

## **The Use of GPS-Based Distress Mapping to Improve Pavement Management**

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## **ABSTRACT**

Utilizing recent inspection data of portland cement concrete (PCC) pavements at airports and military installations in the United States and Canada, the enhancement of long-term pavement management through Global Positioning Satellite (GPS)-based distress mapping is examined. Specifically, examples of distress pattern identification, improvements to the determination of localized maintenance repair quantities, the process of selecting appropriate rehabilitation methods, and applying identified deficiencies to future construction and repair projects are discussed.

Distress pattern identification illustrates how various types of distresses within and across slabs are related to one another, which allows for the isolation of required repairs and leads to more effective maintenance planning. Comparisons between actual repair quantities from the distress mapping process and standard repair quantities from pavement management software are also analyzed. Distress mapping allows maintenance needs to be located and repaired by maintenance crews, and provides more accurate funding requirements for improved planning. It also offers the ability to track the progression of distresses and the effectiveness of repairs over time. Distress mapping also provides greater insight to selecting the proper rehabilitation method. Pavement repair options can be weighed against rehabilitation or reconstruction options to determine what option will yield the best combination of future pavement condition, cost, and operational requirements. In some instances, the existing distresses can assist in modifying current design, construction, or repair methods being employed. With these benefits, distress mapping can improve the pavement condition and reduce the overall funding requirements.

## **BACKGROUND**

Examples from recent inspections that utilized GPS-based distress mapping of PCC pavements at airports and military installations in the United States and Canada are examined. For the various pavements discussed, the data collection method used was more robust than a traditional Pavement Condition Index (PCI) survey, allowing the survey team to accurately and precisely map distresses identified throughout the network using a GPS-based distress data collection tool.

The process before and during these inspections differs in several ways when compared to a traditional pavement management survey. First, additional mapping is required before the start of the survey. Every pavement section, sample unit, and slab must be defined by a closed polygon, with each pavement management level being on a unique layer of a Geographical Information Systems (GIS) map. For a traditional PCI survey, these three feature classes are often only defined in Computer-Aided Design and Drafting (CADD) by line work (not by closed polygons). Second, a reference grade GPS unit is connected to a tablet computer to track the location of the inspector. The GIS map must be properly geo-referenced to ensure accurate GPS locations are reported and show the inspector's current location on a facility and within a slab. Lastly, for each distress, the inspector records the distress type, size, and exact location including position within a slab during the inspection using software developed for distress mapping. A traditional PCI simply identifies quantities and severities at the sample unit level; it does not

identify the exact locations or the presence of multiple distresses of a singular type within a slab. During distress mapping, most distresses are also drawn to represent the physical characteristics of each distress; however, distresses that affect the entire slab, such as popouts, are identified as being present or not present in any given slab. Additional information is still gained for the select distresses that do not have the physical extents defined within a slab. The end result is a complete depiction of the distresses on a pavement facility, which allows for visualization of the distresses observed and recorded during the visual distress survey. In figure 1, a legend for concrete distresses recorded at the slab level is shown for reference.

**DISTRESS AND SEVERITY LEGEND FOR PCC PAVEMENTS**

LOW	MED	HIGH	DISTRESS	DESCRIPTION	LOW	MED	HIGH	DISTRESS	DESCRIPTION
			61	BLOWUP				71	SETTLEMENT
			62	CORNER BREAK				72	SHATTERED SLAB
			63	CRACK - LONGITUDINAL, TRANSVERSE & DIAGONAL				73	SHRINKAGE CRACKS
			66/67	PATCHING				74	SPALLING - JOINT
			68	POPOUTS				75	SPALLING - CORNER
			69	PUMPING				76	ASR
			70	SCALING					

