NCAT Report 21-02

July 2021

National Center for Asphalt Technology
NCAT
at AUBURN UNIVERSITY

Asphalt Pavement: A Critically Important Aspect of Infrastructure Resiliency

Benjamin F. Bowers, Fan Gu

Asphalt Pavement: A Critically Important Aspect of Infrastructure Resiliency

NCAT Report 21-02

By

Benjamin F. Bowers, PhD, PE
Assistant Professor
Auburn University, Auburn Alabama

Fan Gu, PhD, PE
Assistant Research Professor
National Center for Asphalt Technology
Auburn University, Auburn Alabama

Sponsored by
National Asphalt Pavement Association

July 2021

ACKNOWLEDGEMENTS

The authors wish to thank the National Asphalt Pavement Association and State Asphalt Pavement Associations for sponsoring this research project and for providing technical review of this document. The authors gratefully acknowledge the following members of the NCAT Applications Steering Committee for their review of this technical report: Heather Dylla, Heather Hall, Gerry Huber, Steve Muench, Debbie Schwerman, and Geff Uhlmeyer.

DISCLAIMER

The contents of this report reflect the views of the authors who are responsible for the facts and accuracy of the data presented herein. The contents do not necessarily reflect the official views or policies of the sponsoring agency, the National Center for Asphalt Technology or Auburn University. This report does not constitute a standard, specification or regulation. Comments contained in this paper related to specific testing equipment and materials should not be considered an endorsement of any commercial product or service; no such endorsement is intended or implied.

CONTENTS

1 INTRODUCTION 6
1.1 Defining Resilience 7
1.2 Adaptation as A Model for Improving Resilience 8
2 KEY TOPICS AROUND ASPHALT PAVEMENT RESILIENCE 9
2.1 Flooding 9
2.2 Sea Level Rise/Groundwater Intrusion 11
2.3 Snow Events 12
2.4 Climate Related Temperature and Precipitation Changes 13
2.5 Drought 14
2.6 Fires 14
3 WORKSHOP 15
3.1 Lessons Learned and Workshop Outcomes 15
3.2 Implementation Needs 16
3.3 Identified Research Gaps 16
4 TOOLS FOR RESILIENCE 16
4.1 Rapid Reconstruction 17
4.2 Perpetual Pavements 17
4.3 Use of Recycled Materials 17
4.4 Warm Mix Asphalt (WMA) Technologies 18
4.5 Climate Models 18
4.6 Climate Adaptable Materials 19
4.7 Porous Asphalt Pavements 20
5 CASE STUDIES 20
5.1 Iowa Flooding of 2019 20
5.2 Alaska Earthquake of 2018 25
6 CONCLUSIONS 27
7 RECOMMENDATIONS 28
REFERENCES 30
APPENDIX 37
A.1 Workshop Goals and Objectives 37
A.2 Topic 1: Introduction to Resilience as it Relates to Pavements – Dr. Jon Epps, Texas Transportation Institute 37

A.3 Topic 2: Designing Pavements for Resilience and Climate Change – Dr. Jo Sias, University of New Hampshire 38

A.4 Breakout Session 1: Defining Resilience 39

A.5 Topic 3: Introduction to FHWA Resilience Programs and Work in Progress – Dr. Heather Dylla and Robert Kafalenos, Federal Highway Administration 40

A.6 Topic 4: Resilience at AASHTO – Melissa Savage, AASHTO 41

A.7 Topic 5: Pavement Flooding – Dr. Rajib Mallick, Worcester Polytechnic Institute; Bill Rosener, Asphalt Pavement Association of Iowa 41

A.8 Topic 6: Hurricane Response – Kevin Wall, Anderson Columbia 41

A.9 Topic 7: “People’s Choice” – Asphalt Plants and Operations 43

A.10 Topic 8: Arizona DOT Infrastructure Resilience, Asset Management, Extreme Weather, and Climate Trends: Blending Risk / Science / Technology / Engineering – Steve Olmsted, Arizona DOT 43

A.11 Topic 9: How Resilience Might Be Added to Project Scope / Requirements – Amanda Gilliland, The Transtec Group 43

1 INTRODUCTION

The topic of resilience has begun circulating in many different fields and forums. The transportation community is no different, with the Transportation Research Board (TRB) hosting their second transportation resilience conference in 2019, the *2nd International Conference on Transportation System Resilience to Natural Hazards and Extreme Weather*, bringing together researchers and practitioners to discuss this important topic. The asphalt paving community needs to join this discussion and work specifically to understand the benefits and appropriate applications of asphalt pavement in preparation of, or in response to, natural disasters or changing climate conditions.

Asphalt pavements inherently possess resilient features, though the typical pavement engineer/designer does not necessarily think of these characteristics through the lens of resilience. The rapid constructability of asphalt pavements enables a producer to become a "first responder" after a disaster; if a pavement is damaged due to an extreme event, it can be quickly restored through fast construction. Tools and methods such as warm mix asphalt, adaptable materials (e.g., polymer modified binders to resist high temperature or traffic load deformation), porous asphalt systems for storm water management, and the ability to recycle materials that have been compromised during an event as a means of compensating for disrupted materials supply chains enhance the resilience of the system. Design approaches such as perpetual pavement design can be used to enhance the resilience of critical corridors. In addition to designing perpetual pavements for new construction, existing routes can be elevated to a perpetual pavement status through typical maintenance schedules (i.e., add 2 inches of HMA to the current surface elevation of the pavement as opposed to milling and replacing 2 inches of HMA).

There are many needs when addressing infrastructure resilience. These include the development of funding, planning, and policy guidance on local and national levels. Agencies and localities need clarity regarding funding requirements and the allowable level of rehabilitation/reconstruction to build resilient qualities into infrastructure damaged during a natural disaster. The two case studies presented herein, Iowa's flood response and Alaska's earthquake response, not only highlight the resilient qualities of asphalt pavements but also the need for strong partnerships and clear communication between agencies and industry to rapidly respond in the face of a disaster. These examples shed light on the planning aspect of resilience. To respond rapidly, a plan must be in place (formally or informally) for rapid contracting and quick, effective solutions. Resilience should also be considered when planning future routes with attention paid to the resilience of the entire pavement network as a means to move people and goods if a route is temporarily inaccessible. Finally, agencies need policy guidance to address how funds are spent – both annual funds and disaster relief funds – and how to best plan for the various types of events to which different parts of the roadway network may be subjected.

This report provides insight to the asphalt community through a literature review, summary of the findings from the 2019 Asphalt Resiliency Workshop hosted by the National Center for Asphalt Technology, two comprehensive case studies, and conclusions and recommendations.

1.1 Defining Resilience

Resilience is defined by the Federal Highway Administration (FHWA) as “The ability to anticipate, prepare for, and adapt to changing conditions and withstand, respond to, and recover rapidly from disruptions” (FHWA 2014). The concept of designing resilient infrastructure systems is a design philosophy that results in an action or combination of actions, as opposed to a single, specific “resilient” action. For example, resilience doesn’t necessarily mean “hardening”, or building stronger, a common singular reaction to the concept of enhancing resilience, though there are cases where using higher binder grades and/or perpetual pavement designs are the appropriate and warranted solution. Resilience may also take the form of a design approach that embraces nature, such as allowing for the flooding of an appropriately designed highway to occur knowing that (1) it will be an inconvenience to the citizens and (2) the road will withstand the event and normal traffic will be able to resume at the conclusion of the flood event. It may take the form of a calculated choice to not change current policy and procedure, but rather expecting that the roadway may be washed out or damaged and that funds will be made available for rapid reconstruction. Resilience may be inherently shown through rapid reconstruction or community coordination when the event was unanticipated, similar to those discussed in the forthcoming case studies of the Iowa flooding and Alaska earthquake.

Barami (2013) noted that there are three main resiliency performance criteria for infrastructure: efficiency, sustainability, and survivability. Efficiency considers traditional infrastructure metrics such as cost-effectiveness and functional performance. Sustainability infers that the design considers natural, human, and manufactured resources in a way that does not compromise any of these resources for the future. Finally, survivability considers the ability of infrastructure to withstand and manage an event with minimal impact to that which, or those whom, it serves. Remarkably, these three tenants of resilience align with the triple bottom line of sustainability: economy, environment, and social. Efficiency is in line with economic impacts of resilient infrastructure, while sustainability aligns with environmental association of resilient infrastructure, and survivability is intended to serve the societal implications of infrastructure.

This leads to an important distinction between resilience and sustainability. While these two terms and their subsequent design practices are similar and cross over, they are two distinct concepts. The Venn diagram in Figure 1 shows, as related to asphalt pavement, some of the distinctly resilient and sustainable design practices as well as practices that overlap. The examples provided are debatable, which shows the blurred line between sustainability and resilience, but the intention of the authors is to provide a distinct interpretation and some relative examples of this difference for the readers’ understanding. As Barami (2013) concluded, sustainability may be a key performance criterion for infrastructure resiliency, but it is not the same as resiliency.

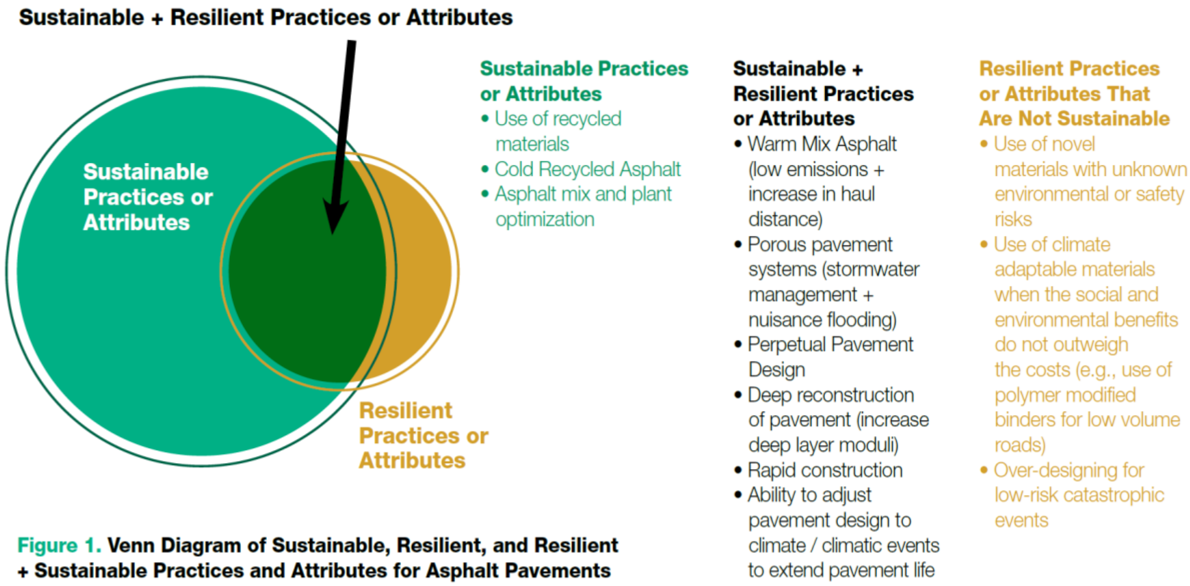

Figure 1. Venn Diagram of Sustainable and Resilient Practices and Attributes for Asphalt Pavements (Bowers and Gu 2021)

Risk is at the heart of the resilience equation. Are we prepared for a major disaster/event? To what degree should we prepare for such an event, and what are the potential results of inadequate preparation? A report by the FHWA Volpe Center (Barami 2013) provides the insight that risk-analysis assesses the likelihood that a threat/hazard will occur and the consequences if it does. The authors define the "threat" component further by highlighting that the exposure of the infrastructure and its inherent vulnerabilities must be considered. Risk is essentially the product of what happens if an event occurs and the vulnerability of the infrastructure to that event. There is a need to assess how much an event will impact the infrastructure and what the short- and long-term effects will be on the people that the infrastructure serves.

Marriam-Webster defines vulnerability in two ways, as "capable of being physically or emotionally wounded" and "open to attack or damage". From an infrastructure perspective, we might ask whether our pavements along the coast are vulnerable, or capable of being damaged, by more frequent tidal flooding as well as whether the people in the local community that the roadway serves are vulnerable to negative side effects of being "cut off" from society during the flood event (e.g. unable to get groceries, mail, access to schools, etc.). This sort of analysis is typically included in a vulnerability assessment conducted by agencies, such as one following the FHWA Vulnerability and Adaptation Framework (Filosa et al. 2017). Agencies are used to managing risk and vulnerability – perhaps it is time that the context of resilience should be added to that equation.

