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Best practices and promising technologies that can be used now to enhance concrete paving

Climate Change, Resilience, and Concrete Pavements

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Climate Change, Resilience, and Concrete Pavements

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Introduction

Roadways, airfields, ports, and other forms of transportation infrastructure are vitally important to economic activity and daily life in the United States. Pavements are critical to nearly all of these modes of transportation, providing smooth, consistent surfaces for travel that help the public get where it needs to go and that connect communities, businesses, and markets. During and after emergencies, pavements also provide access for first responders and disaster recovery efforts.

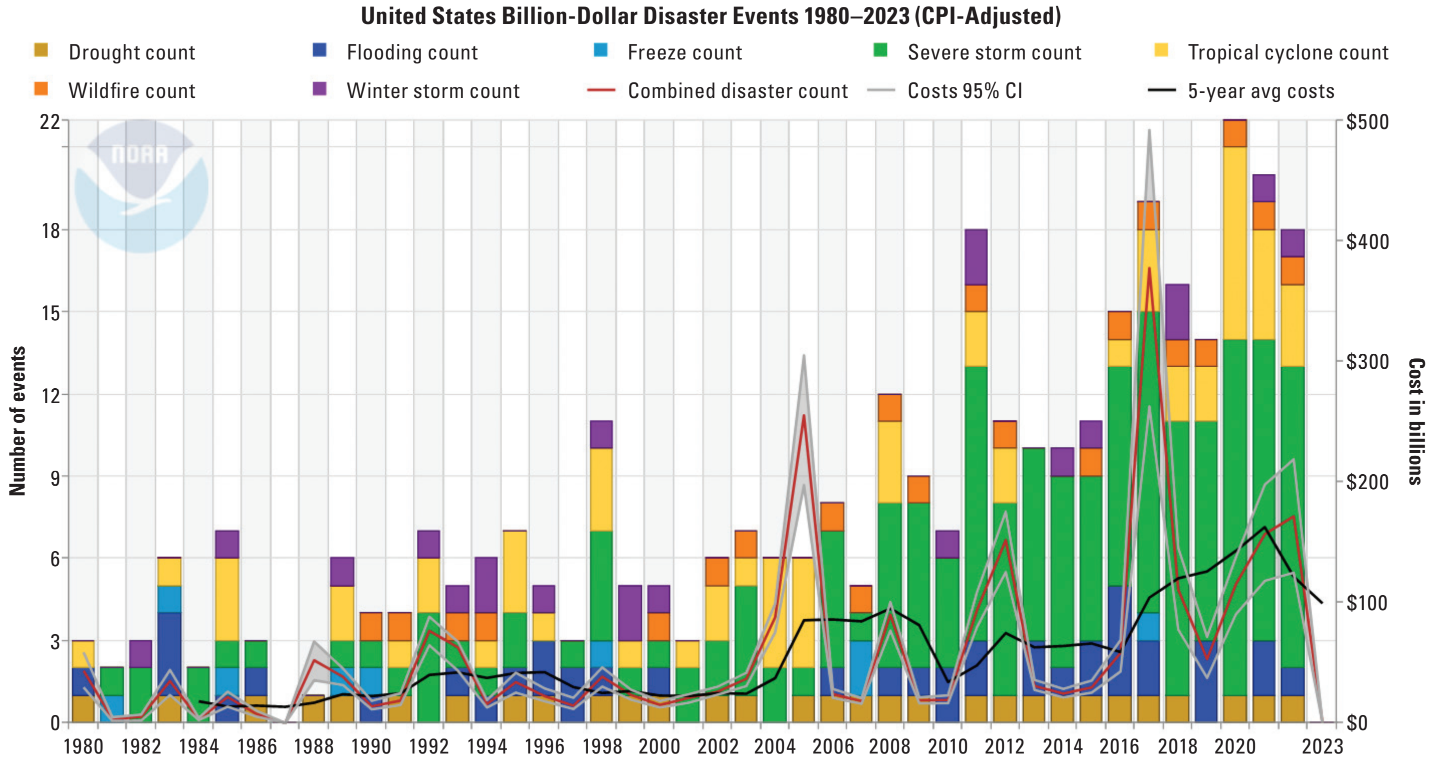
Pavements must be designed to carry a wide variety of traffic loads and, since they are continuously exposed to the elements, to hold up in a wide range of seasonal and climatic conditions. Significant investment is needed to build and maintain a safe, reliable pavement network, and the United States spends more than $200 billion each year on public highway and aviation infrastructure (CBO 2018). Even at these funding levels, however, significant additional funding is needed to improve pavement condition and functional capacity. On roadways alone, the American Society of Civil Engineers (ASCE) estimates that the United States has a backlog of more than $400 billion in repairs and $200 billion in needed capacity and enhancements (ASCE 2021). In the future, population growth and increasing urbanization and international trade are projected to place even greater demands on pavements in all transportation modes (Jacobs et al. 2018).