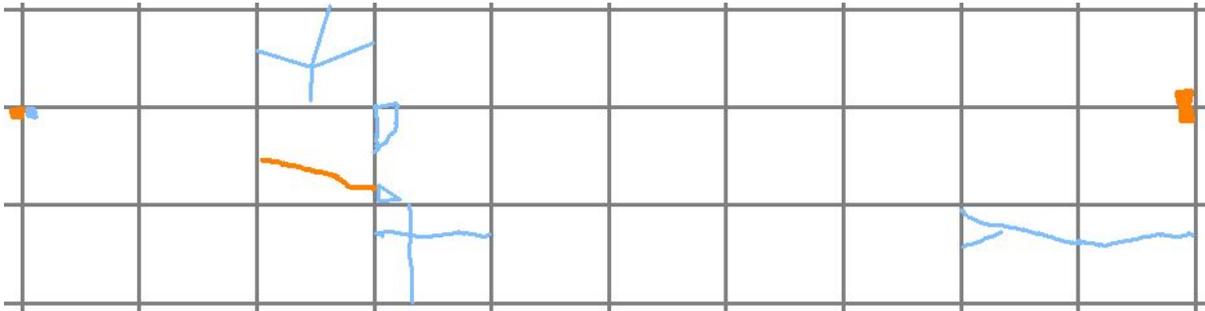
**FIGURE 1 Distress map legend.**

**DISTRESS PATTERN IDENTIFICATION**

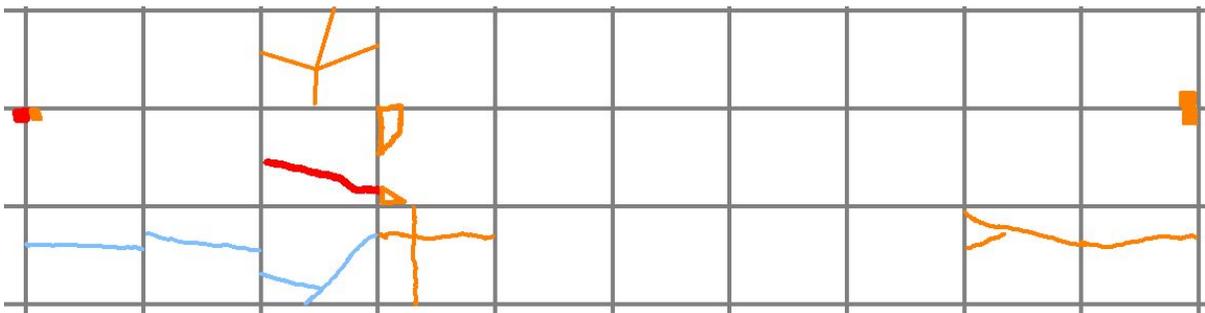
The identification of distress patterns can be an important first step in effective pavement management. Distress mapping at different times also offers the ability to track the progression of distresses over time. This feature can show the stabilization of the pavement condition or it can provide a visual depiction of the continued deterioration of a pavement over time. The deterioration of an isolated area of pavement at a general aviation airport in a dry-freeze climatic zone that experienced temporary overloading in late fall is examined. Following the overloading situation, the distresses on the pavement were mapped shortly thereafter and then again the following summer. The goal of the multiple inspections was to determine if the occurrence of freeze-thaw and daily temperature cycling between inspections would reveal the progress and/or propagation of damage initiated during the overload situation. Between the two inspections, which were about 6 months apart, significant freeze-thaw and daily temperature cycling occurred.

As displayed in figures 2 and 3, there are two areas where structural distresses are present. In the area indicated on the right side, during the initial inspection there were two slabs with low-severity linear cracks present. These cracks appeared to have recently developed and were still tight, non-working cracks. These two slabs deteriorated since the original inspection and the low-severity linear cracks were rated at medium-severity in the follow-up survey. The crack width increased between the two inspections and spalling and Foreign Object Damage (FOD) potential became evident. In the distressed area on the left side, during the initial inspection there were two slabs with low-severity shattered slabs, one slab with a medium-

severity linear crack, and a slab with two low-severity corner breaks. These structural distresses continued to deteriorate over the next months as the concrete experienced substantial temperature cycling, which led to greater internal stresses. The severity of the distresses increased one severity level between the surveys. In addition, three other slabs in this area revealed low-severity linear cracks on the pavement surface after the initial inspection.



**FIGURE 2 Distresses from initial inspection of overloaded slabs.**



**FIGURE 3 Distresses from second inspection of overloaded slabs.**

Over time, it was possible to see how the condition of the pavement and of specific distresses changed. The use of GPS-based distress mapping allowed for the tracking of the condition of individual slabs with structural-related distresses.

## **LOCALIZED MAINTENANCE REPAIR QUANTITIES**

One of the most important results from a complete pavement management project is the determination of localized repair needs. Without this product, a meaningful and cost-effective pavement maintenance program is difficult if not impossible to implement. While repair quantities and costs can be determined using a traditional PCI approach, one of the goals of the distress mapping procedure is to improve upon the determination of required localized maintenance and repair quantities, as well as to pinpoint their specific location.

For PCC pavements using traditional PCI surveys, only the count of each distress/severity combination is recorded for each group of slabs inspected (i.e., a sample unit). To obtain the approximate quantities required to address maintenance and repair needs, default conversion factors in the PAVER™ pavement management software are applied to each distress/severity combination that requires attention. For example, if one slab contained a large

high-severity patch in a sample unit, the calculated replacement patch from PAVERTM would be the typical slab width (for the pavement section) multiplied by 1.5 meters (4.9 feet) wide (1). If the typical slabs in the pavement section were 6 meters (19.7 feet) wide, this would lead to a replacement patch of 9 square meters (97 square feet). For some pavements, this may be an appropriate repair quantity; however, it is more likely that this quantity does not represent the specific pavement conditions. This repair quantity may be inaccurate because the repair of the existing high-severity patch would require a patch substantially larger or smaller than the typical slab width multiplied by 1.5 meters (4.9 feet), the typical slab width of the pavement section may not be representative of the true slab width where the existing patch is located, or there may be multiple patches in the same slab that require repair. Because only one distress at the highest severity for a given distress is recorded for each slab, per ASTM D5340-12 procedures, there may be multiple large high-severity patches in one slab (2). Since only one of these patches would be recorded in PAVERTM, a maintenance quantity would be provided for only one patch.

