IMPROVING PAVEMENT RESILIENCY & DISASTER RECOVERY
A Case for Concrete Pavements

Jim Mack, P.E.
Director of Market Development – Infrastructure

September 2020

TOPICS COVERED

- The Need for Resilient Pavements
- Defining Resiliency
- Improving a Pavement's Resiliency

INCREASE OF DAYS WITH HEAT INDEX > 90° F DEGREES BY 2050

Many cities will experience a month or more sweltering days each year.

Source:
- Killer Heat in the United States: Climate Choices and the Future of Dangerously Hot Days, Union of Concerned Scientists, July 2019

THE NUMBER OF EXTREME HEAT DAYS WILL INCREASE DRAMATICALLY

Urban Areas exposed to 30 or more days with a heat index > 105° F degrees
Compared with just 3 urban areas historically

Midcentury No Action
(150+ Urban Areas)

Midcentury Slow Action
(60+ Urban Areas)

Cities Experiencing
Heat Index >105°F

- More than 30 Days per Year
- More than 30 Days per Year, Historically
- Fewer than 30 Days per Year

Extreme heat will not occur in isolation. There will also be droughts, wildfires, floods, and other extreme weather events that will compound the impacts of the heat.
INCREASED TEMPERATURES CREATE OTHER CLIMATE RISK

Risk can occur as both sudden shocks & long-term recurring chronic pressures

<table>
<thead>
<tr>
<th>Transportation Asset</th>
<th>Sea-level rise &amp; tidal floods</th>
<th>Riverine &amp; pluvial flooding</th>
<th>Hurricanes, typhoons &amp; storms</th>
<th>Tornadoes &amp; wind events</th>
<th>Drought</th>
<th>Heat (air &amp; water)</th>
<th>Wildfires</th>
</tr>
</thead>
<tbody>
<tr>
<td>Airports</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Rail</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Roads</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>River</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Seaports</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Climate risk increases operating costs & exacerbates the infrastructure funding gap

WARMER SUMMERS WILL AFFECT THE ABILITY TO WORK OUTDOORS

In extreme cases, this could put human lives at risk.

- Extreme Heat Days
  - Heat Index Above 90°F
  - Heat Index Above 100°F
  - Heat Index Above 105°F
  - Heat Index Off the Charts

OUTDOOR WORKERS BECOME MORE SUSCEPTIBLE TO HEAT-RELATED ILLNESSES.

- Children, elderly adults, pregnant women, and people with underlying conditions are at heightened risk of heat-related illness.
- Anyone could be at risk of heat-related illness or even death as a result of prolonged exposure.
- Underrated: any level of exposure is presumed extremely dangerous for all people and leads to result in heat-related illness or death.

EXTREME FLOOD EVENTS ARE INCREASING IN BOTH FREQUENCY AND MAGNITUDE

<table>
<thead>
<tr>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>Significant decrease</td>
<td>Insignificant decrease</td>
</tr>
</tbody>
</table>

Average number of flood days per year:

NORTH CAROLINA HAS BEEN HIT BY TWO 500 YEAR FLOOD EVENTS


- I-95 Lumberton, NC (2016)
- I-40 Pender County (2018)

With Hurricane Florence, NC had over 2500 road closures
HOUSTON TEXAS HAS BEEN HIT BY 4 FLOOD EVENTS IN THE LAST SEVERAL YEARS – THE WORST WAS HURRICANE HARVEY

RIVER FLOODING IN THE PLAIN STATES HAS BEEN SEVERE THE LAST SEVERAL YEARS

SEA LEVEL RISE IS ALREADY IMPACTING COASTAL ZONES

Flooded streets, Hurricane Sally Pensacola, Florida on September 16, 2020.
EXTREME HEAT INCREASES THE INCIDENCE OF LARGE FOREST FIRES

The number of fires has increased with high statistical significance in 7 out of 10 western US States

Contributing Factors
- Warmer & drier conditions
- Increased pest populations
- Increased land management practices
- Increased fire suppression practices
  - Denser vegetation (increased fuel)

"Outdated policies and human-caused climate change [have] increased burn area [by] 900% across the western U.S. since 1984"

2020 IS THE WORST YEAR ON RECORD FOR FOREST FIRES

More than 85 large wildfires are ripping across the West Coast

California – more than 3.2 million acres have burned
- Double the state's average of 500,000 acres burned annually

Oregon – 46 large fires burned more than 1 million acres between Sept 7 – 13.
- Twice the state's total from all of 2019.