Climate Challenges for Pavements

On top of these existing challenges, the effects of climate change are also poised to have significant and costly impacts on the US pavement network. The most immediate effects of climate change are already being felt today through the increased frequency of natural hazards and disaster events. As seen in Figure 1, these types of events have become increasingly common in recent decades. In the United States alone, the number of climate and weather disasters that cause more than $1 billion in economic losses (adjusted for inflation) has increased from an average of three per year in the 1980s to an average of 18 per year in the last five years ending in 2022 (NOAA 2023).

Extreme weather can be highly disruptive to roadways, airfields, and other transportation facilities. Pavements may be closed when hazards make them impassible, and they sometimes require immediate repairs before they can be re-opened to traffic. Even when they remain intact, pavements may become more susceptible to damage during the disaster response and recovery phases of an event. Some of the most critical weather and climate hazards for pavements include the following:

- More frequent and intense rainfall events and riverine flooding can close roadways or airfields for days or months at a time, and resulting washouts or mudslides can cause acute damage to pavements that requires immediate repairs before re-opening to traffic (Jacobs et al. 2018, Lu et al. 2018).



Recreated from National Oceanic and Atmospheric Administration (NOAA 2023)

Figure 1. Annual disaster events categorized by type

- Storm surge and flood events during hurricanes and coastal storms can inundate and close pavements and are increasingly exacerbated by sea level rise (Jacobs et al. 2018).
- Floods can weaken pavement subgrade and subbase layers for extended periods as water subsides, leaving them prone to damage during the immediate response to the storm as well as after the return of normal traffic (Tye and Giovannettone 2021).
- Heat waves and drought can cause buckling in concrete pavements and accelerate rutting damage in asphalt pavements (Tye and Giovannettone 2021).
- Wildfires can close roadways and lead to debris flows that can cause obstructions and increase the susceptibility of nearby pavements to future flooding events (Jacobs et al. 2018).

In addition to these immediate stressors, other aspects of climate change will be felt gradually and require medium- to long-term changes to pavement design practices and material usage (Tye and Giovannettone 2021). Some of the more gradual impacts of climate change include the following:

- Rising average annual temperatures may require accommodations to allow for more thermal expansion in concrete slabs as well as changes to binder grade selection in asphalt pavements. By some estimates, changes to asphalt binder grades that will be needed due to climate change could add around $19 billion to US pavement costs by 2040 (Underwood et al. 2017).
- Changes to the number of freeze-thaw cycles could necessitate adjustments to paving material specifications as well as mix design practices to ensure freeze-thaw durability (Tye and Giovannettone 2021).
- Variations in precipitation patterns could require changes to the design of drainage structures as well as to subbase and subgrade design (Tye and Giovannettone 2021)
- Rising sea levels could cause high tide flooding of roadways and airfields in low-lying coastal regions. In addition to the day-to-day disruptions caused by flooding, continuous inundation of the pavement can weaken subgrade and subbase layers and accelerate deterioration under loading (Jacobs et al. 2018).
- Sea level rise could also raise the groundwater table inland from the coasts. A rising groundwater table can lead to continuous saturation of subgrade and subbase layers, weakening the foundation layers even for pavements that do not experience flooding over the top of the surface (Knott et al. 2017).

The risks posed by climate change have the potential to cause major disruptions and damage to the nation's pavement infrastructure. The costs to repair and restore serviceability to pavements affected by climate and extreme weather can be significant, and they loom increasingly large at a time when the United States is already struggling to meet the existing and projected future needs of its pavement users.