Given the distress mapping procedure used, it is possible to compare the calculated localized maintenance quantities from pavement management software like PAVERTM and the calculated localized maintenance quantities from the distress mapping procedure. These comparisons are based on 100 percent inspection density for both methods. Additional comparisons could be made if the sampling rate for the traditional pavement inspection was reduced. Like repair quantities provided by pavement management software, conversion factors were also used to calculate the necessary repair quantities based on the distress maps, but the factors were able to be customized for the specific conditions of an airfield or individual pavement section. For example, all medium- and high-severity patches needing replacement were assumed to be replaced with a patch that was 25 percent larger than the original patch. This allows for additional area around the patch to be replaced if it has deteriorated. This conversion factor also compensates for imperfections in distresses that are drawn slightly smaller than the actual distress. These conversion factors can be adjusted for each site, as applicable, and are based on actual distress quantities rather than a typical slab length.

Table 1 provides a comparison for select medium- and high-severity distresses for a 20-year-old PCC pavement section with approximately 1,200 slabs in a wet-freeze climatic zone. These distresses were selected as they have the potential to produce FOD and the physical extents of these distresses were known from the distress mapping procedure. For seven of the nine distresses in this table, the differences in repair quantities in terms of area are small; however for medium- and high-severity large patches, the combined difference is 660 m<sup>2</sup> (7,104 ft<sup>2</sup>). It should be noted that many of the existing deteriorated distresses are located adjacent to a drain in the center of the pavement section where water gathers. The large discrepancy between the calculated repair quantities would significantly impact future maintenance planning in regards to funding required. At the network level, these systematic differences could cause substantial programming and funding issues if not corrected.

**TABLE 1 Comparison of Repair Quantities in 20-year-old PCC Pavement**

Distress	Severity	PAVER™ Repair Quantity	Distress Map Repair Quantity	Repair Quantity Difference	Units	PAVER™ vs. Distress Map Repair (%)
Corner Break	M	12.5 (41)	17.9 (58.7)	-5.4 (-17.7)	m (ft)	-30.2%
Joint Spall	M	1.8 (19.4)	4.7 (50.6)	-2.9 (-31.2)	m <sup>2</sup> (ft <sup>2</sup> )	-62.5%
	H	0.5 (5.4)	0.7 (7.5)	-0.2 (-2.1)	m <sup>2</sup> (ft <sup>2</sup> )	-24.9%
Large Patch	M	27.2 (293)	137.2 (1,477)	-110 (-1,184)	m <sup>2</sup> (ft <sup>2</sup> )	-80.2%
	H	136.1 (1,465)	686.1 (7,385)	-550 (-5,920)	m <sup>2</sup> (ft <sup>2</sup> )	-80.2%
Linear Crack	M	208.2 (683)	203.5 (668)	4.7 (15.4)	m (ft)	2.3%
	H	4.6 (15.1)	1.9 (6.2)	2.7 (8.9)	m (ft)	137.6%
Small Patch	M	0.5 (5.4)	0.4 (4.3)	0.1 (1.1)	m <sup>2</sup> (ft <sup>2</sup> )	39.5%
	H	0.3 (3.2)	0.4 (4.3)	-0.1 (-1.1)	m <sup>2</sup> (ft <sup>2</sup> )	-41.0%

Table 2 provides a comparison for select medium- and high-severity distresses for a 60-year-old PCC pavement section with approximately 700 slabs in a dry-freeze climatic zone. Once again these distresses were selected as they have the potential to produce FOD and the physical extents of these distresses were known from the distress mapping procedure. In contrast to Table 1, the repair quantities for the large patches from PAVER™ are estimated to be much larger than the repair quantities from the distress map. This is because many of the large patches are actually only slightly larger than the required 0.5 m<sup>2</sup> (5 ft<sup>2</sup>) to be classified as a large patch. In addition, the length of the repair for medium-severity linear cracks is much larger from PAVER™. This is the result of certain medium-severity cracks being located in slabs that are half or less than the typical (or average) slab size that is recorded in PAVER™. These over-estimations of the repair quantities can also impact localized maintenance planning. Recognition of the actual repair quantities may allow for the reallocation of funding to other pavement sections that require maintenance in the network.

**TABLE 2 Comparison of Repair Quantities in 60-year-old PCC Pavement**

Distress	Severity	PAVER™ Repair Quantity	Distress Map Repair Quantity	Repair Quantity Difference	Units	PAVER™ vs. Distress Map Repair (%)
Corner Break	M	7.5 (80.7)	6.5 (69.9)	1 (10.8)	m <sup>2</sup> (ft <sup>2</sup> )	15.4%
Joint Spall	M	7.5 (80.7)	10.0 (107.6)	-2.5 (-26.9)	m <sup>2</sup> (ft <sup>2</sup> )	-25.0%
Large Patch	M	138.9 (1,495)	16.3 (175)	122.6 (1,320)	m <sup>2</sup> (ft <sup>2</sup> )	752.1%
	H	18.3 (197)	3.5 (37.7)	14.8 (159.3)	m <sup>2</sup> (ft <sup>2</sup> )	422.9%
Linear Crack	M	87.9 (288.4)	33.9 (111.2)	54 (177.2)	m (ft)	159.3%
Small Patch	M	6.8 (73.2)	6.3 (67.8)	0.5 (5.6)	m <sup>2</sup> (ft <sup>2</sup> )	7.9%
	H	2.3 (24.8)	0.9 (9.7)	1.4 (15.1)	m <sup>2</sup> (ft <sup>2</sup> )	155.6%

