and aluminum substrates. Sufficient hydrophobic water contact angles (150°) were achieved with almost all SHC application parameters, except for the one with the shortest spray duration and PTFE dosage. Friction measurements with a ball-on-flat microtribometer showed several spray durations and dosages had higher friction (up to 0.27) than the control, untreated specimens (0.21) (Arabzadeh et al., 2016). In contrast, friction measurements with a British pendulum tester showed significantly lower friction (BPN around 15) than control samples (BPN 30) (Ceylan et al., 2016). Ice adhesion, ice shearing, and durability tests have not been conducted.

University of Wisconsin-Madison conducted Portland cement mortar lab tests. Various silane and siloxane chemicals in isopropanol and water emulsions were screened using water contact angle and ice loss on impact tests. Stabilized emulsions with water, polyvinyl alcohol (PVA), polymethyl-hydrogen siloxane oil (PMHS) and silica fume were then tested for water contact angle and ice adhesion using splitting tensile tests. The uncoated mortars had no water contact angle because water was absorbed by the mortar. Cubes made of half mortar and half ice in splitting tensile tests showed the SHC reduced ice adhesion by about 20%. Samples without the SHC failed within the ice portion, leaving ice bonded to the mortar. Samples with the SHC sheared at the mortar-ice interface. Ice shearing tests in which a column of ice was frozen on a square mortar tile and then sheared by pulling the ice horizontally while hold the mortar still showed SHC samples had bond strengths in the range of 3-17 psi, lower than untreated mortar at 26-48 psi (Sobolev et al., 2013). Abrasion resistance and other durability tests are still needed.

Suleyman Demirel University in Turkey performed asphalt pavement lab tests. Layer-by-layer base coat and top coat SHC was applied to gyratory puck asphalt samples. According to communications with the author, the SHC they tested is Rust-Oleum NeverWet Multisurface 2-part aerosol consumer version. An industrial version also exists with longer durability, available by the gallon (also 2-part base coat and top coat). Uncoated samples had a water contact angle of 43°, whereas the SHC samples had a water contact angle of 145°. British pendulum tests on gyratory puck samples with during dry, wet and iced conditions showed the SHC samples had BPN values of 77 (iced) to 81 (dry), whereas the uncoated samples had BPN values of 48 (iced) to 70 (dry). Durability testing was performed with an accelerated pavement tester. A slab of asphalt pavement was produced and treated with the SHC and exposed to 100 passes of a tire under a 9000-lb load and speed of 3.1 mph. No change in water contact angle was observed after the trafficking (Eriskin et al., 2017).

China University of Geosciences prepared a superhydrophobic silicone coating on asphalt pavement surface in laboratory to investigate the anti-icing properties by measuring the freezing time of water droplets and the ice adhesion force on the sample surface (Peng et al., 2018). The compound coating obtained by mixing No. 107 room temperature vulcanized silicone rubber with ϒ-methacryloxypropyltrimethoxysilane (KH550) modified LDHs was sprayed on sample surface followed by spraying No. 120 solvent naphtha on it to form the micro/nano-scale rough surface. The result showed the contact angle of the prepared superhydrophobic coating reached 152.3° if 100 g/m^2 of the solvent was applied. It was also indicated, for the sample surface with the prepared superhydrophobic coating, the freezing time of water droplets was 3 times longer and the ice adhesion force was reduced by 71%, compared to that without coating. Vehicle traffic tests indicated the superhydrophobic coating had long anti-icing durability.

There is a commercially available product developed by the China Academy of Transportation Sciences and Highway Engineering Technology (Beijing) Co., Ltd. The following information is publicly available from (CATS, 2018a, 2018b). The product has been applied a section of the road in the Yunnan Province of China, as shown in Figure 11 and Figure 12. It showed highly effective and efficient anti-icing/de-icing performances at low temperatures from 0 to -40°C, more than 2-year anti-icing/de-icing durability and preventive maintenance functions. Moreover, the construction of this environmentally-friendly product was cost-effective.

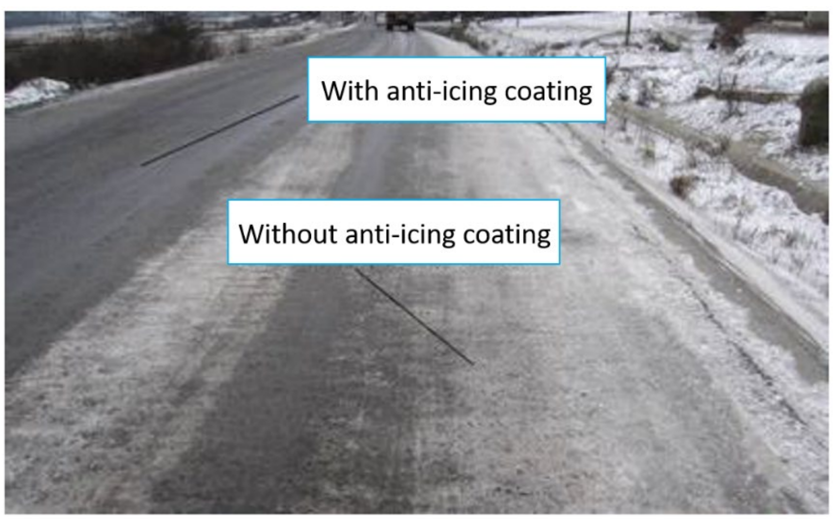

Figure 11. Pavement with and without anti-icing coating.