To address these growing climate challenges, federal, state, and local agencies are increasingly focused on improving the resilience of vulnerable pavements.

Resilience

The Federal Highway Administration (FHWA) defines resilience as the ability to anticipate, prepare for, and adapt to changing conditions and withstand, respond to, and recover rapidly from disruptions (FHWA 2014). Improving the resilience of an asset or system does not mean designing it to be impervious to damage or disruption from any possible event. Instead, resilient systems are designed to do the following:

- Reduce the probability of a negative shock
- Absorb pressure without collapsing if a shock occurs
- Limit the amount of time needed to recover and restore functionality to the system

Greater public attention on climate-related issues in recent years has led state and local governments to begin incorporating resilience into their decision-making, including for their transportation infrastructure (Jacobs et al. 2018). Even more directly relevant to pavements, federal legislation passed in 2021 and 2022 includes significant funding to support resilient design objectives in highway and airfield projects.

Many agencies may first perform a vulnerability assessment as they begin to integrate resilience into their planning. In a climate context, the vulnerability of an asset or system may be defined as its exposure to climate and weather events, its susceptibility to damage from those events, and its adaptive capacity, or ability to withstand the impacts (Filosa et al. 2017).

In addition to vulnerability, agencies can also use this information to quantify risks to the system. Figure 2 illustrates a common characterization of risk as the combination of the probability that an extreme event will occur and the severity of the event's potential consequences (Filosa et al. 2017, Lu et al. 2018). Quantification of risk can also incorporate asset values and the costs of potential impacts to the system (Lu et al. 2018).

A vulnerability assessment begins with data collection on the asset(s) of interest and future climate projections for the region of study. From there, agencies can use a number of methodologies to test the probability of different climate and weather hazards and their impact on the performance and design life of the affected asset(s) (Filosa et al. 2017, Tye and Giovannettone 2021). Combined with an estimate of the costs of the various possible levels of damage, the overall risk posed by climate change to a given asset or system may be quantified (Lu et al. 2018).

After characterizing the risks to a given asset or system, agencies can analyze potential adaptation measures to improve its resilience using qualitative and quantitative methods, such as a cost-benefit analysis or life-cycle cost analysis (LCCA).