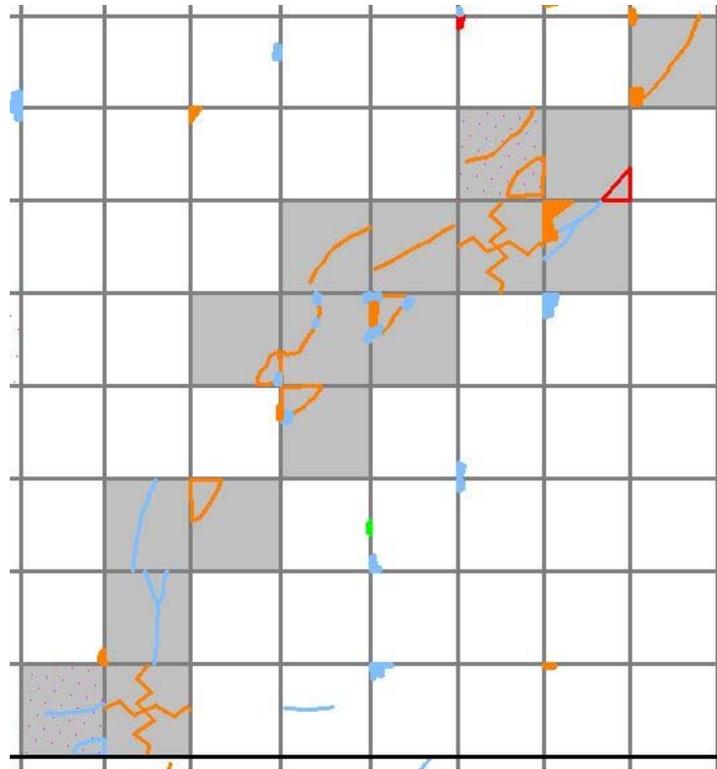
## CHOOSING APPROPRIATE REHABILITATION METHODS

For PCC pavements in which more than minor localized maintenance needs exist, distress mapping can aid in the selection of rehabilitation methods. By analyzing the distress maps created, decisions can be made about the most appropriate rehabilitation method, such as whether a pavement section should be reconstructed or if selective slab replacements can successfully restore the condition of the pavement section. Furthermore, the extent of the necessary slab replacements can be evaluated via a distress map.

In traditional network-level PCI surveys, the PCI of a PCC pavement section is used to determine rehabilitation costs. Approximations can be made when establishing these costs, such as associating a PCI with an estimated percentage of necessary slab replacements. For the example provided, 20 percent of slabs were assumed to need replacement at a PCI of 50, 10 percent of slabs at a PCI of 60, and 5 percent of slabs at a PCI of 70. These quantities of slab replacements are approximations and were determined with the goals of improving the condition, operational function (i.e. reductions in routine pavement inspections, FOD removal activities, and emergency repairs) and service life, and reducing future emergency repair requirements. The same goals are applied to selecting the quantity of slab replacements when a distress map is referenced; however, more detailed information is available to refine the required quantity of slab replacements.

The distress map allows for patterns of slabs with significant distresses to be identified and marked for replacement. Figure 4 provides an example area of a distress map from an apron in a dry-freeze climatic zone. In these slabs, there are low- and medium-severity linear cracks, low-, medium- and high-severity corner breaks, and medium-severity shattered slabs in a diagonal pattern. With these load-related distresses present in this pattern, it would be beneficial to replace all of the slabs identified in figure 4 with gray shading. In addition, other existing distresses throughout these slabs, such as patching, would be eliminated by the recommended slab replacement and reduce the future maintenance requirements. By analyzing the distress patterns, additional improvement requirements, such as strengthening of slabs with a weak subgrade or improving areas of poor drainage, can also be identified with this process. The repair of these distresses would dramatically improve the condition of the pavement in this area.