Figure 12. A section of the road in the Yunnan Province of China (it showed better anti-icing performance, with the snow thickness of 6 cm and the ambient temperature of -9°C).

1.5 CONCLUSIONS

Built-in pavement surface treatments (PSTs) have not been widely adopted by state or local agencies, even for select ice-prone locations. Life cycle cost analyses have also not been conducted to assess the benefits of PSTs to pavement life or reduced (if any) snow and ice control operation costs. Accelerated laboratory tests to mimic service-life expectations of traffic and the effect of environmental exposure over multiple winter seasons (particularly plowing) and rainy seasons (which can wash away or dilute SRFPDSP effectiveness) can be helpful in identifying suitable PSTs for further field demonstrations. There is anecodtal evidence suggesting that HFST has worked effectively in the field environments (including on Illinois highways). However, the data to validate the long-term durability and success are yet to be developed.. For SRFPDSP, the Chinese product showing some success in case studies is not commercially available in the U.S., whereas other products like Verglimit, Mafilon, IceBane, IceGuard, and WinterPave have shown some negative results based on various case studies. The effect of SHCs on the friction condition of ongoing traffic pavement surfaces more likely depends on their surface microtextures.

In conclusion, some of these built-in PST technologies are promising but all of them (other than HFST) are premature at this stage for any field deployment by Illinois. The major concerns stem from their high cost of implementation and potential lack of long-term durability as an effective anti-icing tool. IDOT should consider conducting traffic safety analyses of their HFST sites, including winter maintenance operations data and winter crash statistics.

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APPENDIX A BLANK SURVEY QUESTIONNAIRE

Q1. Please provide your Name, Title, Agency, Email and Phone number.

Q2. What's the total number of snow events in an average snow season?

- ☐ 10-15 times
- ☐ 16-20 times
- ☐ 21-25 times
- ☐ 26-30 times
- ☐ Other:______________________.

Q3. What's the average total snow accumulation in an average snow season?

- ☐ 0–15 inches
- ☐ 15–30 inches
- ☐ 30–45 inches
- ☐ 45–60 inches
- ☐ Other:______________________.

Q4. Which temperature range is the most common during a typical winter storm?

- ☐ 32–41 °F
- ☐ 23–32 °F
- ☐ 14–23 °F
- ☐ -4–14 °F
- ☐ Other:______________________.

Q5. Has your agency used any Pavement Surface Treatments (PSTs) specifically designed for anti-skid or snow and ice control benefits in problem areas? If so, which kinds of PSTs have been used? Do the PSTs meet your agency's expectation (longevity of pavement treatment and snow/ice improvement)? Please check the boxes for the types of PSTs you selected, then it will be skipped to Q5a, Q5b or Q5c depending on your selection (Multiple Answer).

- ☐ High friction surface texture (HFST) – (http://www.highfrictionroads.com/hfs-101/what-is-hfs/), anti-skid treatment made of tough aggregate bonded to pavement with epoxy or polymer binder.
- ☐ Super-hydrophobic coating (SHC) – thin layer of Teflon-like coating on pavement to reduce bond strength of ice to pavement
- ☐ Slow-release freezing point depressant (SRFPD) storage pavement – examples include
    - Verglimit with calcium chloride,
    - Mafilon with sodium chloride,
    - Cargill's SafeLane.
- ☐ Other:______________________.

☐ None (End of survey if it's selected)

Q5a - Please evaluate the performance of the HFST compared to the asphalt or concrete pavements adjacent to the HFST.

	Better	No Effect	Worse
1. Friction/Skid Resistance	☐	☐	☐
2. Easy to de-bond ice from road surface			
3. Visual observation of snow/ice melting	☐	☐	☐
4. Rutting Resistance	☐	☐	☐
5. Stripping Resistance	☐	☐	☐

Q5b - Please evaluate the performance of the SHC compared to the asphalt or concrete pavements adjacent to the SHC.

	Better	No Effect	Worse
1. Friction/Skid Resistance	☐	☐	☐
2. Easy to de-bond ice from road surface			
3. Visual observation of snow/ice melting	☐	☐	☐
4. Rutting Resistance	☐	☐	☐
5. Stripping Resistance	☐	☐	☐

Q5c - Please evaluate the performance of the SRFPD compared to the asphalt or concrete pavements adjacent to the SRFPD.

	Better	No Effect	Worse
1. Friction/Skid Resistance	☐	☐	☐
2. Easy to de-bond ice from road surface			

3. Visual observation of snow/ice melting	☐	☐	☐
4. Rutting Resistance	☐	☐	☐
5. Stripping Resistance	☐	☐	☐

Q6. Please describe the locations that the PSTs have been applied, and why?

Q7 - Can the asphalt or concrete pavements with the PSTs be recycled?

- ☐ Yes
- ☐ No
- ☐ I don't know

Q8 - Is road surface marking compatible with the asphalt or concrete pavements that the PSTs have been applied? If not, please simply state the phenomenon you observed.

- ☐ Yes
- ☐ No

Q9 - If your agency has used more than one PSTs, please rank them?

Q10 - Has your agency evaluated the cost-effectiveness of the adopted PSTs? If so, do you have data or report that you could share? Here is the email you can send to: xianming.shi@wsu.edu

- ☐ Yes
- ☐ No

Q11 - Were the PSTs used in combination with other strategies for snow/ice control, for example, deicer application or plowing? If so, which other strategies were used? If those strategies were adjusted for the PSTs, please describe the adjustments that were made.

Q12 - Do you have any other information, comments or suggestions you would like to provide on PSTs? We'd appreciate any data or reports you can share.

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