1.2 Adaptation as A Model for Improving Resilience

The FHWA defines adaptation as, "adjustment in natural or human systems in anticipation of or response to a changing environment in a way that effectively uses beneficial opportunities or reduces negative effects" (FHWA 2014). Barami (2013) pointed out that adaptation is not simply a coping strategy, but a strategy that seeks “smart solutions to the risks that confront any complex infrastructure system.” In order to do so, we must employ what Pearson (2014) defines as an “adaptive strategy” or an “adjustment in natural and human systems in response to actual or expected disturbances when frequencies tend to increase.” In essence, our pavements may need to adapt through recognizing their critical role in society and understanding the potential resilience ramifications, and then planning, designing, and/or retrofitting the pavement and the larger highway system for those scenarios as appropriate. For example, the pavements community must be prepared to adapt to changing conditions such as more drastic or prolonged temperature extremes, speed and frequency of temperature fluctuations, wildfires, hurricanes, major non-tropical precipitation events, sea level rise, ground water fluctuation, and the cascading effects of disaster relief efforts (e.g., increased traffic loads during tornado or hurricane relief).

Examples of adaptive strategies may involve integrating climate-adaptable materials into routine pavement maintenance schedules, reconstructing pavements to strengthen their base or make them perpetual, or potentially relocating roadways all together. For example, if a section of coastal roadway is flooding frequently, the owner agency may decide to:

- Build the roadway up so that it is above the current flood crest;
- Raise the roadway completely using an elevated structure;
- Move the roadway inland and abandon the current structure; or
- Map/video log the roadway, record plans/shop drawings, and locate reference appurtenances, so they can be replaced expediently and cost effectively.

Each of these options carries a different level of risk and cost. If you build the roadway above the current flood crest, you still risk subgrade weakening, and the benefit to the roadway may be short-lived because flood waters will rise. Building elevated structures is often very costly and may not be worth the necessary financial resources. The third option could have economic impacts on the community, and at the very least will create a permanent inconvenience for those who live along that roadway as they will need to find an alternative route to return home or to a place of business. The fourth option would allow the owner to rebuild the roadway quickly and efficiently if there were no other viable options to places of business. The owner agency may select one of these options, but there is also a need for agencies, industry, and academics to come up with new adaptive strategies for these types of situations as their need becomes more frequent.

2 KEY TOPICS AROUND ASPHALT PAVEMENT RESILIENCE

The following literature was compiled around key topics related to asphalt pavement resilience.

2.1 Flooding

Flooding is bad for pavements. Among other things, water inside an asphalt pavement structure can weaken the structure’s ability to withstand loading. Flooding can also saturate underlying layers (e.g., unbound base and subgrade), which weakens the structural bearing capacity. Thicker pavements help manage these challenges, and routes should be prioritized for hardening or other adaptive approaches as such.

There are many studies focused on modeling how flooding influences pavement performance. Khan et al. (2014, 2017a&b) developed project and network level roughness and rutting-based road deterioration models considering different probabilities of flooding. They found extreme moisture significantly reduced the resilient modulus (stiffness) of unbound materials, thereby affecting the pavement responses to traffic load. They employed the Pavement ME Design model to estimate the resilient modulus loss in unbound granular materials. Using the Method of Equivalent Thickness (MET), they computed the critical responses (i.e., compressive strain at the top of subgrade and tensile strain at the bottom of asphalt layer) and related them to incremental change of pavement roughness and rutting. The models were calibrated using a database from the Transport and Main Roads Authority in Queensland, which contains 10-12 years of performance data of after-flooded pavements. They implemented the road deterioration models to a variety of pavement scenarios including different pavement types, loading, and strength. They concluded that increasing overlay thickness and/or stabilizing granular and subgrade layers can improve the asphalt pavement resiliency to flooding. After a review of these studies done by Khan et al. (2014, 2017a&b), the following limitations were identified:

- Extreme moisture intrusion reduced the tensile strength of asphalt materials.
- Pavement ME Design model was not accurate to reflect the moisture-sensitivity of resilient modulus of unbound materials (Gu et al. 2015).
- MET is a simplified approach to compute pavement responses, which ignores the nonlinear nature of granular materials. The most sophisticated model that considers the nonlinear stress and moisture-dependent cross-anisotropic characteristics of unbound material can be found in Zhang et al. (2018).

Khan et al. (2016, 2017a) utilized the flood-incorporated road deterioration model to estimate the long-term performance of after-flooded pavements with several maintenance strategies. Based on the predicted performance results, they conducted a cost-effectiveness analysis to compare these maintenance strategies. They found that placing a 1.2-inch (30-mm) thick overlay is an optimum strategy to structurally strengthen pavement. Compared to a post-flood strategy, an overlay placed at one year prior to flooding provides better long-term performance for flooded pavement. In reality, however, the timing and location of flood events are uncertain, which makes the implementation of pre-flood strategy nearly impossible.

Mallick et al. (2017a) developed a framework for evaluating the condition of a pavement after flooding. This framework included a hydraulic model to predict the degree of saturation of unbound materials at different times after flooding and a structural model to estimate the corresponding pavement response to traffic load. They proposed empirical relationships between material stiffness and post-flooding time. For instance, the modulus of asphalt mixture without antistripping additive was reduced by 8%, and the subgrade modulus was kept constant. The predicted surface deflection was related to the potential damage and safety of flooded pavement. The potential safety factor was then used to determine the critical post-flooding times for a variety of pavement conditions, including low subgrade modulus, thin asphalt thickness, and heavy traffic load. The results help agencies make decisions about whether and how long to close a flooded pavement for recovery after flood waters recede.

Mallick et al. (2017b) performed a sensitivity analysis and found that the permeability, thickness, and after-flooding retained tensile strength of asphalt material had significant influences on the critical post-flooding time, while base thickness and base matric suction had moderate and minor effects. They also suggested that surface cracks should be sealed in time to reduce the infiltration of water into the pavement system.

Nivedya et al. (2018) improved the pavement flooding model in two ways: using a finite element approach to predict water intrusion into pavement systems and a mechanistic-empirical model to estimate the resilient modulus of unbound base materials at various saturation levels. They concluded that the granular material properties, including gradation and permeability, play an important role in defining the resilience of asphalt pavement to flooding. However, Gu et al. (2015) found that the current mechanistic-empirical model underestimated the resilient modulus of unbound materials at a high saturation level and overestimated it at a low saturation level. Moreover, these studies did not consider the influence of moisture condition on subgrade modulus.

Qiao et al. (2017) developed a Bayesian decision tree approach for transportation agencies to make appropriate choices to operate post-flooded roadways, including whether to open or close the road and whether to perform non-destructive testing to evaluate the structural performance of flooded pavement. This approach accounted for the inherent uncertainties from engineering judgment on structural performance of pavement, non-destructive testing processes, back-calculation analysis, and estimates of user delay costs.

In 2005, Hurricane Katrina caused sustained flooding in New Orleans. Gaspard et al. (2007) found that the flooded asphalt pavements caused by Hurricane Katrina had strength loss equivalent to approximately 2-inch asphalt concrete and that flooding caused more damage to thin asphalt pavements than thick ones.

Wang et al. (2015) incorporated flood risk into the structural analysis of flexible pavements. They used the Kenpave program to compute the load-induced critical responses of flooded pavements and then employed the damage functions in Pavement ME Design to estimate the corresponding fatigue life and permanent deformation. The authors found that flooding caused noticeable damages to flexible pavements with thin asphalt layers and suggested that highway agencies use post-flood traffic control by restricting heavy vehicles for a certain period to facilitate pavement recovery.

2.2 Sea Level Rise/Groundwater Intrusion

Sea levels rose on average 3 mm/year between 1993 and 2003, which is two times faster than the early 19th century. Roshani et al. (2015) predicted that the sea level would increase by 0.8 m prior to 2100, resulting in substantial rise of the groundwater tables, not only along the coast but also significant distances inland. The anticipated groundwater rise will increase the degree of saturation in unbound base and subgrade, and thereby weaken the pavement structure.

Knott et al. (2017) suggested that new guidance for designing and rehabilitating pavement systems is needed to consider the effects of long-term groundwater rise on pavement performance. They developed a regional groundwater flow model for coastal New Hampshire, which was used to identify roads vulnerable to groundwater intrusion during their design life.

By utilizing the current pavement design system, they estimated reductions of 5% to 17% in fatigue life and 38% to 92% in rutting life for vulnerable roads in the coastal New Hampshire.

Knott et al. (2018) investigated the efficacy of pavement structural modifications to mitigate coastal-road pavement damage from groundwater rise caused by sea level rise. They concluded that increasing the thicknesses of granular base by at least 6 inches (15 cm) and asphalt surface by at least 6 inches (15 cm) could significantly reduce the impact of groundwater rise on pavement service life and delay pavement inundation. For pavements with adequate base thickness, the most cost-benefit effective modification is to increase asphalt layer thickness without excavation of existing structures to avoid premature pavement failure from sea level rise induced groundwater rise.

2.3 Snow Events

In the United States, over 70 percent of roads are located in regions that receive more than 5 inches of snowfall annually. Snow makes roads slippery, which reduces capacity and causes accidents. According to the FHWA (2020), over 1,300 people are killed and more than 116,800 people are injured every year in vehicle accidents on snowy or icy pavements. To improve driving safety and efficiency on snowy pavements, state and local agencies spend more than 2.3 billion dollars annually on snow and ice control operations. The maintenance procedures for snowy pavements vary with pavement type, material composition, and driving speed, etc.

Hossain et al. (2016) conducted a field study to compare the performance of road salt on different pavement types for snow and ice control. They conducted approximately 400 tests on three different pavement types (i.e., asphalt pavement, Portland cement concrete pavement, and interlocked concrete pavements) over 27 snow events. They found that the pavement clearing speed on asphalt pavement was 10% faster than concrete pavements, indicating that salt application for asphalt pavement could be approximately 15% less than the amount for concrete pavements. The difference in pavement clearing speed between Portland cement concrete and interlocked concrete pavements was not found to be significant via statistical analysis.

Hossain et al. (2015) evaluated the performance of different types of deicing materials for winter maintenance of transportation infrastructure. They found that the blend of salt and other chemicals (e.g., magnesium chloride and polyol) outperformed rock salts in terms of melting speed.

Russ et al. (2008) developed a pretreatment decision tree for winter maintenance of roadways using salt brine. They found that the salt residue on asphalt pavements followed an exponential decay with a lifetime of about 18 hours. Thus, they suggested to pretreat asphalt pavement within a day of the anticipated weather event.

As an alternative to chemical deicing, hydronic and electric sub-surface heating has been used to control snow and ice formation on pavements. In this system, a heated fluid is circulated through a series of pipe circuits that are usually laid in a serpentine configuration below the pavement surface. By eliminating salt, the heating system can reduce the rate of corrosion and thereby extend the life of the transportation infrastructure. Liu et al. (2007a&b) designed a snow melting system model and validated it in a full-scale pavement during snow event.

However, these alternative methods are still under experimental evaluation and are not ready yet for wide-scale deployment. Further, some tools being studied (such as sub-surface heating) will likely be localized solutions that are hard to deploy across an entire route or network.

2.4 Climate Related Temperature and Precipitation Changes

Climate, namely temperature and precipitation, have direct impacts on materials selection (e.g., binder grade) and design (e.g., climate inputs in MEPDG). Future climate model's data have been applied to various asphalt pavement scenarios to predict the impact of temperature fluctuation or precipitation fluctuation on performance. One common model database used is that of the Coupled Model Intercomparison Project Phase 5 (CMIP5), which is described in more detail in section 4.5 of this report. While CMIP5 is referenced in this portion of the literature review, it is important to remember that these models and datasets are constantly evolving and updated. For example, the CMIP6 model database is now available for use.