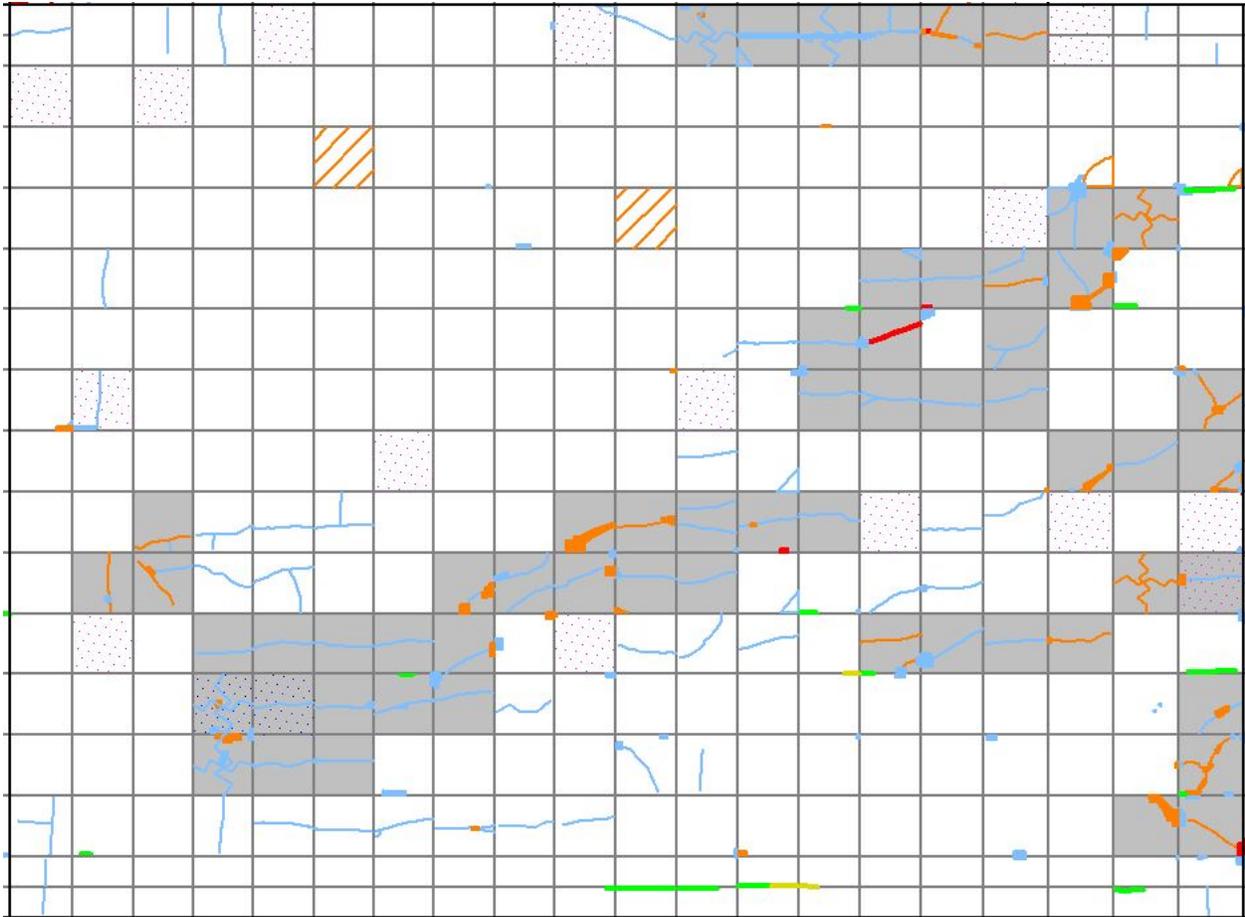
Even within the same network, it is possible for two pavement sections with the same PCI to require different quantities of slab replacements. For a network in a dry-freeze climatic zone, there were two sections (identified as A and B in this case study) that had the same PCI, construction history (age and cross section), and typical slab size, as well as similar traffic loading, yet the recommended quantity of slab replacements differed significantly. It should be noted that the structural capacity (from a previous investigation) was shown to be adequate for the typical traffic for both sections. The PCI was 58 for both sections at the time of inspection. By selecting the slabs to be replaced via the distress map, it is possible to determine the benefit (in terms of the PCI increase) that would result from replacing specific slabs.



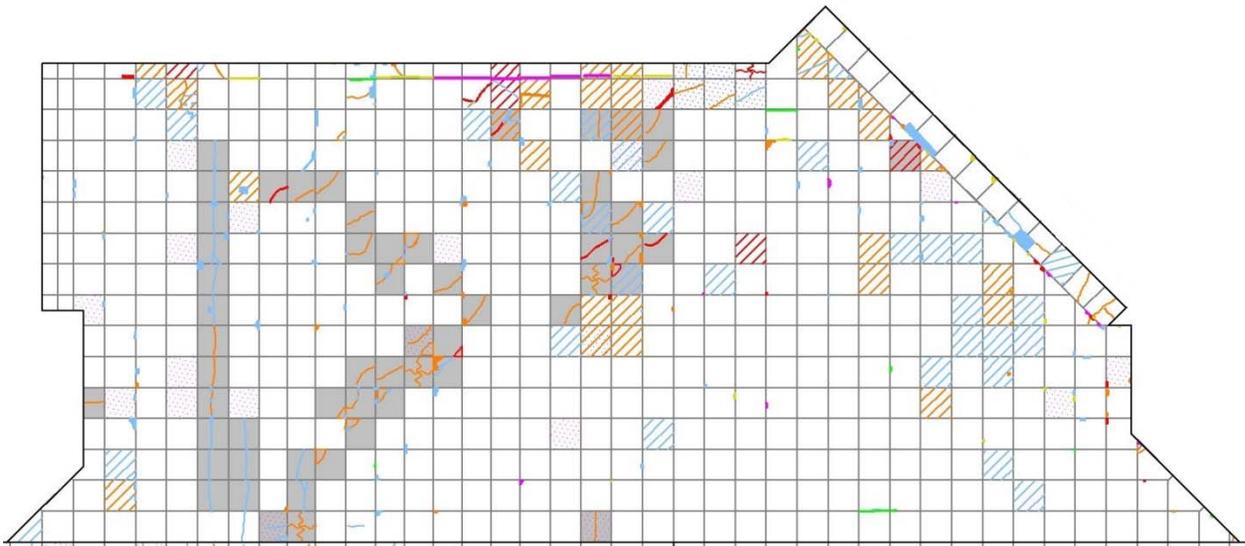
**FIGURE 4** Example area with projected replacement slabs shaded.