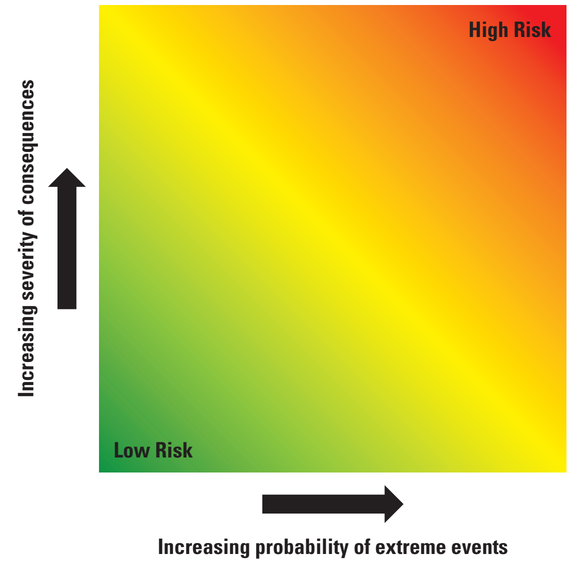


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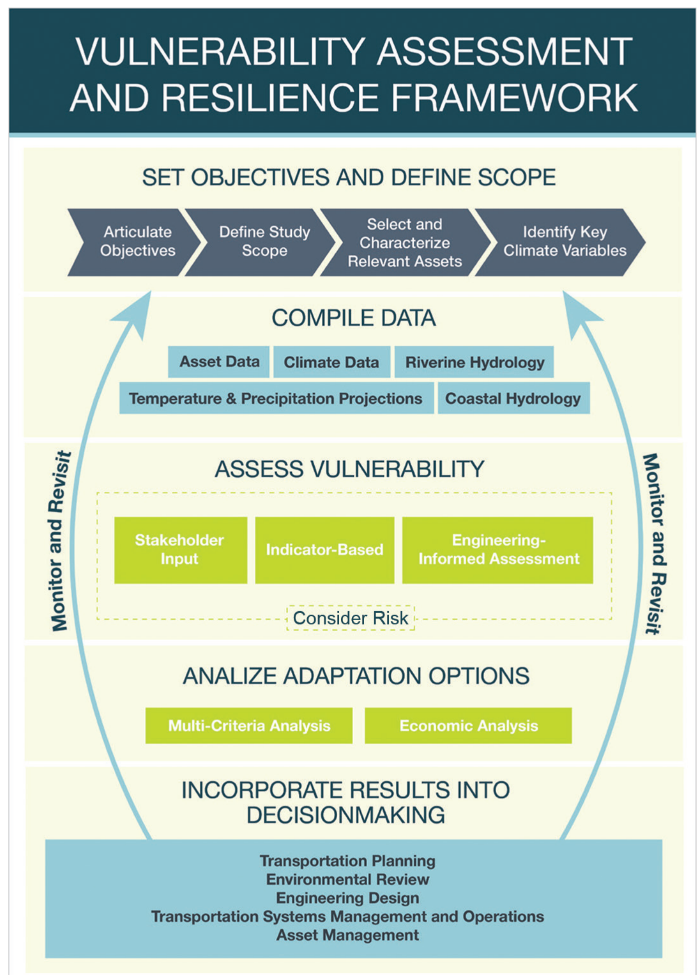
Figure 2. Quantification of risks due to extreme events



Filosa et al. 2017

Figure 3. Illustrated vulnerability assessment and adaptation framework

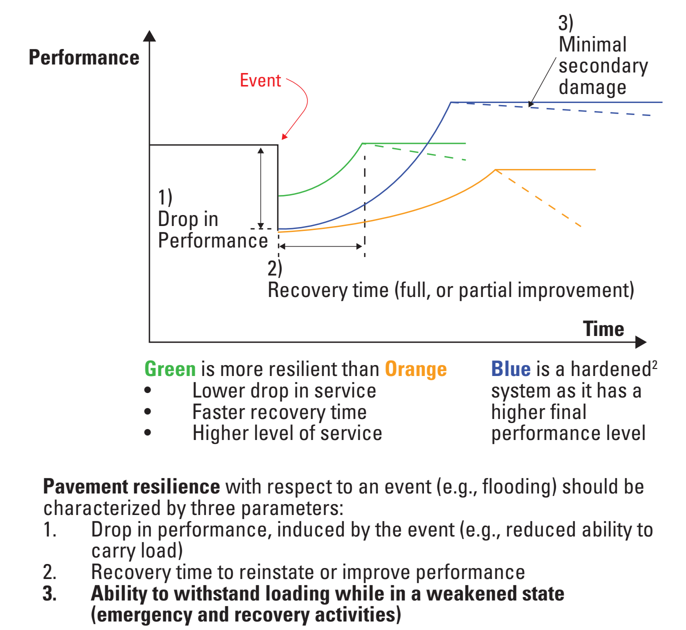
Stakeholders may then use these results to inform planning or decision-making processes. Figure 3 illustrates this process as outlined in the FHWA publication *Vulnerability Assessment and Adaptation Framework* (Filosa et al. 2017).

Frameworks for Improving Pavement Resilience

The FHWA's framework (Filosa et al. 2017) provides guidance on different methodologies for assessing vulnerability and risk and analyzing adaptation options. Agencies can adopt these methods as part of an overall framework to improve the resilience of all types of transportation infrastructure assets, including pavements (Filosa et al. 2017). Other frameworks have been established for specific cases, including one developed by Mack et al. (2022) for improving pavement resilience.

As noted above, one essential aspect of pavements is their role in supporting first responders and relief efforts after disasters. Therefore, pavements are not just vulnerable to immediate disruption and damage from a hazard, but also to secondary impacts during the response and recovery phases of a disaster. During these stages, emergency response traffic may subject pavements to loading when they are still in a weakened state due to the original hazard (Mack et al. 2022). Secondary damage can also occur when a pavement is slow to recover to its initial level of performance but regular traffic loads have returned, such as after long-term inundation from a major flooding event.

To account for secondary impacts, Mack et al. (2022) proposed a modified resilience framework for pavements, which is presented in Figure 4. Like most models, the framework accounts for the initial drop in performance of the system in the immediate wake of a disruption and the time to fully or partially recover to the previous level of performance. The dashed lines in Figure 4 indicate secondary damage, a decrease in performance after the system has recovered from the initial disruption but is still in a weakened state.