Mallick et al. (2018) examined the impact of climate change on pavement infrastructure using CMIP5 data applying the maximum temperature and precipitation information for seven cities in the United States over 50 and 100 year spans. The analysis was conducted by applying a system dynamics approach and statistical analysis techniques. The authors found that there are expected to be significant increases in roadway deterioration when considering climate change than without. Valle et al. (2017) examined the impact of CMIP5 data on Life Cycle Assessments (LCA) for pavements. The authors presented a framework for incorporating climate change into pavement LCA and found that climate is important to include in the LCA process, citing that there is a large difference in LCA outcomes when future climate versus historical climate data are used. Underwood et al. (2017) examined the economic impact of temperature rise using CMIP5 different Representative Concentration Pathway scenarios (RCP4.5 and RCP8.5) on pavements. Continuing traditional pavement management approaches without adaptation, the authors found that RCP4.5 projections could result in an increase of up to $19.0 billion and RCP8.5 projections resulted in a rise in cost of $26.3 billion by 2040, and even higher by 2100, to maintain our roadway networks in the U.S. Further, they found that 35% of the 799 observed locations for asphalt binder grade were incorrect due to using stationary climate data. There is also concern about the changing of frost cycles in northern climates as vehicle weight limits are often adjusted in accordance to the higher load carrying capacity due to the subsurface freezing of the roadway. Daniel et al. (2018) examined an ensemble of 19 climate models from CMIP5 to evaluate the effect of temperature and seasonal change on frost depth for low volume roads in New England. The researchers found that, depending on emissions scenarios, there would be a shift in when the pavement freezes, if it freezes at all, of up to two weeks by the end of the century.

Mills et al. (2009), Meagher et al. (2012), and Qiao et al. (2013) each used climate data from other models and/or approaches to predict the effects of climate change on pavement performance using the Mechanistic Empirical Pavement Design Guide (MEPDG). Nills et al. (2009) found that rutting was predicted to increase in all sites, and that 6 of 17 sites in Southern Canada would experience rutting and cracking issues that were intensified by climate change. Meaghar et al. (2013) examined the impact of using future climate models for the Northeast U.S. region on pavement performance through MEPDG and compared it with outputs using typical climate data. Similar to the work of Nills et al. (2009), the authors found that rutting was the dominant form of distress when using the future climate models. Qiao et al. (2013) conducted a pavement sensitivity analysis to changes in temperature, precipitation, wind speed, percent sunshine, and ground water level. The authors found that there is a loss of pavement service life due to climate change, with temperature being the leading factor.

FHWA's Transportation Engineering Approaches to Climate Resiliency (TEACR) study provides a series of relevant case studies that evaluate future temperature and precipitation impacts on transportation infrastructure (FHWA 2020). One case study investigated the impact of temperature and precipitation changes on pavements in cold regions, specifically State Route 6 / State Route 15 / State Route 16 in Piscataquis County, Maine. A key finding was the impact rising temperatures could have on seasonal load allowance restrictions due to shortened winters (FHWA 2016a). A second case study examined impacts on pavements located on expansive clay soils in North Texas, namely a proposed project near Dallas (FHWA 2016b). These soils are particularly challenging in design due to their tendency to swell when wet and shrink when dry, which will naturally be impacted by changing precipitation trends. In both case studies, climate models were used to make projections, which were then used in the MEPDG to predict pavement performance. Importantly, adaptation options were provided for consideration. These ranged from increasing the pavement's structural design to changing materials (i.e., binder PG grade).

2.5 Drought

Drought can lead to serious issues within the pavement structure. The central issue of drought as it relates to pavements is focused on the subgrade soils and their moisture content. For example, there are highly expansive clays in areas like central Texas. These clays will shrink and swell based on their moisture content, and prolonged drought followed by rain can lead to cracking in the pavement (Cambridge Systematics 2015).

2.6 Fires

In recent years, wildfires have become increasingly common in the United States. According to the National Interagency Fire Center, the 2018 wildfire season in California had over 7,500 fires burning an area of 1.67 million acres (ca.gov Cal Fire 2020). Since asphalt is typically combustible with a flash point less than 300°C, wildfires can cause devastating damages to asphalt pavements. Extreme heat can melt and ignite asphalt, resulting in wide cracks on the pavement surface. The cracks will then allow water and debris to enter into the underlying layers, which weaken the pavement structure and create potholes.

There is also the question of what to do in the case of a tunnel fire. The work of Schartel et al. (2010) investigated three asphalt mixtures under conditions similar to that of a tunnel fire and found that some mixes tend to grow fire and produce more smoke than others. Flame retardant materials can be added to suppress the combustion of asphalt. Xiao et al. (2019) pointed out that the ideal flame retardant should have five key characteristics: 1) high efficiency of flame suppression, 2) non-toxicity or low toxicity, 3) satisfactory thermo-stability and temperature compatibility with asphalt, 4) no degradation effect on pavement performance, and 5) simple production and low cost. Xu et al. (2019) evaluated the combustion performance of asphalt with different flame retardant materials. They found that the addition of compound fire retardant with 48% aluminum hydroxide, 32% magnesium hydroxide, 5% expanded graphite, and 15% encapsulated red phosphorous at a dosage rate of 10% yielded the best combustion performance for asphalt. Li et al. (2017) found that the warm-mix additive (Sasobit) is also beneficial for improvement of flame resistance of asphalt mixtures.

3 WORKSHOP

On September 10-11, 2019 the National Center for Asphalt Technology hosted a workshop that brought together contractors, asphalt pavement associations, agencies, and academics to define and discuss resilience as it relates to asphalt pavements. A detailed summary of the workshop is presented in the Appendix, but the main lessons learned, identified implementation needs, and research gaps are as follows.

3.1 Lessons Learned and Workshop Outcomes

The workshop participants provided the following lessons learned and outcomes.

- The FHWA definition of resilience was agreed upon as the best fit for application to asphalt pavements. That definition is, “the ability to anticipate, prepare for, and adapt to changing conditions and withstand, respond to, and recover rapidly from disruptions” (FHWA 2014).

Contribution of Asphalt Pavement to Resilient Communities

- Relationships between the DOT, contractor, and mix suppliers must be formed in advance of a potential event. These relationships are critical not only to infrastructure resilience, but community resilience as well. Trust and a teamwork approach bolster the ability to address a disruption rapidly.
- The DOT and contractor should work together to solve the problem. Sometimes the DOT and the contractor will have different ideas about how to address the problem. In some cases, the best solution may not fall within standard practice and could necessitate requiring waivers.
- The ability to construct asphalt pavements rapidly in addition to expeditious contracting allows the road to be repaired and opened quickly.
- In many cases, the pavement structure is rebuilt to a near-equivalent state, but perhaps mechanisms to repair to a new, more resilient state should be investigated from both a funding and design perspective.
- The use of portable asphalt plants in response to an extreme event as well as the resilience of stationary asphalt plants should be considered by agencies and mix producers.

Resilience of Asphalt Pavement as an Engineering Material

- Consideration should be given to whether broad policy or technical solutions should be developed and applied across an agency to develop a more resilient roadway infrastructure, or if focus should be on acute/specified solutions for specific projects/designs that are known or expected to be subjected a disruption.

- Perhaps adopting “risk factors” similar to what is applied in structural design should be applied to pavement designs. For example, a design factor based on risk of flooding may be applied to reduce the design modulus during the design phase of a project.
- In many cases we do not need to invent a new design method for a changing climate, but rather look to states/agencies nationwide who have historically managed a climate similar to what is now being experienced or is expected within the pavement design life.
- Consideration should be given to designing for failure, accepting the risk of failure, and having a rapid rebuilding plan in place in the case of an extreme event that compromises the roadway.

3.2 Implementation Needs

The workshop participants identified the following implementation needs:

- Educational tools that define and explain the concept of resilience and provide insight into how and when to plan, design, and construct resilient pavements are required for implementation;
- A better understanding of the opportunity to use pavement maintenance cycles to build in resilience (e.g., place an asphalt overlay as opposed to mill and fill to thicken the pavement structure);
- Examination of the different implementation modes within the DOT structure. For example, Pavement Management Systems contain significant amounts of data that are used to understand the performance of the pavement system. This data can be mined for insights into the resilience of the system (e.g., pavement performance in flood-prone regions versus the rest of the network) and track performance of pavements that were designed to be resilient; and
- Funding to build resilience into the system as well as for emergency response and resilient rebuilding. To implement this there is a requirement for updates in codes and policies.

3.3 Identified Research Gaps

The workshop participants identified the following research gaps:

- Development of guidance documents around: action plans / best practices, project delivery methods, and policies for DOT rapid response;
- Evaluation of temporary materials and tools for enhanced protection of pavements from disruptions;
- Further investigation of the effects of groundwater intrusion due to sea level rise; and
- Integration of future temperature and climate models into pavement performance prediction models (such as those used in the Mechanistic Empirical Pavement Design Guide) and planning.

4 TOOLS FOR RESILIENCE

There are a number of tools already available to the asphalt community that may provide resilient attributes to the system. However, these tools have not necessarily been thought of in a “resilient” context throughout the literature. Therefore, these tools are listed below along with a brief description of their resilient aspects and some of the key literature used to define them.

4.1 Rapid Reconstruction

Rapid reconstruction is an inherent benefit of asphalt pavements, whether in a standard paving project or in an expeditious repair scenario after an event. The key to rapid reconstruction is to lower the impact on road user costs, which are defined by LaMondia et al. (2018) as "the total monetary and temporal costs experienced by both personal and freight vehicle road users when faced with delays caused by lane or total road closures…" This definition encapsulates the costs of lost time, operations, and emissions. Another consideration is the cost to local businesses, also known as local business impact costs, if the roadway is closed due to a disruptive event (LaMondia et al. 2018). Examples of rapid reconstruction in practice are provided in the case studies section of this report.

4.2 Perpetual Pavements

Perpetual Pavements are defined by the Asphalt Pavement Alliance as "an asphalt pavement designed and built to last longer than 50 years without requiring major structural rehabilitation or reconstruction, and needing only periodic surface renewal in response to distresses confined to the top of the pavement" (APA 2002; Newcomb et al. 2010). This concept, which designs pavements to a sufficient thickness to withstand long-term structural loading without over-designing, can be employed along major corridors as a method to withstand heavier than usual traffic due to rerouting around a highway closure or as the result of debris removal after a catastrophic event. The FHWA notes that perpetual pavements are more resistant to moisture damage due to the thicker asphalt layer and therefore are expected to be more resilient to a major flood event (Flintsch et al. 2020).

Maintenance overlays can also be used to work toward building a perpetual pavement. Instead of milling two inches and replacing the milled material with two inches of HMA, an agency could mill half an inch to an inch and replace it with two inches of HMA, resulting in a structure that is one to one and a half inches thicker. This would not theoretically cost any different in pavement materials, but the thickening of the asphalt layer would move the pavement toward a perpetual pavement structure, which would make the pavement more resilient. It is important, however, to ensure that the milled surface is free of any cracks or other deterioration that would ultimately propagate through the new layer.

4.3 Use of Recycled Materials

There are cases where material supply chains are reduced or even temporarily eliminated due to a major disruptive event. In this case, it can be a challenge to gather the materials needed in order to rapidly construct a new pavement. Fortunately, asphalt pavements are highly recyclable, not only from an aggregate perspective but also the asphalt binder. The pavement that was damaged from the event can be recycled into a new pavement. Techniques such as hot recycling or cold recycling can be used to replace the lower layers of the pavement with 100% recycled material, allowing for the surface to be paved with a limited supply of available virgin materials. Further, the damaged pavement can be used as RAP in the surface mixture up to allowable percentages (often 20-30% by weight of the mix), reducing the need for virgin materials.

4.4 Warm Mix Asphalt (WMA) Technologies

Warm mix asphalt technologies are used to lower the production and placement temperatures of hot mix asphalt by 55°F to 85°F using chemical or wax-based additives or foamed asphalt binder. The lowering of the asphalt temperature reduces greenhouse gas emissions and energy consumption, creates a more pleasant work environment for the production and placement of the mixture, allows for increased density during placement, and increases the haul distance (NAS 2017). WMA contributes to the resilience of asphalt pavement most notably through the ability to achieve density, namely in the event of a disaster that requires repair during cold weather (Kuennen 2014), and through increased haul distance in a case where an event occurs that closes the local asphalt plant(s) (Howard et al. 2012), requiring materials to be trucked from further away.