Washington - over 500,000 acres have burnt in seven days,
- Twice the state’s total from all of 2019.

Photo: Noah Berger/AP

HUMANS HAVE MOVED CLOSER TO FORESTLANDS

Expanded the Wildland–Urban Interface

TOPICS COVERED

The Need for Resilient Pavements
- Defining Resiliency
- Improving a Pavement’s Resiliency
INTRODUCTION TO RESILIENCE

The ability to anticipate, prepare for, and adapt to withstand, respond to, and recover rapidly..." 1

Performance

1) Drop in Performance

2) Recovery time (full, or partial improvement)

Resilience with respect to an event (e.g., flooding, fire, earthquake, etc.) is characterized by two parameters:
1. Drop in performance, induced by the event (e.g., reduced ability to carry load).
2. Recovery time to reinstate or improve performance.

Green is more resilient than Red
- Faster recovery time
- Higher level of service

Blue is a hardened system as it has a higher final performance level

INCREASED FLOODING IS IMPACTING OUR PAVEMENT STRUCTURES

Need to distinguish between Inundation and Washout Impacts

Washout
- Rapid flow of flood water / high current that scours and washes out the pavement structure
- Pavement type has little impact

Inundation
- The rise of water that submerges the pavement. No rapid flow or current
- Pavement type does have an impact

CONCRETE AND ASPHALT PAVEMENTS ARE DIFFERENT DUE TO HOW THEY TRANSMIT LOADS TO THE SUBGRADE

Asphalt Pavements are Flexible
- Load - more concentrated & transferred to the underlying layers
- Higher deflection
- Subgrade & base strength are important
- Requires more layers / greater thickness to protect the subgrade

Concrete Pavements are Rigid
- Load – Carried by concrete and distributed over a large area
- Minor deflection
- Low subgrade contact pressure
- Subgrade uniformity is more important than strength

FUNDAMENTALS TO CREATING RESILIENT SYSTEMS

Prevention, Protection & Mitigation Strategies have Benefit / Cost Ratios range from 2:1 to 9:1

Hierarchy to Resilient Systems 1

1. Prevention: stop a ... manmade or natural disasters
2. Protection: secure against ... manmade or natural disasters
3. Mitigation: reduce ... by lessening the impact of disasters
4. Response: ... meet basic human needs after an incident
5. Recovery: ...assist communities affected by an incident to recover effectively

Developing a resilient pavements / roadway infrastructure requires an understanding the risk and damaged caused for each climate hazards

1. FHWA Order 5520: Transportation System Preparedness and Resilience to Climate Change and Extreme Weather Events
2. Hardening Infrastructure – Elevating, upgrading, relocating assets, flood walls, berms and levees, etc.
5. Estimating the benefits of Climate Resilient Buildings and Core Public Infrastructure (CRBCPI), Institute for Catastrophic Loss Reduction, February 2020

INCREASED FLOODING IS IMPACTING OUR PAVEMENT STRUCTURES

Need to distinguish between Inundation and Washout Impacts

Washout
- Rapid flow of flood water / high current that scours and washes out the pavement structure
- Pavement type has little impact

Inundation
- The rise of water that submerges the pavement. No rapid flow or current
- Pavement type does have an impact

CONCRETE AND ASPHALT PAVEMENTS ARE DIFFERENT DUE TO HOW THEY TRANSMIT LOADS TO THE SUBGRADE

Asphalt Pavements are Flexible
- Load - more concentrated & transferred to the underlying layers
- Higher deflection
- Subgrade & base strength are important
- Requires more layers / greater thickness to protect the subgrade