Recreated from Jim Mack, used with permission

Figure 4. Resilience framework for pavements

Figure 4 illustrates that a more resilient pavement experiences a lower drop in service after a shock, recovers more quickly to its previous level of functionality, and will be less susceptible to secondary damage, preventing further deterioration or reduction in service life. This framework can guide agencies as they evaluate the vulnerability of their existing pavements and consider adaptation measures for improving resilience. Like other frameworks, it can be used to analyze the resilience of individual pavement assets as well the resilience of a wider pavement network.

In addition, the blue line in Figure 4 demonstrates the potential benefits of a hardened pavement system. Adaptive capacity is built into a hardened pavement to raise its overall performance. Building additional capacity into the pavement can reduce the drop in performance during future hazards and mitigate the potential for secondary damage afterwards (Mack et al. 2022). The costs and benefits of adding capacity can be analyzed as an adaptation option during a vulnerability assessment, as illustrated in Figure 3.

Concrete Pavements as a Resilient Solution

All types of pavements will require adaptations to become more resilient to climate and extreme weather impacts, and concrete pavements are no exception. Various aspects of structural design, materials selection, and construction practices can be adjusted, depending on local conditions, to account for the changing climate. Some of these changes for concrete pavements may include the following:

- Adopting principles of performance-engineered mixtures in concrete pavement mix design to ensure that pavements remain durable in the face of changes to seasonal temperatures, precipitation patterns, and the number of freeze-thaw cycles
- Using a shorter joint spacing design and changing joint filling and sealing practices to accommodate increasing temperature and moisture gradients, which drive curling and warping behavior, and to accommodate increased thermal expansion from higher average and extreme temperatures, which can cause buckling (Dylla and Hyman 2018)
- Raising the elevation of the pavement and/or using roadside elements such as articulated concrete block (ACB) systems to line embankments to increase resistance to washout during extreme rainfall and flooding events (Mack et al. 2022)

These and other changes to current practices will ensure that concrete pavements are resilient to the impacts of climate change. If these adaptations can be achieved, concrete pavements are very well-suited to handle increasing user demands in a changing world and climate. In fact, concrete pavements may be able to serve as a resilient pavement solution in situations where other pavements cannot be easily adapted to certain climate impacts. In particular, concrete pavements offer significant resilience against the effects of flooding and inundation.

Impacts of Flooding and Inundation on Pavement Foundations

As previously mentioned, even if pavements remain intact after extreme rainfall and flooding events, inundation of subgrade and subbase layers weakens the foundation and increases susceptibility to damage from traffic loadings. Additionally, as sea levels rise, the groundwater table will also rise and threaten to continuously saturate and weaken pavement foundations, even when the surface does not flood (Knott et al. 2017, Jacobs et al. 2018).

Given their important role in disaster recovery and in everyday life, pavements will inevitably be re-opened to traffic before their foundation layers have fully recovered from flooding. In fact, the impacts of inundation on the strength of foundation layers have been found to persist for months after a single flooding event. In coastal areas, pavements will remain in service while their foundations are continuously saturated by the rising groundwater table.

Overall, flooding can significantly reduce the strength of the subgrade. After Hurricane Katrina struck New Orleans in 2005, researchers found that the subgrade resilient moduli of pavements that flooded during the storm declined by up to 25% compared to pre-storm conditions and remained lower four months later than pavements that did not flood (Gaspard et al. 2007, Zhang et al. 2008). In another study of a pavement in Florida that flooded after Hurricane Irma in 2017, subgrade resilient modulus declined by 32% to 36% after the storm. Even after floodwaters receded from the roadway, the water table did not return to its pre-storm level for about five months. While the foundation eventually began to recover, subgrade strengths measured six months after the storm were still 30% lower than pre-flood conditions (Gundla et al. 2020).