For Section A, there are 323 total slabs and approximately 18 percent of the slabs are recommended for replacement. By replacing this quantity of slabs, the condition, operational function, and service life will be reasonably improved without extensive expenditures. In this example, some slabs with low-severity linear cracks are not recommended for replacement; however, if it is desired and adequate funding is available, all slabs with linear cracks could be replaced. The distress map and the projected replacement slabs for Section A are shown in figure 5. The PCI is predicted to increase 21 PCI points by replacing the 59 slabs marked.

For Section B, there are 557 total slabs and approximately 10 percent of the slabs are recommended for replacement. The distress map and the projected replacement slabs for Section B are shown in figure 6. The PCI is predicted to increase 11 PCI points by replacing the 57 slabs indicated. It should be noted that there are additional slabs along the top and right boundaries of the section that would typically be replaced based on the distresses present, but they were not identified for repair because they are in close proximity to a fence and a hangar and do not receive aircraft traffic, and the distresses could be addressed through localized maintenance. Even though there are many similarities between these two sections, the process of distress mapping and selecting specific slabs for replacement is able to provide two different, section-specific rehabilitation plans. The quantity of the slabs to be replaced and the distresses they are addressing can also lead to dramatic differences in the PCI improvement. For these two pavement sections, the recommended rehabilitation plans should be able to successfully extend the service life and can easily be communicated with the individuals performing the rehabilitation.



**FIGURE 5** Section A with projected replacement slabs shaded.



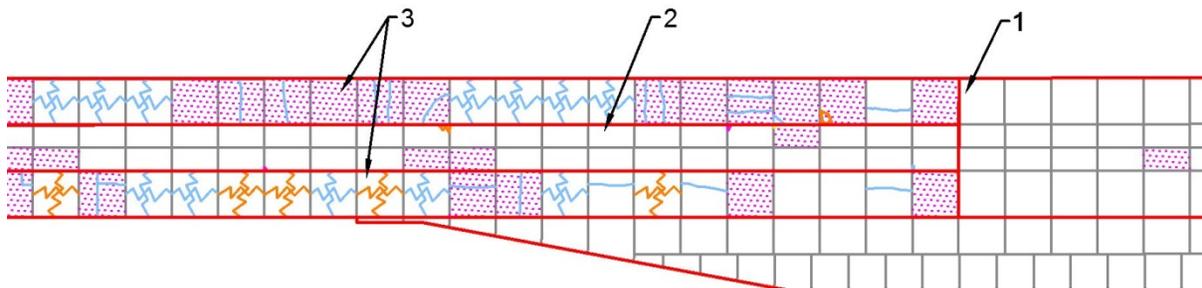
**FIGURE 6** Section B with projected replacement slabs shaded.

Instead of selecting the quantities of slab replacements with the goals of improving the condition, operational function and service life, and reducing future emergency repair requirements, it is also possible to create multiple repair maps with varying quantities of slab replacements. By adjusting the quantities of slab replacements, the repair maps would visually depict what slabs could be replaced. For example, repair maps could be made for a section at 3 percent, 6 percent, 9 percent, and 12 percent slab replacement. The PCI increase can be calculated for each repair map. Then the repair maps and PCI increase can be weighed against the cost of slab replacement to determine the best rehabilitation option available.

## APPLYING IDENTIFIED DEFICIENCIES TO FUTURE CONSTRUCTION PROJECTS

There are many factors that affect the performance of a pavement section. The pavement structure (cross section), climate, traffic, and construction techniques are a few of the factors that will impact the pavement condition. By examining these factors in combination with the distress types and patterns, it is possible to learn how to improve future construction projects.

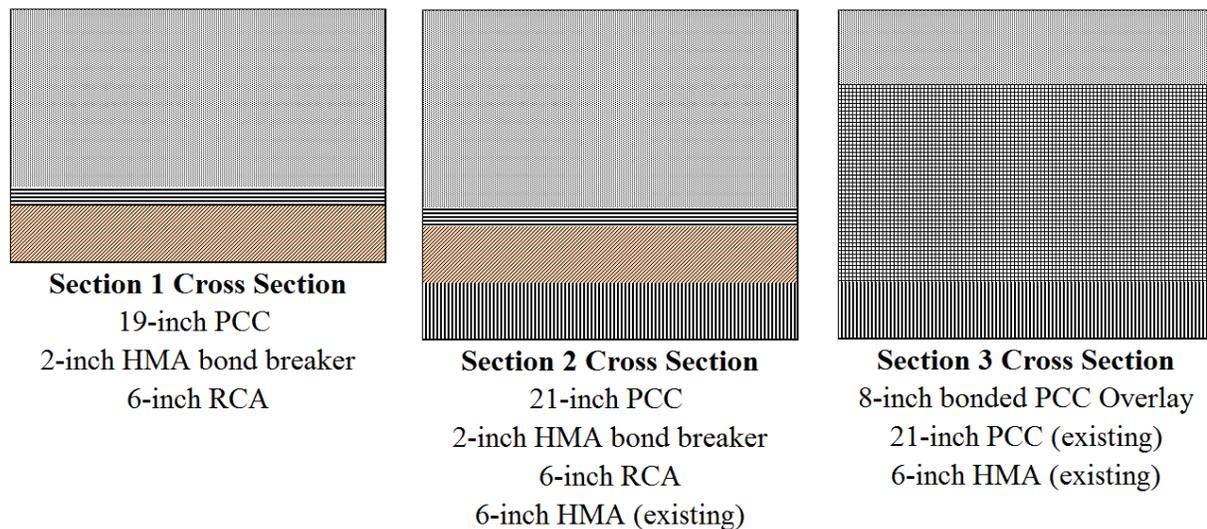
A distress map of a parallel taxiway at a large-hub commercial airport in a wet-nonfreeze climatic zone is presented in figure 7. This taxiway was rehabilitated between two and three years prior to the inspection and is often used by wide-body aircraft preparing for departure. For this discussion, Section 1 is on the far right side, Section 2 is the keel on the left side, and Section 3 is the outer slabs on the left side. The outside slabs throughout the distress map are 25 feet (7.6 meters) wide and the keel slabs throughout are 12.5 feet (3.8 meters) wide. All slabs are 25 feet (7.6 meters) in length. Figure 7 only shows a small area of these three sections but it is representative of the condition throughout its length. From this distress map, it is clear that Section 3 has not performed adequately. The PCI of Section 1 was 98, the PCI of Section 2 was 95, and the PCI of Section 3 was 52 with 85 percent of the distresses being load-related in nature. Corner breaks, linear cracks, and shattered slabs were the structural distresses recorded for Section 3.