Concrete Pavements are Rigid
- Load – Carried by concrete and distributed over a large area
- Minor deflection
- Low subgrade contact pressure
- Subgrade uniformity is more important than strength

Developing a resilient pavements / roadway infrastructure requires an understanding the risk and damaged caused for each climate hazards

1. FHWA Order 5520: Transportation System Preparedness and Resilience to Climate Change and Extreme Weather Events
2. Hardening Infrastructure – Elevating, upgrading, relocating assets, flood walls, berms and levees, etc.
5. Estimating the benefits of Climate Resilient Buildings and Core Public Infrastructure (CRBCPI), Institute for Catastrophic Loss Reduction, February 2020
FLOODING CAUSES THE SUBGRADE TO BECOME SUPERSATURATED

Moisture infiltrates base, pushes the subgrade particles apart and weakens the system. Flooding does not impact the concrete's load carrying capacity to the same degree as asphalt's.

Asphalt Pavements are Flexible
- Lowered subgrade strength & reduced modulus
- Reduced load carrying capacity
- Takes ~1 year to regain strength
- Loading during this times accelerates pavement damage / deterioration

Concrete Pavements are Rigid
- Maintains high level of strength / stiffness
- Subgrade is weak, but still uniform
- Spreading of the load means subgrade is not overstressed
- Little impact on the serviceability / life

RESEARCH FINDINGS INDICATE IT TAKES UP TO 1 YEAR FOR THE SUBGRADE STRENGTH TO RECOVER FROM FLOODING

When looking at pavement's resiliency, need to recognize damage from 2 different sources / times:

1. Primary / Direct Impacts – alters the pavement structural or functional capabilities
2. Secondary / Indirect Impacts – Impacts due to recovery activities or use
   - Rescue and Emergency response during the disaster
   - Recovery activities (clean up and rebuilding) after the disaster

To have a resilient pavement system requires that both aspects be addressed.

WHEN LOOKING AT PAVEMENT'S RESILIENCY, NEED TO RECOGNIZE DAMAGE FROM 2 DIFFERENT SOURCES / TIMES

Impact Types / Timing

1. Primary / Direct Impacts – alters the pavement structural or functional capabilities
2. Secondary / Indirect Impacts – Impacts due to recovery activities or use
   - Rescue and Emergency response during the disaster
   - Recovery activities (clean up and rebuilding) after the disaster

For this case, this strength loss is a 40 to 60% reduction load carrying capacity and about 3 years of life.
RELIEF AND RESCUE EFFORTS WILL TAKE PLACE
Loading occurs both during the crisis and long after

Joplin, MO Tornado (2011)
Debris Hauling from Camp Fire, Paradise, CA (2018)
3.66 million tons removed over a nine-month period

NEED TO ACCOUNT FOR LONG TERM SECONDARY IMPACTS WHEN DISCUSSING PAVEMENT RESILIENCE
Weakened pavement & additional loading can lead to early rehabilitation needs

Pavement Resilience should be characterized by three parameters:
1. Drop in performance, induced by the event (eg. reduced ability to carry load).
2. Recovery time to reinstate or improve performance.
3. Ability to withstand emergency and recovery activities

TOPICS COVERED
The Need for Resilient Pavements
Defining Resiliency
Improving a Pavement’s Resiliency

APPROACHES TO IMPROVE A HIGHWAY’S / PAVEMENTS RESILIENCE
Adapted from Bruneau, 2003 and McDaniels, 2008

Adaptive Resilience – Capacity to learn and make decisions to avoid future loss based on the type of disturbance

Green is more resilient than Red
- Faster recovery time
- Higher level of service
- Less Secondary damage

Performance
Time

Lost Performance
Time to Full Recovery
Event

1) Modifications before disruptive events that improve system performance
2) Repairs after disruptive event to restore system functionality
ONE OFTEN DISCUSSED APPROACH IS ELEVATING THE ROAD ABOVE FLOODING ELEVATION

Elevating the roadway is not cheap and it is not possible to raise all roadways.