4.5 Climate Models

If agencies, engineers, and designers are going to build resilience into the design process they must consider the *future* climate, not simply our historical climate. Climate models use GHG scenarios and other climate "forcing agents" (such as aerosols) to conduct simulations of future climate when considering the earth's various components (atmosphere, land surface, oceans, etc.) (FHWA 2011). Models are assembled in a series of three-dimensional, time dependent grid points around the globe. Practically, a pavement engineer may use this information for materials selection (e.g., binder) or structural pavement design. There are numerous climate models that can be used to predict future climate and the relevant data are often in the form of expected future temperature and precipitation patterns.

While factoring climate into the design process is not a new concept, engineers have relied on *historical* climate data to ensure design performance. For example, Pavement-ME© uses historical climate data from either the North American Regional Reanalysis (NARR) dataset from the National Oceanic and Atmospheric Administration (NOAA) or the Modern Era Retrospective-Analysis for Research Applications (MERRA) dataset from the National Aeronautics and Space Administration (NASA). Agencies are familiar with the LTPPBind software, which is used to determine the appropriate performance grade (PG) asphalt binder to use in a given region. LTTPBind uses the MERRA database, Long Term Pavement Performance (LTPP) data, or user input data, all of which are based on historical records (FHWA, 2020a).

One of the most readily available climate model databases is the Coupled Model Intercomparison Project. There are two major downscaled climate projections that are used, CMIP3 (Phase 3) and CMIP5 (Phase 5). CMIP3 allows for an ensemble of 9 different climate models to be used, whereas CMIP5 allows for up to 21. The FHWA makes access available for use by linking to the US Bureau of Reclamations Downscaled CMIP3 and CMIP5 Climate and Hydrology Projections website (FHWA 2020c). CMIP5 is a more recent version of CMIP3, although significant differences in projects have not been found. One of the biggest differences is that CMIP5 allows for continuous time periods of analysis from 1955-2099, whereas CMIP3 data is divided into time periods (1961-2000, 2046-2065, 2081-2099) (FHWA 2016c). Within

CMIP5 there are four major *Representative Concentration Pathways* (RCP) that are used to project changes in climate through the year 2100. These are based on scenarios agreed upon by the Intergovernmental Panel on Climate Change (IPCC) that consider greenhouse gas (GHG) emissions, aerosol levels, developments in technology, energy generation, land use, socio-economics, and population growth. The four RCP's — RCP2.6, RCP4.5, RCP6, and RCP8.5 — represent varying GHG emission scenarios with RCP2.6 reflecting "peak-and-decline" (least severe) and RCP8.5 representing high GHG concentration levels (most severe) (Wayne 2013). While these models provide projections of many different climate-related factors, arguably the two most valuable for pavement design and materials selection are future temperature and precipitation projections, though Meagher et al. (2012) also used wind speed, downswelling shortwave radiation (for percent sunshine), and surface humidity and pressure (for relative humidity) for input use in the MEPDG. One challenge, however, is that the CMIP tool does not give hourly temperature required by the MEPDG. Therefore, methods such as that used by Gudipudi et al. (2017) must be used to further process the data, converting it from daily maximum and minimum temperatures to hourly temperatures. For instance, Gudipudi used the Modified Imposed Offset Morphing Method to project hourly future climate data by using the historic hourly temperature distribution and the predicted future minimum and maximum temperatures.

In general, one issue with climate data is its resolution. Climate models typically have grid cells between 120-190 miles per side, which is beyond what we might consider the "project scale" for a roadway design. "Downscaling" in the roadway design context is the process by which data is taken from larger grid cells and the resolution is adjusted to meet a smaller, more manageable grid cell size for project consideration, something that the FHWA CMIP tool helps to accomplish. There are two methods of downscaling: dynamic, which uses regional climate models within the larger model, or statistical, which relates the outputs of the model to historical precipitation and temperature measurements. For example, the statistically Downscaled Climate and Hydrology Projections (DCHP) offered through the Scripps Institution of Oceanography (2020) offers downscaled data at a resolution of 7.5 miles per grid cell side (Beucler 2017).

4.6 Climate Adaptable Materials

Climate adaptable materials are an inherent benefit of asphalt. The asphalt binder is selected in accordance to the temperatures in which the pavement must perform. Binder grades can be adjusted to account for changing climates (e.g., increasing the binder grade in the surface layers to account for higher temperatures during major heat-related events). Further, there are other technologies that can be incorporated into the binder or the mix matrix to enhance performance under varying stresses. Polymers are added the asphalt binders to enhance the high temperature strength and/or the low temperature elasticity, which will help in the resistance to rutting and cracking. Likewise, tire rubber has been recycled into asphalt pavements and has been shown to enhance both rutting and cracking resistance in addition to reduced pavement noise (Rodezno et al. 2018). These technologies and others like them can be used to help the pavement resist distress induced by irregular climatic events or a slowly changing climate.

4.7 Porous Asphalt Pavements

Porous asphalt pavements are typically used for stormwater management, turning a traditionally impervious surface into a surface that can actually bring a hydrological benefit to a site. These pavements are typically found in parking lots or low volume roads (Schwartz and Hall 2018). There is work that suggests they may be beneficial for minimizing deicing chemicals for winter maintenance (Rossen et al. 2013), though clogging is always a cause for concern for these pavements (Weiss et al. 2019). Porous pavements can be thoughtfully designed and strategically applied in a way that allows for the management of large precipitation events.

5 CASE STUDIES

Two case studies were conducted that focused on major natural disasters and how asphalt pavements were used to recover after the event. The first is the 2019 flooding of Iowa and the second is the 2018 7.0 magnitude earthquake in Alaska. These two studies were identified through the workshop and expanded on through follow-up interviews with relevant parties, although many others were discussed.

5.1 Iowa Flooding of 2019

This case study is based on conversations and information provided by Dr. Scott Schram of the Iowa Department of Transportation and Mr. Bill Rosener, formerly of the Asphalt Pavement Association of Iowa.

Figure 2. Flooding in Iowa on Interstate 29 South at Interstate 680 in June 2019 (*Photo Credit Dr. Scott Schram, Iowa DOT*)

Iowa experienced significant flooding in the Spring of 2019 (Figure 2) as a result of heavy rains and saturated soils, which generated significant runoff into the Missouri river (Des Moines Register 2019). This specific case study examines the efforts made to reopen Interstate 680 and Interstate 29 in Iowa near Omaha, NE. Two flood events within a three-month period closed sections of both interstates. The first event occurred in early March and the second occurred in early May, resulting in significant damage to the interstates. Figure 3 provides an example of the undermining of the roadway that occurred beneath the shoulders on both rigid and flexible pavement sections of the interstate. In some cases, this undermining went beneath the pavement structure itself, which then called for the entire pavement structure to be reconstructed.

Figure 3. Shoulder Failures as a Result of Flood Water Undermining (*Photo Credit Dr. Scott Schram, Iowa DOT*)

There were four sections of roadway that needed significant work: US-34, IA-2, I-29 south of Council Bluffs, and a section of I-680 / I-29 at Crescent, Iowa. The project was placed out to bid as a dual-option contract (rigid and flexible). The rigid cross section reflected the rebuild that occurred after I-680 flooded in 2011 because those sections weathered the first 2019 flood well. The rigid option had an 11-inch PCC surface (7-inch shoulders) over a 6-inch modified subbase and 18 inches of stone backfill (noted in Iowa plans as "special backfill"). The flexible option was designed using PerRoad, a perpetual pavement design software, to determine the HMA thickness. The final design was a 2-inch surface course over a 2-inch intermediate course over 4 inches of 3/4 inch NMAS base course over an additional 4 inches of ½-inch NMAS base course, resulting in a final design thickness of 12 inches of HMA in the mainline (8-inch shoulders). The HMA was placed over 10 inches of modified subbase and 12 inches of special backfill. In both design options, a polymeric subgrade stabilization fabric was used to mitigate any issues that could occur due to the saturated soils. The flexible pavement option was awarded the contract $3 million below the alternate bid, specifically on Interstate 29 south the of Council Bluffs portion of the project.

Longitudinal subdrains were also included at the edge of the mainline, but inside the shoulder, for both options. Dr. Schram noted that the Iowa DOT found that roads subject to significant flooding did not perform as well when the edge drains were installed along the edge of the shoulder because those drains tended to lead to undermining of the structure. The Iowa DOT ran falling weight deflectometer tests to investigate change in modulus, but this data was collected for informational purposes.

The next critical aspect of this project was time. The Iowa DOT estimated that user cost was nearly $200,000 per day of interstate closure. Incentives were leveraged by the DOT to open the roadway as fast as possible. The first step in the process was to remove debris, then assess damage, and ultimately repair the damage. Table 1 highlights the status of the roadway, from closed to water receding, contractor mobilization, and ultimately the opening of the road for both flood events. In the case presented, the road was open to traffic for the first (March) flood within four days of the contractor mobilizing, and the road was open to traffic after the second (May) flood after only three days. As an example of the incentives offered, the contractor received $8.6 million in incentives on a different section of I-29 for having one lane of traffic open in each direction, and an additional $2 million in incentives for having two lanes in each direction, totaling $10.6 million of a possible $12.2 million.

Table 1. Flood Status and Dates for I-680 / I-29 in Crescent, IA During 2019 Flood Events

Status	Flood 1 (Date)	Flood 2 (Date)
Closed	3/14/2019	5/31/2019
Water Receded	3/27/2019 (Debris cleared for testing)	6/10/2019
Contractor Mobilized	3/30/2019	6/10/2019
Open	4/2/2019	6/12/2019

The rapid speed of construction was highlighted as one of the most important aspects of this project. However, a number of other significant features of this project highlighted keys to pavement resilience. One was that the DOT and the contractor worked closely together and discussed different options and hurdles, as well as the best way to get the roadway open to the general public. For example, the DOT waived some typical requirements at the contractor’s request such as not switching mix types so the contractor did not have to make changes at the asphalt plant in order to open the road more quickly. The DOT worked closely with their hydrologist to examine flood projections, especially because while the roadway was not flooded, flood waters on the land adjacent to the roadway often had not yet receded, as shown in Figure 4. Contractors had to plan on what would happen if the floodwaters once again topped the roadway. The general plan was to mobilize the equipment and remove it from the roadway so that it would not be damaged. This fortunately did not occur, but it was critical to both monitor the situation and have a plan in place if the road was in fact inundated during construction.

Figure 4. Floodwaters Adjacent to Roadway (*Photo Credit Dr. Scott Schram, Iowa DOT)*

A second innovation occurred as a result of failed flexible concrete geogrid mats that were placed to keep water away from the shoulder in a flood scenario. The failure, as shown in Figure 5a, occurred because of failed or lost anchors. An additional asphalt wedge was placed just over the top of the mats to help mitigate further failures as shown in Figure 5b. While flexible concrete geogrid mats remain the preferred mitigation method, there was a further risk of flooding prior to replacement and/or placement on other sections of the roadway. Through discussions it was decided that the contractor would pave an additional shoulder-width wide since many pavement failures without the mat were due to undermining beneath the shoulder. The concept was that the additional shoulder would bear the most damage and the true shoulder would be unaffected. Figure 6 shows the additional shoulder-width after paving. These examples show the advantages of forming trust between the DOT and contractor, as well as open communication and dissemination of ideas.

(a) **(b)**

Figure 5. (a) Failed Grid Matting and (b) Asphalt Wedge Placed to Assist in Maintaining Mat Stability (*Photo Credit Dr. Scott Schram, Iowa DOT)*

Figure 6. Extended (Additional) Shoulder as Temporary Flood Mitigation Technique in Case Additional Flooding Occurred Before Geogrid Mats Were Installed

The Iowa flood scenario was unique as two floods occurred over the same stretches of roadway in a matter of months. The asphalt industry mobilized rapidly, working closely with the DOT, to rebuild the roadway and have it open to traffic in as little as a few days. Further, asphalt was used in innovative ways to create temporary flood damage mitigation techniques in the event that additional flooding occurred (e.g., shoulder wedge over flexible concrete geogrid mat or paving an additional shoulder). Close working relationships with the DOT proved to be critical and allowed for fast recovery of the roadway once the flood waters receded.

5.2 Alaska Earthquake of 2018

This case study is based on conversations with Mr. Mahear Abou Eid, P.E., Project Engineer for the Alaska Department of Transportation and Ms. Amanda Gilliland, P.E., of The Transtec Group.