**FIGURE 7 Recently rehabilitated parallel taxiway distress map.**

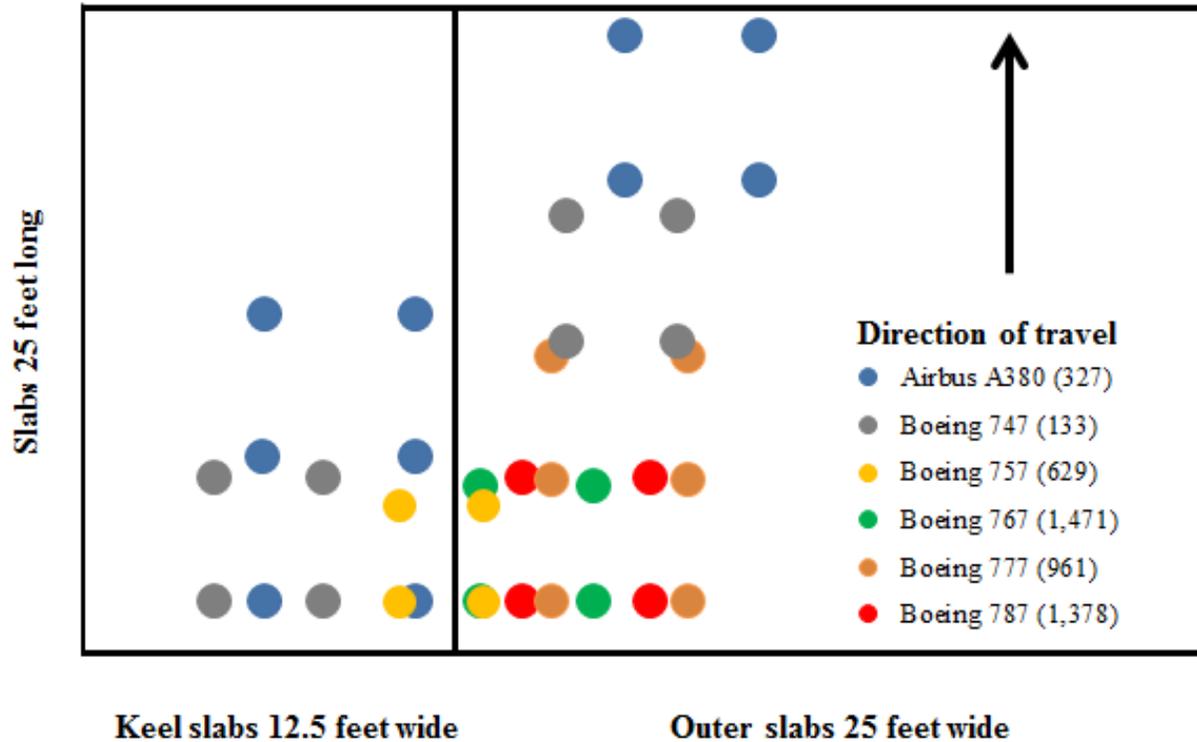
The cross sections for these three sections are quite different, with varying thicknesses of PCC, hot-mix asphalt (HMA), and recycled concrete aggregate (RCA), as depicted in figure 8. The thickness of the structure that was placed recently is much less for Section 3 than it is for Sections 1 and 2; however, the overall pavement structures do not vary substantially. It is theorized that the top layer of PCC in Section 3 did not bond properly with the underlying layers. If this layer is not properly bonded, the top 8 inches (203 millimeters) of PCC would act independently rather than as a monolithic slab as assumed for design.