ANOTHER APPROACH IS ROAD ABANDONMENT

Abandoning the roadway is not always possible.

STIFTER PAVEMENTS ARE MORE RESILIENT TO INUNDATION FLOODING

Stiffer Pavements are less impacted by subgrade strength loss and recover faster (stiffer = concrete, cement stabilized bases, increased asphalt thickness).

KEY FINDINGS FOR PAVEMENTS THAT WERE SUBMERGED BY HURRICANE KATRINA

Submerged pavements were weaker than non-submerged pavements

- Asphalt pavements
  - Overall strength loss = two inches of new asphalt concrete
  - Damage occurred regardless of the length of time the pavement was submerged
  - Cost: $50 million to rehabilitate 200 miles of submerged asphalt roads
- Concrete Pavements
  - Little relative loss of strength due to flooded conditions
  - Resilient modulus (Mr) is similar for submerged and non-submerged pavements
  - No information given on repairs or repair costs
FLOODED PAVEMENTS RESEARCH IN AUSTRALIA FOUND SIMILAR RESULTS

Road authorities may want to consider changing their roads into flood resilient pavements.

A rigid pavement performs better than composite and flexible road groups:
• Composite and flexible road groups show similar performance up to 2-3 years.
• Rigid pavement performs the best at any probability of flooding and flooding effect is not critical.

A pavement’s strength may be enhanced by:
• Strengthening with an overlay
• Layer stabilization.
• Converting the road into a rigid or composite pavement through granular layers’ stabilization.

"It is settled that a rigid pavement is the more flood-resilient." (p. 5)

PVEMENTS IN HOUSTON HAVE BEEN FLOODED SEVERAL TIMES

But roadways are opened as soon as water has receded.

Estimating Pavement’s Flood Resilience; Misbah U. Khan, CPEng; Mahmoud Mesbah, Ph.D.; Luis Ferreira, Ph.D.; and David J. Williams, Ph.D.; American Society of Civil Engineers' Journal of Transportation Engineering, Part B Pavements, 2017

"It is settled that a rigid pavement is the more flood-resilient." (p. 5)

"It is settled that a rigid pavement is the more flood-resilient." (p. 5)

ACTIVITIES THAT CAN BE USED TO “HARDEN THE PAVEMENT SYSTEM”

Adopt & Use Concrete Pavement

Yacht Harbor Manor Neighborhood Improvements, Riviera Beach, Florida

Almost All Pavement Designs in Australia are based on soaked subgrade conditions
Concrete overlay increases both the height and the structural strength of the roadway.

ACTIVITIES THAT CAN BE USED TO “HARDEN THE PAVEMENT SYSTEM”
Use Concrete Overlays

7000 lbs load.

Road Elevation raised the height of the overlay

Pressure ~3 - 7 psi at the top of the Asphalt layer
Base & subgrade pressures are even lower

Concrete overlay increases both the height and the structural strength of the roadway.

ACTIVITIES THAT CAN BE USED TO “HARDEN THE PAVEMENT SYSTEM”
FDR w/ Cement increases rigidity, reduces permeability, & reduces moisture susceptibility

Un-stabilized Granular Base
Pressure ~3 - 7 psi

FDR w/ Cement-Stabilized Base
Pressure ~15 - 20 psi at the top of the Asphalt layer
Base & subgrade pressures are even lower

Moisture infiltrates base
• Through high water table
• Capillary action
• Causing softening, lower strength, and reduced modulus

High water table

Cement stabilization reduces permeability
• Helps keep moisture out
• Maintains high level of strength and stiffness even when saturated

CONCLUSIONS

1. We are beginning to recognize the need to make our infrastructure “Resilient”
   - Need to define specific actions that agencies should consider when dealing with pavements
   - Need to define how each specific “climate risk” will impact the system
   - Must account for secondary impacts

2. In areas where pavements have a history of flooding (or in flood prone areas)
   - Require pavement designs be based on lowered subgrade strength
   - Use Stiffer or stiffen the existing pavement
   - There are many solutions that are viable that are low costs, such as concrete overlays and FDR with cement that can be used as mitigation / hardening strategies

DEFINING A PAVEMENT’S FIRE RESILIENCY


Howe Ridge Fire from across Lake McDonald in Montana’s Glacier National Park (2018)
FIRE DAMAGES CONCRETE & ASPHALT PAVEMENTS DIFFERENTLY

While there are no studies on wildfires & pavements, there are studies from tunnel fires.