Figure 7. Failed Section of Minnesota Drive Ramp after 2018 7.0 Alaska Earthquake (*Photo Credit Knik Construction)*

On November 30, 2018, a 7.0 magnitude earthquake struck just north of Anchorage, Alaska and caused wide devastation, including major highway damage. This specific case study will examine a section of the Minnesota drive ramp at West International Airport Road, which leads to the Ted Stevens Anchorage International Airport. A major rotational slope failure occurred due to intensity of the earthquake and impact of drainage at the toe of the slope (low point on the site). The roadway, as shown in Figure 7, broke apart and collapsed under the dynamic loading.

Within hours of the earthquake, work began on repairing the roadway. Due to a declared State of Emergency, the DOT was able to work through informal agreements with local contractors. Time and materials were tracked and paid based on normal time/materials data. The department put together a rough estimate of the materials, cut and fill, etc. for the project for their own record keeping. The first step was removal of the vehicle stuck in the middle of a failed portion of the road, followed by excavating all of the failed material. A drainage pipe that ran beneath the roadway had to be replaced in the process.

An Alaska Type-A subbase material was placed and compacted to bring the roadbed to the proper elevation. Fortunately, the subbase material was available nearby at a contractor's yard.

Due to the time of year (cold, non-construction season) and the scheduled paving of a nearby section the following construction season, the pavement solution was designed to be temporary. The contractors used a standard 3/4 inch NMAS Alaska Type-2 blend with 5% PG58-34 binder. The material was produced at temperatures between 320-330°F and arrived on site at approximately 280°F. A 3-inch mat was placed with the intention of keeping the mat thick to retain heat and achieve adequate compaction. The mix was compacted before it reached 250°F and, despite the cold, the contractor had to wait 30 to 40 minutes for it to cool enough for striping. One controlling time factor on the job was the fact that the asphalt binder had to be heated and some of the tanks were frozen. The remarkable thing about this project is that, despite the cold temperatures and the fact that it was not construction season, the project was completed and the roads were opened after only 112 hours from the earthquake occurring to the road opening. Table 2 provides some additional information about the project and Figure 8 shows a picture of the repaired road (Abou Eid, 2020).

Table 2. Project Data

Project Detail	Data
Time to opening	112 hours
Excavation	3300, SY
Subbase	4600 tons
Slope stabilization	1250 SY
Striping	500 feet

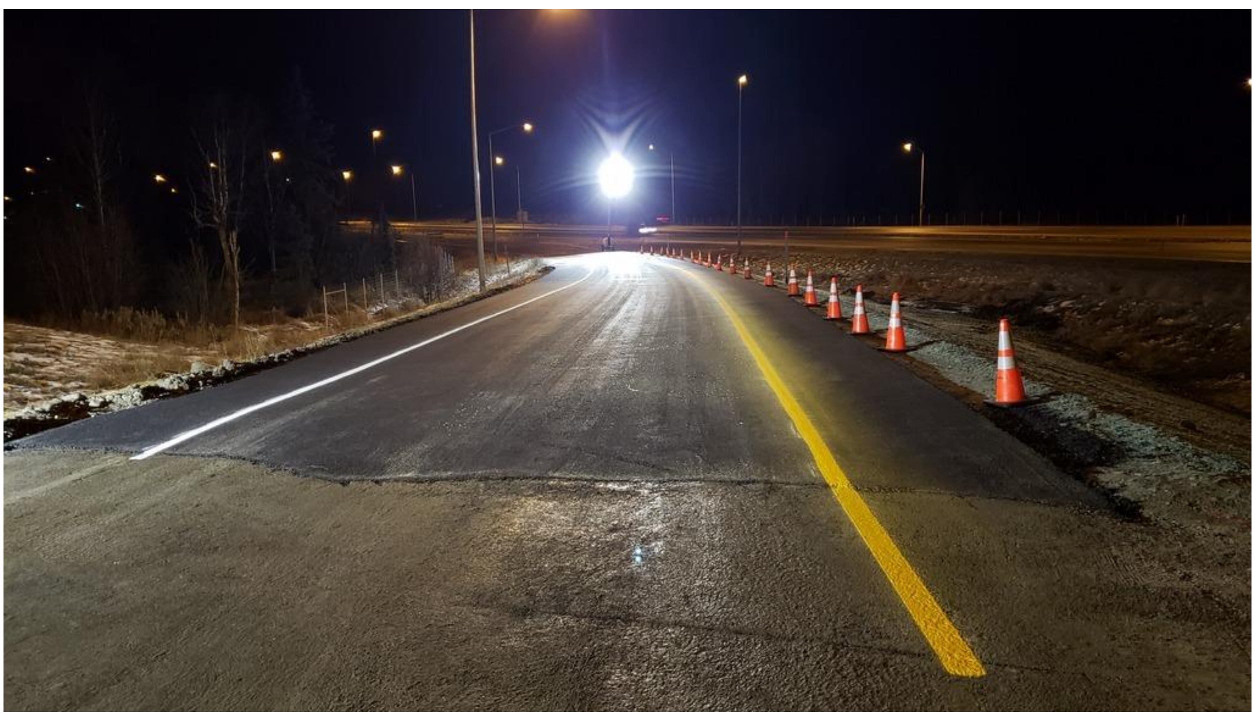

Figure 8. Completed Project (*Photo Credit Mahear Abbou Eid, Alaska DOT*)

A critical element of this project was the ability for the contractor and the DOT to work together rapidly. Numerous companies worked on this project — six in total plus local utilities — in order to accomplish this work in an accelerated fashion. Removal of specific contractual requirements and the ability to lean on historical data also allowed for the project to run smoothly. Ultimately, the positive relationships between the DOT and the various contractors, including amongst the contractors themselves, impacted the resilience of the roadway infrastructure.

6 CONCLUSIONS

The following conclusions were reached as a result of the literature review and discussion at the 2019 Asphalt Resiliency Workshop.

The Federal Highway Administration's definition of resilience as defined in FHWA Order 5520 is applicable to asphalt pavements without any recommended modifications or changes. That definition is as follows, "*Resilience or resiliency is the ability to anticipate, prepare for, and adapt to changing conditions and withstand, respond to, and recover rapidly from disruptions."*

Asphalt pavements were found to have the following resilient characteristics, as discussed in the literature review or during the workshop.

- ***Fast construction:*** As shown in the Iowa and Alaska case studies, asphalt can be used to quickly repair and/or reconstruct damaged roadways for rapid recovery. The Iowa case study specifically highlighted the cost effectiveness of the solution. The pavement can also be opened to traffic almost immediately after placement.
- ***Perpetual pavement design:*** Asphalt pavements can be designed to resist deep distress for up to 50 years, with only the surface needing to be treated. This approach can be used along critical corridors to ensure that the transportation system is resilient. In theory, these pavements should be less likely to fail under distress during an active climate event and will also withstand excess traffic as the result of a cascading event such as detouring caused by a closed route.
- ***Resilience / hardening can be built into long-term maintenance schedules:*** Many owner agencies replace the surface of their asphalt pavements in accordance with a maintenance treatment cycle (e.g., mill and replace the top 2 inches every eight years). One method of hardening infrastructure is to not mill as deep (e.g., only ½ inch) or do not mill at all before placing a 2-inch overlay (or other thickness). This will thicken and thus harden the pavement structure in a way that may not cost additional money to the agency beyond the planned maintenance dollars.
- ***Warm mix asphalt***: Warm mix asphalt technologies, which lower the viscosity of asphalt binder at lower mixing temperatures to reduce emissions during paving while maintaining adequate compaction, can also be used to increase the haul distance when used but still produced at traditional hot mix asphalt temperatures. This is critical for response in situations where the local asphalt plant has been taken offline due to an extreme event.
- ***Adaptable materials for climate extremes:*** Polymers, fibers, and other additives are regularly used to increase the stiffness and/or other performance criteria of asphalt pavements without compromising their inherent benefits. These technologies can be used as appropriate to enhance the resilience of the pavement infrastructure to climate extremes (e.g., polymer modified binders can help account for higher temperature extremes by increasing the high PG grade without having to change the low PG grade).

- ***Recycling:*** Asphalt pavements are 100% recyclable. When a roadway is destroyed due to a climate event, the existing pavement can be recycled into the new pavement infrastructure by way of traditional hot mix asphalt methods as well as techniques such as cold in-place recycling and full depth reclamation. This is important because of the supply chain disruptions that are often caused due to an extreme event (e.g., aggregate and asphalt binder supplies are reduced or cut off).
- ***Porous asphalt systems:*** Porous asphalt systems have been employed for years to manage stormwater. These systems can be used to manage extreme precipitation events, allowing for water to move through the system rapidly. More research is needed to continue to adapt these forms of infrastructure for certain uses, but there is much promise in this technology as a resilient solution.

More research is needed to understand the impact of specific events on asphalt pavements (or pavements in general). Examples include but are not limited to: wildfires, ground water intrusion, and flooding. Further understanding of the best methods to apply or use climate models and tools to aid in materials selection and pavement structural design is also needed.

7 RECOMMENDATIONS

The following recommendations are made as a result of a study of the literature in addition to the results and discussion provided during the 2019 Asphalt Resiliency Workshop. These recommendations are broken into three categories (industry, agency, academia) that are most likely to take a lead on the recommendation, however all recommendations should be broadly understood and supported amongst all three groups.

Industry

- The National Asphalt Pavement Association should work with the Federal Highway Administration and other key organizations to conduct regional workshops centered on the resiliency of pavement infrastructure. These events should present stakeholders with a clear definition of resiliency, response guidance, options with respect to disaster response funding, and case studies.
- A survey of NAPA members should be conducted to investigate ways that mix producers are making their plants more resilient. This information would provide valuable insight into how to make asphalt plants more resilient and better prepared to be a first responder in the event of a disaster.
- Asphalt contractors and producers should consider ways to make their facilities more resilient to ensure continuity of business operations and provide rapid response to an extreme event. This may include specific elements of the asphalt plant, construction equipment, and/or critical supply points (i.e., aggregate stockpiles, binder tanks, etc.).

Agency

- Agencies and industry should work to agree on a single definition of resilience as it relates to highway infrastructure, specifically pavements.
- Maintenance, preservation, and rehabilitation strategies should be developed by agencies to harden, prepare for, or rapidly recover asphalt pavement after a disaster.

- Clear funding and policy guidance should be provided and implemented at both the national and state/local levels. Clarity needs to be provided to local agencies regarding what level of reconstruction can take place after an event (i.e., repair/replace to the previous state vs. repair/replace to new national/state design standards vs. repair/replace to appropriate levels of resilience as define by the agency and their policy).
- Agencies should formulate guidance and policy around disaster response and ensure that all levels of the agency are prepared to rapidly respond to a disaster.
- Agencies, local contractors, and asphalt producers need to engage in conversations around disaster response, including preplanning for the eventuality of an event. In some cases this may result in formal emergency contract mechanisms, and in other cases it may simply strengthen relationships and communications, which have proven critical for rapid and effective response.

Academic

- A design method or modification to current design methods that factors risk, climate data, and other critical elements that enhance resilience should be considered for pavements.
- Further investigation is needed into methods of adapting infrastructure in critical corridors to enhance the resilience of both the roadway infrastructure and the transportation network.
- Life Cycle Cost Analysis tools should be leveraged to understand to what degree adaptation of infrastructure is effective and appropriate for a given level of risk for specific projects and/or corridors.
- Develop methods for incorporating resilience and adaptation into a Life Cycle Assessment framework.

REFERENCES

Akbari, H., M. Pomerantz, and H. Taha. Cool Surfaces and Shade Trees to Reduce Energy Use and Improve Air Quality in Urban Areas. *Solar Energy*, Vol. 70, No. 3, 2001, pp. 295—310.

Akbari, H., S. Menon, and A. Rosenfeld. Global Cooling: Increasing World-Wide Urban Albedos to Offset CO_2. *Climate Change*, Vol. 94, 2009, pp. 275—286.

Arizona Department of Transportation. Environmental Planning, Sustainable Transportation, Resilience Program. https://origin.azdot.gov/business/environmental-planning/programs/sustainable-transportation/resilience-program. Accessed March 20, 2020.