Next, the traffic must be examined to understand what loading is responsible for the deterioration of Section 3. It is also important to consider where the landing gear is located within the slabs. Given that the inner 12.5 feet (3.8 meters) left and right of the centerline have performed properly, only certain aircraft were studied. The landing gear for aircraft that have maximum take-off weights greater than 250,000 pounds (1,134,000 kilograms), landing gear that extends more than 12.5 feet (3.8 meters) from the center of the aircraft, and aircraft with at least 100 annual average departures were considered. Figure 9 shows a schematic of the tire contact point for the aircraft meeting these criteria. To simplify this figure, the variants for each aircraft were combined into single aircraft model (e.g., the Boeing 747-400 and Boeing 747-800 are represented by the Boeing 747 tire contact points). It was also assumed that the aircraft travel down the centerline of the taxiway. It should also be noted that in figure 9, the tire contact points are not representative of the shape or extent of the contact area for each tire; it is a diagram to demonstrate the approximate loading of the slabs. From figure 9, we can gather that Section 3 does experience substantial loading and that most of the loading is considerably eccentric in nature.



**FIGURE 8 Cross sections for recently rehabilitated parallel taxiway.**

From the data available, the combination of the wide-bodied aircraft traversing the area with a de-bonded PCC layer in Section 3 is most likely the root of the structural distresses in Section 3. Under this condition, an 8-inch (203 millimeter) PCC layer is not able to withstand significant wide-bodied aircraft loading and considerable structural distresses would develop. With the analysis that has been completed, it is possible to apply the identified deficiencies in Section 3 to future construction projects. The cross section and the paving practices for Section 3 should not be utilized at this time without additional analysis. Conversely, the cross sections and paving practices for Sections 1 and 2 can be used within the network for areas with similar traffic pattern and subgrade characteristics.



**FIGURE 9** Tire contact points for wide body aircraft on parallel taxiway.

### **DISTRESS MAPPING CONSIDERATIONS**

Although there are many benefits to GPS-based distress mapping for PCC pavements, the additional effort to successfully complete a project should be understood. When compared to a traditional PCI survey, there is a slight increase in effort in the length of time involved to evaluate a sample unit. Assuming pavement in a mixture of conditions, an experienced PCI survey crew of two people can inspect approximately 10 PCC sample units in an hour, while a proficient crew of two creating a distress map can survey approximately 9 PCC sample units in this same amount of time. The most significant difference in effort between creating a distress map and traditional PCI survey is in the overall quantity of sample units surveyed over a given airfield. For a typical airfield in a traditional PCI survey, it is common to inspect approximately half of the PCC sample units to achieve a 95 percent confidence, as defined in ASTM D-5340-12. For a meaningful distress map to be created, all sample units must be surveyed. By taking into consideration these increases in labor, the field work for a PCC distress mapping project will take between two and two and a half times longer than a tradition PCI survey. The expenditures in additional field work for distress mapping can often be offset by the reduction in the effort to create repair construction plans and may further be offset by the utilization of a more efficient and robust pavement management program.

In an attempt to reduce the field labor required to complete a distress mapping project, the utilization of an automated digital video survey might be considered. With proper video surveying and processing techniques, a PCC distress map for an airfield with acceptable accuracy might be able to be created. There are three chief concerns if this process was

implemented instead of a manual GPS-based distress mapping. First, given the slab layout for a typical airfield, extra care must be taken to properly align and digitally stitch together the slabs. Second, material related distresses such as durability cracking and alkali-silica reactivity (ASR) are notoriously difficult to properly identify and assign the appropriate severity during an automated digital video survey. Other distresses such as faulting, scaling, popouts, pumping, and the condition of joint seals are also often challenging to document via an automated digital survey. Third, for airfield surveys the definitions for ten of the sixteen distresses in ASTM D-5340-12 partially rely on the extent of FOD potential as distress exhibits. To properly rate the FOD potential for a distress, it is often necessary for an inspector to examine a distress in person to determine if material is in a loose or potentially loose state. With continued improvement in the technology used in automated digital video surveys, these concerns will be lessened; however, at this time it is not advisable to produce a distress map solely by an automated digital video survey. Additionally, while automated data collection can reduce the on-site time required to complete an inspection, at this time the overall costs can be considerably more than manual data collection.

## CONCLUSIONS

Overall, there are many benefits of GPS-based distress mapping for PCC pavements. Existing patterns of distresses can be recognized throughout slabs following this process. For future planning, accurate localized maintenance repair quantities and rehabilitation methods can be determined. Lastly, the mapped distresses can identify changes that should be made to design, construction, or repair methods of future construction and repair projects. These benefits of distress mapping can improve the pavement condition and reduce the overall funding requirements.

Other projects with mapping of the location of certain distress types and severities for HMA-surfaced pavements have been performed. These projects have shown to be beneficial for identifying patterns, locating specific repair locations, and tracking long-term performance of maintenance for HMA-surfaced pavements. Unlike PCC pavements, the overall quantities determined for repair quantities and costs are not substantially improved when compared to a traditional PCI survey to the results from a PCC pavement distress mapping survey. However, distress mapping for HMA-surfaced pavements has been effective in identifying detailed maintenance plan requirements, determining the most effective rehabilitation option, and tracking distress progression.

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- (2) American Society for Testing and Materials (ASTM), ASTM D-5340-12, "Standard Test Method for Airport Pavement Condition Index Surveys," *Annual Book of ASTM Standards, Section Four: Construction, Volume 4.03: Road and Paving Materials; Vehicle-Pavement Systems*, American Society for Testing and Materials, West Conshocken, PA, 2012.