Concrete Pavements are Non-Combustible
- Concrete is a fire resistance material
- Inert due to its purely mineral composition
- Minimal or no emission of toxic gases.
- Can get minor cracks, popouts, etc. as the water in the concrete/aggregate vaporizes.

Asphalt Pavements are Combustible
- Approximate ignition temperatures is 300 – 450°C (based on asphalt material/type)
- At lower temperatures, asphalt “melts” and has some thermal degradation (calcination and the detachment of aggregates).
- Burning/melting releases considerable toxic gases (CO, SO₂, NO, NO₂).

Concrete damage is often limited to surface spalling.
Intense heat causes the moisture inside the concrete to boil and fracture.

Sources of Asphalt Pavement Damage
Pavement scarring due to car fire & weakened asphalt binder/structure are the most common.

1. Improving fire safety in tunnels: The concrete pavement solution: CEMBUREAU / BIBM / ERMCO
2. Emanuele Toraldo (2013), Comparative laboratory investigation into pavement materials for road tunnels, Road Materials and Pavement Design

Concrete can be made fire resistant by adding polypropylene fibers (roughly 2% by wt).

No Fibers
- Water in the concrete boils, forms steams and violently spalls (moisture clog spalling)

Fibers
- Polypropylene fibers melt and provide escape path for the steam, preventing spalling
ANOTHER SOURCES OF PAVEMENT DAMAGE IS DRAINAGE PIPE FIRES

Collapsed & Burnt-out Culvert - undermine the roadway.

Slope failure due to burnt-out HDPE Pipe

High-density polyethylene (HDPE) or polypropylene (PP) are plastic, and have a melting point of about 120 – 180 °C

THE MAJOR SOURCE OF DAMAGE IS INCREASED / HEAVIER TRAFFIC

Damage can be a lot or a little; and depends on traffic, weight, and pavement design

Comparing Normal Verse Cleanup/Construction Traffic

Creating this type of structural damage makes the road more susceptible to water and environmental damage – further/rapidly exacerbating the damage!
The average loss of Pavement Condition Index score was conservatively calculated as a reduction of 20 basis points.

LONG TERM EXPOSURE TO INTENSE HEAT DOES IMPACT PAVEMENT STRENGTH
Change in Cubic Compression Resistance (CCR) results due to fire exposure

- First bar chart = Control (no thermal stress)
- Next four bar charts = Specimens subjected to fire tests at 400°C
  - Durations ranging from 60 to 240 min
- Last bar chart = specimens subjected to high-temperature oven test
  - 650°C for 60 min
- Concrete ~ 35% to 40% Strength Reduction (due to the micro-evaporation of water)
- Asphalt ~ 90% to 98% Strength Reduction (due to the bitumen burning, which occurs after only 15 min of fire exposure)

GM = Grouted Macadam: An open-grade bituminous mixture (voids content equal to 35%) filled with cement mortar

About the Presenters

Jim Mack, P.E. – Director, Market Development, CEMEX

- Provides customer & internal support to identify and develop cement and concrete pavement application opportunities
- Works with State DOTS, Federal Agencies and industry Assns. to improve and develop standards related to cement and concrete pavement applications
- 30 years of pavement engineering experience
  - Concrete pavement design, rehabilitation; construction;
  - forensic evaluation, materials and specifications
  - Pavement management, life cycle cost analysis and life cycle assessment (environmental impact).

Education
- MBA – University of Chicago
- MSCE – University of Illinois at Urbana-Champaign
- BSCE – University of Illinois at Urbana-Champaign

Registered Professional Engineer – Illinois and Texas