Rigid versus Flexible Pavement Response to Flooding and Inundation

Fundamental differences between flexible (asphalt) and rigid (concrete) pavements cause these types of pavements to be impacted by flooding and inundation differently. One of the key distinguishing features between rigid and flexible pavements is how they transfer traffic loads to underlying layers, including the subgrade and base and subbase courses. Concrete has a high modulus of elasticity and distributes loads to the foundation over a wide area, so stresses in rigid pavements are not especially sensitive to the strength of underlying layers. In comparison, because asphalt is more elastic than concrete, more concentrated loads are transmitted to the underlying layers of a flexible pavement. As a result, stresses in flexible pavements are more sensitive to the strength of the base, subbase, and subgrade (Huang 2003). Figure 5 depicts loading behavior for both pavement types.

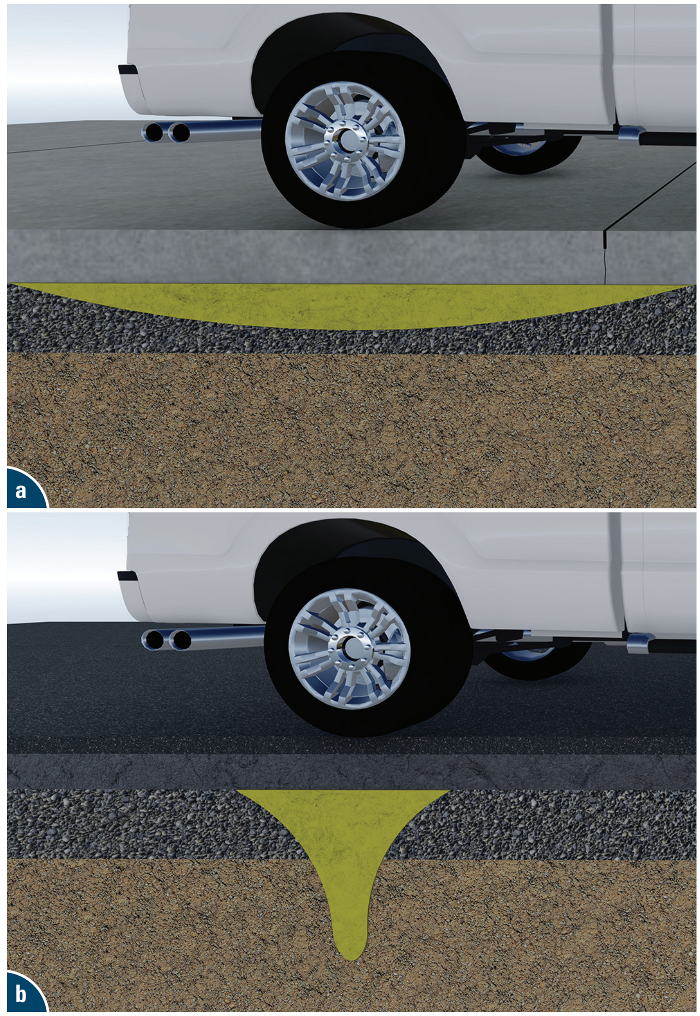


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Figure 5. (a) Rigid versus (b) flexible pavement structural response

Given the sensitivity of pavement response to the strength of the foundation layers, several studies have demonstrated significant performance impacts caused by loading during and after inundation. In New Orleans, researchers determined that the effects of inundation on the structural capacity of flexible pavements flooded by Hurricane Katrina were equivalent to reducing the thickness of the asphalt surface layer by two inches (Gaspard et al. 2007, Zhang et al. 2008). Mack et al. (2022) determined that an asphalt pavement in Florida flooded by Hurricane Irma saw its load carrying capacity reduced by 40% to 60% in the wake of the storm.

As noted above, these potential impacts are not limited to just extreme weather events. Modeling by Knott et al. (2017) found that a rising water table due to sea level rise could reduce the fatigue life of vulnerable asphalt pavements located significant distances inland by 5% to 17% if the subgrade layer was fully saturated and by up to 50% if the water table rose to penetrate the base layers. Overall, the impacts of flooding and inundation on flexible pavements leave them prone to both primary and secondary damage from loading in a weakened state, with major potential consequences for long-term service life.

Meanwhile, studies have found that concrete pavements do not suffer comparable impacts after flooding events. Researchers in Louisiana found that, in contrast to the asphalt pavements flooded during Hurricane Katrina, concrete pavements that had been flooded did not exhibit any significant damage or loss of strength (Gaspard et al. 2007, Zhang et al. 2008). Researchers in Australia have also observed disparities between the responses of flexible and rigid pavements after major flooding events, finding that concrete pavement was more resilient to inundation of the underlying layers (Khan et al. 2017).