Asphalt Pavement Alliance. *Perpetual Pavements: A Synthesis*. APA 101, Lanham MD, 2002.

Barami, B. Infrastructure Resilience: A Risk-Based Framework. Summary prepared for *Beyond Bouncing Back: A Roundtable on Critical Transportation Infrastructure Resilience.* John A. Volpe National Transportation Systems Center, USDOT, 2013.

Bhave, A. G., A. Mishra, and N. S. Raghuwanshi. A Combined Bottom-Up and Top-Down Approach for Assessment of Climate Change Adaptation Options. *Journal of Hydrology*, Vol. 518, 2014, pp. 150—161.

Bowers, B. F., and F. Gu. *Resilient Asphalt Pavements: Industry Solutions for the Resilience Goal.* NAPA Sustainability in Practice Report 105. National Asphalt Pavement Association, Greenbelt, MD.

Buecler, B. Rivers, Rainfall and Resilient Roads. *Public Roads Magazine*. Federal Highway Administration, 2017. https://www.fhwa.dot.gov/publications/publicroads/18autumn/05.cfm.

Cambridge Systematics, Inc. *Central Texas Extreme Weather and Climate Change Vulnerability Assesment of Regional Transportation Infrastructure*. January 2015. Austin, TX.

Carnielo, E., and M. Zinzi. Optical and Thermal Characterisation of Cool Asphalts to Mitigate Urban Temperatures and Building Cooling Demand. *Building and Environment*, Vol. 60, 2013, pp. 56—65.

Daniel, J. S., J. M. Jacobs, H. Miller, A. Stoner, J. Crowley, M. Khalkhali, and A. Thomas. Climate Change: Potential Impacts on Frost-Thaw Conditions and Seasonal Load Restriction Timing for Low-Volume Roadways. *Road Materials and Pavement Design*, 19:5, 2018, pp. 1126—1146.

Missouri River Basin Has Taken on More Runoff In 3 Months Than It Typically Gets in A Year. *Des Moines Register*, May 29, 2019. https://www.desmoinesregister.com/story/news/2019/05/29/iowa-flooding-2019-missouri-river-basin-record-runoff-hamburg-levee-interstate-29-fremont-county/1273103001/. Accessed March 31, 2020.

Federal Highway Administration*. The Use of Climate Information in Vulnerability Assessments.* Memorandum Prepared by ICF International for the Federal Highway Administration. January 2011.

Federal Highway Administration (2016a). *TEACR Engineering Assessment, Temperature and Precipitation Impacts on Cold Region Pavement: State Route 6/State Route 15/State Route 16 in*

Maine. US DOT, Washington, D.C., 2016. https://www.fhwa.dot.gov/environment/sustainability/resilience/ongoing_and_current_research/teacr/me_freeze_thaw/fhwahep17019.pdf

Federal Highway Administration (2016b). *TEACR Engineering Assessment, Temperature and Precipitation Impacts on Expansive Soils: Proposed State Highway 170 in North Texas.* US DOT, Washington, D.C., 2016. https://www.fhwa.dot.gov/environment/sustainability/resilience/ongoing_and_current_research/teacr/texas_i-70/fhwahep17018.pdf

Federal Highway Administration (2016c). *U.S. DOT CMIP Climate Data Processing Tool User's Guide*. US DOT, Washington, D.C., 2016.

Federal Highway Administration. *FHWA Order 5520*. Effective December 15, 2014. https://www.fhwa.dot.gov/legsregs/directives/orders/5520.cfm#par6. Accessed March 30, 2020.

Federal Highway Administration. *Resilience 2020*. https://www.fhwa.dot.gov/environment/sustainability/resilience/.

Federal Highway Administration (2020a) *Products*. Accessed May 20, 2020. https://cms7.fhwa.dot.gov/research/ltpp/products/products

Federal Highway Administration (2020b) *Transportation Engineering Approaches to Climate Resilience (TEACR) Study.* Accessed June 9, 2021. https://www.fhwa.dot.gov/environment/sustainability/resilience/ongoing_and_current_research/teacr/index.cfm

Flannery, A., M. A. Pena, and J. Manns. *NCHRP Synthesis of Highway Practice 527: Resilience in Transportation Planning, Engineering, Management, Policy, and Administration*. Transportation Research Board of the National Academies, Washington, D.C., 2018.

Filosa, G., A. Plovnick, L. Stahl, R. Miller, and D. Pickrell. *Vulnerability and Adaptation Framework.* FHWA Final Report, December 2017, Washington, D.C.

Flintsch, G., J. Meijer, and K. Smith. *Improved Asphalt Sustainability Through Perpetual Pavement Design*. FHWA-HIF-19-080, January 2020, Washington, D.C.

Gaspard, K., M. Martinez, Z. Zhang, and Z. Wu. *Impact of Hurricane Katrina on Roadways in the New Orleans Area*. Technical Assistance Report No. 07-2TA, Louisiana Transportation Research Center, 2007.

Gudipudi, P.P., B.S. Underwood, and A. Zalghout. Impact of Climate Change on Pavement Structural Performance in the United States. *Transportation Research Part D*. 57, pp. 172-184, 2017.

Gu, F., H. Sahin, X. Luo, R. Luo, and R. Lytton. Estimation of Resilient Modulus of Unbound Aggregates Using Performance-Related Base Course Properties. *Journal of Materials in Civil Engineering*, Vol. 27, No. 6, 2015.

Hossain, K., L. Fu, F. Hosseini, M. Muresan, T. Donnelly, and S. Kabir. Optimum Winter Road Maintenance: Effect of Pavement Types on Snow Melting Performance of Road Salts. *Canadian Journal of Civil Engineering*, Vol. 43, 2016, pp. 802—811.

Howard, I. L., B. A. Payne, M. Bogue, S. Glusenkamp, G. L. Baumgardner, and J. M. Hemsley. *Full Scale Testing of Hot-Mixed Warm-Compacted Asphalt for Emergency Paving*. SERRI Report 70015-011, for the US Department of Homeland Security under US Department of Energy Interagency Agreement, 2012.

Hossain, K., L. Fu, and R. Lake. Field Evaluation of the Performance of Alternative Deicers for Winter Maintenance of Transportation Facilities. *Canadian Journal of Civil Engineering*, Vol. 42, 2015, pp. 437—448.

Infrastructure Climate Network. 2020. http://theicnet.org/. Accessed March 21, 2020.

Khan, M., M. Mesbah, L. Ferreira, and D. Williams. Developing a New Road Deterioration Model Incorporating Flooding. *Proceedings of the Institution of Civil Engineers – Transport*, Vol. 167, No. 5, 2014, pp. 322—333.

Khan, M., M. Mesbah, L. Ferreira, and D. Williams. Estimating Pavement's Flood Resilience. *Journal of Transportation Engineering*, Vol. 143, No. 3, 2017, https://doi.org/10.1061/JPEODX.0000007.

Khan, M., M. Mesbah, L. Ferreira, and D. Williams. A Case Study on Pavement Performance due to Extreme Moisture Intrusion at Untreated Layers. *International Journal of Pavement Engineering*, 2017, DOI: 10.1080/10298436.2017.1408272.

Khan, M., M. Mesbah, L. Ferreira, and D. Williams. Preflood Road Maintenance Strategy for a Road Authority. *Journal of Transportation Engineering*, Vol. 142, No. 12, 2016, https://doi.org/10.1061/(ASCE)TE.1943-5436.0000901.

Khan, M., M. Mesbah, L. Ferreira, and D. Williams. Development of a Post-Flood Road Maintenance Strategy: Case Study Queensland, Australia. *International Journal of Pavement Engineering*, Vol. 18, No. 8, 2017, pp. 702—713.

Kuennen, T. *Able to Reconnect – Warm Mix Plays Big Role in Colo. Flood Recovery*. Roads & Bridges Magazine, March 2014, Arlington Heights, Ill.

Knott, J., M. Elshaer, J. Daniel, J. Jacobs, and P. Kirshen. Assessing the Effects of Rising Groundwater from Sea Level Rise on the Service Life of Pavements in Coastal Road Infrastructure. *Transportation Research Record: Journal of the Transportation Research Board No. 2639*, Transportation Research Board of the National Academies, Washington, D.C., 2017, pp. 1—10.

Knott, J., J. Daniel, J. Jacobs, and P. Kirshen. Adaptation Planning to Mitigate Coastal-Road Pavement Damage from Groundwater Rise Caused by Sea-Level Rise. *Transportation Research Record: Journal of the Transportation Research Board, No. 2672*, Transportation Research Board of the National Academies, Washington, D.C., 2018, pp. 11—22.

LaMondia, J., M. Fisher, R. Turochy, and W. Zech. *Calculating Road User, Crash Mitigation and Local Business Impact Costs Generated by Pavement Rehabilitation, Maintenance and Other Roadway Reconstruction Projects*. Final Report, September 2018, Auburn, Ala.

Li, H., J. Harvey, and D. Jones. Cooling Effect of Permeable Asphalt Pavement under Dry and Wet Conditions. *Transportation Research Record: Journal of the Transportation Research Board, No. 2372*, Transportation Research Board of the National Academies, Washington, D.C., 2013, pp. 97—107.

Li, H., J. Harvey, Y. He, Z. Chen, and P. Li. Pavement Treatment Practices and Dynamic Albedo Change in Urban Pavement Network in California. *Transportation Research Record: Journal of the Transportation Research Board, No. 2523*, Transportation Research Board of the National Academies, Washington, D.C., 2015, pp. 145—155.

Li, H., J. Harvey, and D. Jones. Development and Preliminary Validation of Integrated Local Microclimate Model for Numerical Evaluation of Cool Pavement Strategies. *Transportation Research Record: Journal of the Transportation Research Board, No. 2444*, Transportation Research Board of the National Academies, 2014, pp. 151—164.

Li, X., Z. Zhou, X. Deng, and Z. You. Flame Resistance of Asphalt Mixtures with Flame Retardants through a Comprehensive Testing Program. *Journal of Materials in Civil Engineering*, Vol. 29, No. 4, 2017, https://doi.org/10.1061/(ASCE)MT.1943-5533.0001788.

Liu, X., S. Rees, and J. Spitler. Modeling Snow Melting on Heated Pavement Surfaces. Part I: Model Development. *Applied Thermal Engineering*, Vol. 27, 2007, pp. 1115—1124.

Liu, X., S. Rees, and J. Spitler. Modeling Snow Melting on Heated Pavement Surfaces. Part II: Experimental Validation. *Applied Thermal Engineering*, Vol. 27, 2007, pp. 1125—1131.

Mallick, R. B., J. M. Jacobs, B. J. Miller, J. S. Daniel, and P. Kirshen. Understanding the Impact of Climate Change on Pavements with CMIP5, System Dynamics and Simulation. *International Journal of Pavement Engineering*, Vol. 19, No.8, 2018, pp. 697—705.

Mallick, R., M. Radzicki, J. Daniel, and J. Jacobs. Use of System Dynamics to Understand Long-Term Impact of Climate Change on Pavement Performance and Maintenance Cost. *Transportation Research Record: Journal of the Transportation Research Board, No. 2455*, Transportation Research Board of the National Academies, Washington, D.C., 2014, pp. 1—9.

Mallick, R., M. Tao, J. Daniel, , J. Jacobs, and A. Veeraragavan. Development of a Methodology and a Tool for the Assessment of Vulnerability of Roadways to Flood-Induced Damage. *Journal of Flood Risk Management*, Vol. 10, 2017, pp. 301—313.

Mallick, R., M. Tao, J. Daniel, J. Jacobs, and A. Veeraragavan. Combined Model Framework for Asphalt Pavement Condition Determination after Flooding. *Transportation Research Record: Journal of the Transportation Research Board, No. 2639*, Transportation Research Board of the National Academies, Washington, D.C., 2017, pp. 64—72.

Meagher, W., J. S. Daniel, J. Jacobs, and E. Linder. Method for Evaluating Implications of Climate Change for Design and Performance of Flexible Pavements. *Transportation Research Record:*

Journal of the Transportation Research Board, No. 2395, Transportation Research Board of the National Academies, Washington, D.C., 2012, pp. 111—120.

Mills, B. N., S. L. Tighe, J. Andrey, J. T. Smith, and K. Huen. Climate Change Implications for Flexible Pavement Design and Performance in Southern Canada. *Journal of Transportation Engineering*, Vol. 135, No. 10, 2009, pp.773—782.

National Academies of Sciences, Engineering, and Medicine. *Long-Term Field Performance of Warm Mix Asphalt Technologies*. The National Academies Press, Washington, D.C., 2017. https://doi.org/10.17226/24708.

National Research Council. *Disaster Resilience: A National Imperative.* The National Academies Press, Washington, D.C., 2012.

Newcomb, D. E., R. Willis, and D. H. Timm. *Perpetual Asphalt Pavements: A Synthesis*. Asphalt Pavement Alliance, Lanham, Maryland, 2010.

Nivedya, M., M. Tao, R. Mallick, J. Daniel, and J. Jacobs. A Framework for the Assessment of Contribution of Base Layer Performance towards Resilience of Flexible Pavement Flooding. *International Journal of Pavement Engineering*, 2018, DOI: 10.1080/10298436.2018.1533637.

Pearson, L., P. Newton, and P. Roberts (ed.). *Resilient Sustainable Cities: A Future*. Routledge, Taylor & Francis Group, New York, N.Y., 2014.

Qiao, Y., G. W. Flintsch, A. R. Dawson, and T. Parry. Examining Effects of Climatic Factors on Flexible Pavement Performance and Service Life. *Transportation Research Record: Journal of the Transportation Research Board, No. 2349*, Transportation Research Board of the National Academies, Washington, D.C., 2013, pp. 100—107.

Qiao, Y., R. Medina, L. McCarthy, R. Mallick, and J. Daniel. Decision Tree for Postflooding Roadway Operations. *Transportation Research Record: Journal of the Transportation Research Board, No. 2604,* Transportation Research Board of the National Academies, Washington, D.C., 2017, pp. 120—130.

Rodezno, C., D. H. Timm, M. Robbins, and N. Tran. *Material Selection Guidance for Asphalt*. NCAT Report 18-01, National Center for Asphalt Technology at Auburn University, Auburn, Ala., 2018.

Roshani, A., H. Mirfenderesk, J. Rajapakse, and C. Gallage. Groundwater Table Response to Sea Level Rise and Its Impact on Pavement Structure. *Proceedings of the 9th Annual International Conference of the International Institute for Infrastructure Renewal Reconstruction*, Australia, 2015, pp. 531—539.

Rossen, R., T. Ballestero, K. Houle, D. Heath, and J. Houle. Assessment of Winter Maintenance of Porous Asphalt and Its Function for Chloride Source Control. *Journal of Transportation Engineering*, Vol. 140, No. 2, 2013, https://doi.org/10.1061/(ASCE)TE.1943-5436.0000618.

Santamouris, M., A. Synnefa, and T. Karlessi. Using Advanced Cool Materials in the Urban Built Environment to Mitigate Heat Islands and Improve Thermal Comfort Conditions. *Solar Energy*, Vol. 85, No. 12, 2011, pp. 3085—3102.

Santamouris, M. Using Cool Pavements as a Mitigation Strategy to Fight Urban Heat Island – A Review of the Actual Developments. *Renewable and Sustainable Energy Reviews*, Vol. 26, 2013, pp. 224—240.

State of California. *Cal Fire 2018 Incident Archive*. 2020. https://www.fire.ca.gov/incidents/2018/. Accessed April 3, 2020.

Synnefa, A., T. Karlessi, N. Gaitani, M. Santamouris, D. Assimakopoulos, and C. Papakatsikas. Experimental Testing of Cool Colored Thin Layer Asphalt and Estimation of Its Potential to Improve the Urban Microclimate. *Building and Environment*, Vol. 46, 2011, pp. 38—44.

Sen, S., and J. Roesler. Aging Albedo Model for Asphalt Pavement Surfaces. *Journal of Cleaner Production*, Vol. 117, 2016, pp. 169—175.

Stempihar, J., T. Pourshams-Manzouri, K., Kaloush, and M. Rodezno. Porous Asphalt Pavement Temperature Effects for Urban Heat Island Analysis. *Transportation Research Record: Journal of the Transportation Research Board, No. 2293*, Transportation Research Board of the National Academies, Washington, D.C., 2012, pp. 123—130.

Tran, N., B., Powell, H. Marks, R. West, and A. Kvasnak. Strategies for Design and Construction of High-Reflectance Asphalt Pavements. *Transportation Research Record: Journal of the Transportation Research Board, No. 2098,* Transportation Research Board of the National Academies, Washington D.C., 2009, pp. 124—130.

Tsoka, S., T. Theodosiou, K. Tsikaloudaki, and F. Flourentzou. Modeling the Performance of Cool Pavements and the Effect of Their Aging on Outdoor Surface and Air Temperatures. *Sustainable Cities and Society*, Vol. 42, 2018, pp. 276—288.

United States Geological Service. *How Much Distance Does A Degree, Minute and Second Cover on Your Maps*? https://www.usgs.gov/faqs/how-much-distance-does-a-degree-minute-and-second-cover-your-maps?qt-news_science_products=0#qt-news_science_products. Accessed April 2, 2020.

Valle, O., Y. Qiao, E. Dave, and W. Mo. Life Cycle Assessment of Pavements Under a Changing Climate. *Pavement Life-Cycle-Assessment: Proceedings of the Symposium on Life-Cycle Assessment of Pavements*, Champaign, Ill., 2017.

Wang, Y., Y. Huang, W. Rattanachot, K. Lau, and S. Suwansawas. Improvement of Pavement Design and Management for More Frequent Flooding Caused by Climate Change. *Advances in Structural Engineering*, Vol. 18, No. 4, 2015, pp. 487—496.

Wayne, G. P. *The Beginners Guide to Representative Concentration Pathways*. Skeptical Science. 2013, https://denning.atmos.colostate.edu/ats760/Readings/RCP_Guide.pdf.

Schwartz, C. W., and K. D. Hall. *Structural Design Guidelines for Porous Asphalt Pavements*. Information Series 140. National Asphalt Pavement Association. Lanham, MD, 2018.

Scripps Institution of Oceanography. *Downscaled CMIP3 and CMIP 5 Climate and Hydrology Projections*. https://gdo-dcp.ucllnl.org/downscaled_cmip_projections/. Accessed April 2, 2020.

Sikes Asphalt. *How Do Wildfires Affect Asphalt Roads*? 2018. https://sikesasphalt.com/posts/how-do-wildfires-affect-asphalt-roads/.

Yu, B., and Q. Lu. Estimation of Albedo Effect in Pavement Life Cycle Assessment. *Journal of Cleaner Production*, Vol. 64, 2014, pp. 306—309.

Weiss, P. T., M. Kayhanian, J. S. Gulliver, and L. Khazanovich. Permeable Pavement in Northern North American Urban Areas: Research Review and Knowledge Gaps. *International Journal of Pavement Engineering*, Vol. 20, No. 2, 2019, pp. 143—162.

Xiao, F., R. Guo, and J. Wang. Flame Retardant and Its Influence on the Performance of Asphalt – A Review. *Construction and Building Materials*, Vol. 212, 2019, pp. 841—861.

Xu, G., X. Chen, S. Zhu, L. Kong, X. Huang, J. Zhao, and T. Ma. Evaluation of Asphalt with Different Combinations of Fire Retardants. *Materials*, Vol. 12, No. 8, 2019, Article 1283.

Zhang, Y., F. Gu, X. Luo, B. Birgisson, and R. Lytton. Modeling Stress-Dependent Anisotropic Elastoplastic Unbound Granular Base in Flexible Pavements. *Transportation Research Record: Journal of the Transportation Research Board, No. 2672*, Transportation Research Board of the National Academies, Washington, D.C., 2018, pp. 46—56.

Zhang, Z., Z. Wu, M. Martinez, and K. Gaspard. Pavement Structures Damage Caused by Hurricane Katrina Flooding. *Journal of Geotechnical and Geoenvironmental Engineering*, Vol. 134, No. 5, 2008, pp. 633—643.

APPENDIX

A.1 Workshop Goals and Objectives

On September 10-11, 2019 the National Center for Asphalt Technology hosted a workshop that brought together contractors, asphalt pavement associations, agencies, and academics to define and discuss resilience as it relates to asphalt pavements. Table A1 provides participant names and affiliations:

Table A1. Workshop Participants by Group

Academic	Contractor / Asphalt Pavement Association	Agency	NAPA / Consultant / Industry
Benjamin Bowers Auburn University	Charlie Goodhart Pennsylvania Asphalt Pavement Association	Heather Dylla FHWA	Joseph Shacat NAPA
Jo Sias University of New Hampshire	John Hickey Oregon Asphalt Pavement Association	Stephen Olmsted Arizona DOT	Ester Magorka NAPA
Jon Epps Texas Transportation Institute	Kevin Wall Anderson Columbia	Rob Kafalenos FHWA	Robert Horan Asphalt Institute
Rajib Mallick Worcester Polytechnic Institute	Ron Sines CRH	Julia Bond Harris County, TX	Amanda Gilliland The Transtec Group
Karol Kowalski Warsaw Institute of Technology	Jason Fender Knife River	Melissa Savage AASHTO	Carter Ross NAPA
	Bill Rosener Asphalt Pavement Association of Iowa	Grace Tsai Harris County, TX	Amy Miller Asphalt Pavement Alliance

The following subsections summarize the key points, ideas, and conclusions from each of the presentations and breakout sessions.

A.2 Topic 1: Introduction to Resilience as it Relates to Pavements – Dr. Jon Epps, Texas Transportation Institute

Dr. Epps introduced resilience as it relates to pavements and discussed the difference between resilience and adaptation. Resilience was defined as “the ability to anticipate, prepare for, and adapt to changing conditions and withstand, respond to, and recover rapidly from disruptions.” Adaptation was defined as the “adjustment in natural or human systems in anticipation of or response to a changing environment in a way that effectively uses beneficial opportunities or reduces negative impacts” (Epps 2019). Table A2 shows the conditions for which we need to be adapting that were listed by Dr. Epps and also provided by the group during discussion.

Table A2. Presented and Discussed Adaptation Needs (Epps 2019)

Dr. Epps Presentation	Group Discussion
Extreme weather Earthquakes Fires Destruction associated with conflict	Population increases Increased traffic Contractor availability Regulatory issues* Drought/flood impacts on freight movement

*Regulatory issues referred to the ability to adapt quickly while waiving/working through regulatory requirements

The ability to withstand, respond to, and recover from disruptions is another key element of resilience. This may include the hardening of infrastructure to *withstand* extreme events, the ability to *respond* quickly (short term), and the long-term *recovery* of the asset. These tenets of resilience to disruption naturally lead to the need to incorporate resilience into asset planning and decision making as they relate directly and influence public safety, capital costs, and maintenance costs.

Climate change is already affecting our roadway network. Key discussion points on climate impacts were focused around temperature, precipitation, droughts, floods, and wildfires, as well as extreme events, arctic changes, and sea level. Some of these are acute impacts, such as an extreme event, while others may occur slowly over time, such as sea level rise and subsequent flooding impacts. The following pavement impacts were presented and discussed by the group: permanent deformation of pavements; more frequent freeze/thaw cycles; permafrost impacts; inundation of pavements; subgrade support decrease; pavement materials strength decrease; drought and subsequently more longitudinal cracking; age hardening of pavement materials; water susceptibility of pavement materials; impacts on construction, rehabilitation, and maintenance scheduling. The impact of these items on our pavement thickness design methodology was also discussed (Epps 2019).

A.3 Topic 2: Designing Pavements for Resilience and Climate Change – Dr. Jo Sias, University of New Hampshire

Dr. Jo Sias of the University of New Hampshire introduced the group to the Infrastructure Climate Network (ICNet), a National Science Foundation supported network that focuses on climate change impacts on transportation infrastructure and networks in the Northeastern United States (ICNet, 2020).

Dr. Sias also discussed the fact that sea level rise will cause groundwater to rise, potentially into the pavement structure where it was not considered during design. This is potentially an issue for inland streams and rivers as well.