Concrete Pavement Strategies for Improving Resilience

More than 60,000 miles of roadways in the United States lie in coastal regions that are vulnerable to severe storms and sea level rise, and countless further miles of pavements in other regions are vulnerable to river flooding and extreme rainfall events (Jacobs et al. 2018). There is a great need to improve the resilience of pavements vulnerable to inundation, particularly flexible pavements, given their susceptibility to weakening of the foundation layers.

Two of the most straightforward solutions to improving the resilience of vulnerable asphalt pavements involve reconstruction. First, these pavements could be replaced with new concrete pavements that are inherently more resilient to flooding. Alternatively, these pavements could be reconstructed with thicker and stiffer foundation layers. Stabilization of unbound layers with cement, fly ash, or lime could provide additional strength to help harden the system and absorb the impacts of inundation.

These reconstruction strategies would undoubtedly prove effective, but they could also be costly and time-consuming and require large amounts of raw materials. Given the great number of pavements that are vulnerable to flooding and inundation, less expensive and less resource-intensive strategies will also be needed to improve resilience in a cost-effective and sustainable manner.

A less expensive and resource-intensive alternative to improve the resilience of existing pavements could be to construct concrete on asphalt (COA) overlays. COA overlays have multiple designs, as pictured in Figure 6, and can be constructed directly over an existing asphalt pavement with limited surface preparation. A COA overlay can be used to raise the elevation of an existing pavement by several inches, which may help mitigate flooding impacts. More importantly, the final system behaves similarly to a conventional rigid pavement, including in its resilience to inundation (Fick et al. 2021).

Researchers at the University of California Pavement Research Center used a heavy vehicle simulator to test COA overlay sections under continuous flooding conditions and found that the pavements exhibited excellent performance

Concrete on Asphalt

Concrete on asphalt (COA) overlays can be designed to address a broad range of existing pavement conditions on both composite and full-depth asphalt pavements. Both bonded (COA–B) and unbonded (COA–U) options enable designs to cost-effectively match the condition of the existing asphalt—from deteriorated to good—as well as geometric parameters.

COA–B (Full Depth and Composite) | **COA–U** (Full Depth and Composite)

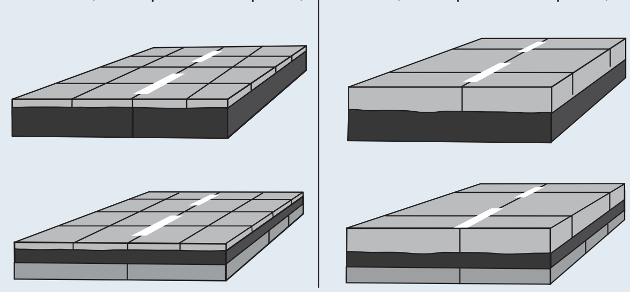

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Figure 6. Concrete on asphalt overlays

under loading (Mateos et al. 2021). Additionally, a pavement design analysis by King and Taylor (2023) found that a variety of COA overlay options were highly resilient to theoretical flooding scenarios, offering greater performance benefits and lower life-cycle costs than a typical asphalt pavement rehabilitation strategy. These findings suggest that COA overlays can improve the resilience of pavements to flooding and inundation, and they may prove especially useful given the scale of pavements that may be vulnerable to these issues and the constraints on funding and resources.

Conclusion

In the years ahead, the impacts of climate change and extreme weather events will place a great deal of stress on the nation's pavement system, and all types of pavements will require adaptations to become more resilient. The resilience of the pavement network can be improved through measures that reduce damage to roadways, airfields, and other critical transportation infrastructure and that allow pavements to return more quickly to their previous level of service and avoid secondary damage after hazards occur.

A number of changes to the design and construction of concrete pavements will be needed to ensure that they are resilient to the effects of climate change. Additionally, concrete pavements themselves are poised to play an important role in improving the overall resilience of the pavement system due to their inherent ability to withstand the impacts of flooding and inundation. Many existing flexible pavements are highly vulnerable to flooding and sea level rise, and the construction of new concrete pavements or overlays is a viable solution that can help improve the resilience of the US pavement network.

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