Dr. Sias provided an example of how to design a climate-ready coastal road. Work by Bhave et al. (2013) where three methods by which we may approach adaptation was presented: top-down, bottom-up, and integrated. In the top-down method, climate scenarios are considered, validated, an assessment of prioritized options is made, and ultimately, suitable adaptation options for a project are selected. The bottom-up methodology begins with stakeholder involvement to provide key qualitative information, adaptation options are then identified, and finally they are prioritized. The integrated method is where the prioritized adaptation options from the bottom-up approach meet the assessment of prioritized options in the top-down approach, ultimately leading to a suitable adaptation option. Using this integrated method, Sias laid out the following steps for the design of a resilient coastal road (Sias 2019).

1. Involve stakeholders;
2. Identify adaptation options for evaluation;
3. Define performance metric(s);
4. Choose asset or system model(s);
5. Develop a Pavement Climate Sensitivity Catalog (PCSC) to determine the pavement's sensitivity to changes in climate parameters;
6. Choose climate change scenarios;
7. Use output from downscaled climate models to determine the timing of adaptation actions;
8. Create an adaptation pathways map and scorecard; and
9. Recommend a staged adaptation plan based on performance and cost.

Two additional major points of discussion in this presentation were climate science data and its application to engineering design problems and the implementation of climate modeling on a design level when necessary. Dr. Sias noted that bridge engineers are interested in 3-second wind gusts for design applications, but climate science data does not yield that level of resolution. Dr. Sias provided insight into the different levels of climate projects: global climate models (which include the ocean and atmosphere) provide a relatively coarse resolution; regional climate models use the global models and bring a finer, more regional resolution into play; finally, regional models are downscaled to a particular grid or weather station. It was highlighted that although models often agree historically, there is a range of possible future scenarios that each model can project. Dr. Sias made the point that we don't necessarily need to incorporate quantitative climate projections into our design methodology, we simply need to know what issues are coming and prepare for them (Sias 2019). Like pavement models, climate models are continuing to change as the science continues to develop. Policy needs to be discussed and disseminated both at the federal and state levels.

A.4 Breakout Session 1: Defining Resilience

The first breakout group was focused on defining resilience. Four groups were formed, each combining the perspectives of academia, agency, contractor, asphalt pavement association, and engineering design consultant. The following definitions were provided: "*The ability to prepare and plan for, absorb, recover from, or more successfully adapt to actual or potential adverse events.*" from the National Research Council (2012) and *"The ability to anticipate, prepare for, and adapt to changing conditions and withstand, respond to, and recover rapidly from disruptions."* from the Federal Highway Administration (2014). Groups were asked to discuss the following questions: 1) Do these definitions have anything missing? and 2) How might these be shaped as they relate to asphalt pavement?

Generally, all groups thought that there was nothing significant missing or that needed to be added to the definitions, and the FHWA definition was agreed upon as the best working definition for the remainder of the workshop. The group generally agreed that no specific definition was needed to define resilient pavements, but that the broad definition provided by FHWA and other similar infrastructure related organizations adequately cover the needs of pavements.

The question was asked if cost effective, economically sustainable, and short term versus long term recovery should be incorporated in some way. It was also noted that the Latin root of the word resilience is to "spring back", which is to say to "return to normal" after an event. They went on to inquire what the best way to quantify infrastructure resilience after an event is.

Feedback on question 2 spoke with specificity to the different aspects of resilience (prepare, withstand, recover) and how asphalt pavement may fit within each of those. Table A3 provides examples given by the groups of what each of these may look like as they relate to asphalt pavements.

Table A3. Examples of Resilient Attributes of Asphalt Pavement

Prepare and Adapt	Withstand and Recover
Perpetual pavement design	Fast construction
Adaptable materials for climate extremes	No cure time, open to traffic almost immediately
Porous asphalt systems	Resilient designs to protect critical corridors
Integrate resilience adaptations into long term maintenance schedules	Recyclable (e.g., crushing old, "failed" roadways and reusing)

A.5 Topic 3: Introduction to FHWA Resilience Programs and Work in Progress – Dr. Heather Dylla and Robert Kafalenos, Federal Highway Administration

Dr. Heather Dylla of the FHWA Office of Infrastructure and Robert Kafalenos of the FHWA Office of the Natural Environment provided an overview of pavement resilience initiatives within FHWA. Dr. Dylla and Mr. Kafalenos pointed out that resilience is critical to protect public safety, reduces life-cycle expenditures, and is included in the USDOT 2018-2022 Strategic Plan which states, "DOT will increase its effectiveness in ensuring that infrastructure is resilient enough to withstand extreme weather" (Dylla and Kafalanos 2019). The question of integrating resilience into transportation decision making is also one that needs to be addressed and should be incorporated into the planning, project level, and operations and maintenance phases of the system.

FHWA has multiple tools either deployed or under development for highway agencies and researchers alike for assistance in resilient design considerations. The first is the aforementioned CMIP Data Processing Tool which can be used to collect and utilize relevant temperature and precipitation data from climate models. Another tool discussed is the Vulnerability Assessment and Adaptation Framework, third edition. This tool provides a structured process for conducting a vulnerability assessment and includes example assessments. The FHWA has sponsored 11 ongoing resilience pilots around the United States. There is also a forthcoming Pavement Resiliency Guidebook from FHWA's Sustainable

Pavements Program, which is expected in 2021. Additional resources can be found online at the FHWA resilience website (FHWA, 2020).

A.6 Topic 4: Resilience at AASHTO – Melissa Savage, AASHTO

Melissa Savage, Director of the Center for Environmental Excellence at AASHTO, provided an overview of their efforts to address resilience. To begin, AASHTO has adopted the definition of resilience as “the ability to prepare and plan for, absorb, recover from, or more successfully adapt to adverse events,” which is related to but differs from that of the Federal Highway Administration.

AASHTO sponsored a two-day Resilience Peer Exchange in November 2017, which had participation from 36 states and included keynote presentations and facilitated breakout sessions. The goal of the peer exchange was to gather transportation professionals to discuss how state DOTs are addressing resilience. AASHTO also organized the Resilience Innovations Summit and Exchange (RISE) in October 2018. The goal was to help state agencies better understand how resilience and risk concerns can be factored into decision making. It also created a forum to exchange ideas and strategies for understanding resilience within the various functions of the DOT (Savage 2019).

A.7 Topic 5: Pavement Flooding – Dr. Rajib Mallick, Worcester Polytechnic Institute; Bill Rosener, Asphalt Pavement Association of Iowa

Dr. Rajib Mallick opened up the discussion by providing an overview of the literature as it relates to flooding. The damage to pavements both during and following a flood event due to traffic loading while the subgrade modulus is weak was a point of emphasis. Some discussion was provided around whether or not roadway owners should require that pavements have time to drain prior to traffic loading. One idea provided was that loads could be reduced during the dry back period. Other suggestions were to prevent or seal cracks to reduce water penetration, use a thick aggregate base to help promote drainage, or use drainage fabrics to lower the permeability of the asphalt layer (Mallick 2019).

Mr. Bill Rosener, formerly of the Asphalt Pavement Association of Iowa, presented a case study of the Iowa flood events from March and May of 2019. These events shut down sections of interstate in Iowa. This case study is discussed in further detail in Section 5.1 of this report.

A.8 Topic 6: Hurricane Response – Kevin Wall, Anderson Columbia

Coastal highways are subjected to unique loads when hurricanes come ashore. Mr. Kevin Wall, formerly of Anderson Columbia, provided an overview of the repair work performed after Hurricane Michael (Category 5) made landfall on the Florida Panhandle in 2018. The specific project was in Franklin County on State Route 30 (US-98). Water encroaching on the road, and specifically wave action, were discussed as a major cause of damage. In this scenario, the waves break over the edge of the pavement repeatedly, while the structure beneath the surface is subjected to scour potential. As a demonstration of the hurricane’s might, riprap was moved to the other side of the road in the case presented. Wall emphasized the devastation of the area with descriptions of the level of debris and the lack of essential utilities such as water and power. The railroad lines were shut down due to the storm, so aggregate could not be easily received for HMA production. To address this, FDOT figured out how many asphalt plants were operational in the panhandle and how many tons of asphalt could be produced and then prioritized routes. Some plants nearest to the coast were partially destroyed, so in some cases there was approximately a 150-mile haul distance for the HMA to reach the location of the project (Wall, 2019).

FIGURE A1. Hurricane Damage as A Result of Hurricane Michael on State Route 30 (US-98) in Franklin County Florida (*Photo Credit Kevin Wall, Anderson Columbia*)

The allocation of recovery funding was a point of much discussion. There is general confusion amongst contractors and agencies about funding sources and capabilities. The looming question is whether or not emergency funds used to reconstruct a roadway or other form of infrastructure can be used to “upgrade” the infrastructure to make it more resilient, or if it must be used to replace the road to its condition before the event. In some cases, it is to be replaced to its previous condition; in other cases, it can be upgraded to the current code or design requirements. An additional question that must be answered is how resilience is quantified to determine what the resilient solution is for any given roadway and/or infrastructure.

A.9 Topic 7: "People's Choice" – Asphalt Plants and Operations

There was also an opportunity for individuals to discuss and share experiences on resilience related topics of interest. Important discussions arose around the benefits of having portable asphalt plants in certain situations (e.g., where disasters destroy roadway access in remote or rural areas). Further, there was discussion about asphalt plant resilience, namely what are contractors doing to make their plants resilient to extreme events. Best practices included:

- Know which plants are vulnerable to natural disasters and consider communicating that with the local agency for planning purposes;
- Seek clarity and solutions regarding fuel source regulations if the original fuel source is no longer available due to a disaster;
- Building of a temporary dike (e.g., using RAP) around the plant in preparation of an expected flood event; and
- Elevate control units and other critical components to keep them out of flood waters.

A.10 Topic 8: Arizona DOT Infrastructure Resilience, Asset Management, Extreme Weather, and Climate Trends: Blending Risk / Science / Technology / Engineering – Steve Olmsted, Arizona DOT

In 2015, the Arizona Department of Transportation began a resilience program charged with developing a "programmatic approach to addressing all aspects of weather and natural hazards – including extreme weather and future measurable climate trends" (ADOT 2020). The program states that the challenge to public entities is to "continue considering the balance between predictable asset deterioration curves, the sudden and unpredictable nature of extreme weather events and long-term climate trends, new models for risk assessment and lifecycle cost analysis, and appropriate adaptation strategies" (ADOT 2020).

Steve Olmsted, NEPA Assignment Manager in Environmental Planning at the Arizona DOT, presented on their approach to resilience. It was emphasized that ADOT is approaching resilience with an asset management mindset and deals with numerous extreme climate-related events, from wildfires and extreme heat to intense precipitation and flooding. ADOT worked with the FHWA to conduct a vulnerability assessment and has looked at ways to incorporate climate change into their planning process. While ADOT isn't making planning or design decisions based on climate impacts at the time of publication, they are investigating the potential impacts of climate on their planning and design processes.

Areas where ADOT has made progress are the development climate inputs including average and extreme temperature as well as precipitation for design using the CMIP databases, building a resilience Global Information Systems (GIS) database (over 500 nuisance logs have been input by ADOT engineers and maintenance districts), and work on developing links between extreme weather, climate, and asset management (Olmsted 2019).

A.11 Topic 9: How Resilience Might Be Added to Project Scope / Requirements – Amanda Gilliland, The Transtec Group

As a consultant, it is important to consider how resilience may be built into future project scopes and requirements. Amanda Gilliland of The Transtec Group provided some insight into how this might occur. While a resilience context was not necessarily being directly used in design as of yet, Gilliland postulated that perhaps it was being used but just not called resilience. An example that was provided is traffic and projected growth as used in design, the idea being that pavements are designed to be “resilient” to traffic loading. An idea that was introduced is the concept of building risk factors for roadways, similar to that done for structures (e.g., building design codes for hospitals are more stringent than commercial properties) as a way to build more resilient roads. There are currently no standards or design codes that provide guidance or direction on how to build resilient roadways using this concept.

Gilliland then provided insights into what Alaska has done to combat an extreme environment where earthquakes and seasonal flooding is common. This includes hardening of infrastructure to withstand loading as well as strong agency and contractor communication channels, which is a form of community resilience.

Gilliland also discussed a project on the Alaska North Slope where a bridge and section of roadway were designed to be submerged for a short period of time each year during the spring thaw. This concept is less expensive than building an elevated structure but comes with the tradeoff that there will be some predicted local inconvenience each year (Gilliland, 2019).