The High Performance of the Concrete at the Shuttle Landing Facility

William R. Weiss[1], P.E., Bob Bryan[2]

Abstract

The Shuttle Landing Facility (SLF) located at the Kennedy Space Center (KSC), FL, is the prime landing location for orbiters returning from space. The facility was constructed in the mid-1970's to address the need of having a landing facility near the Space Shuttle launch site. The primary pavements were constructed of portland cement concrete (PCC) and have performed very well up to this point, in part due to an on-going aggressive maintenance approach. Stringent operational requirements make this runway unique in several ways, and maintaining the runway surface to a high standard is critical. Condition measurements have been conducted on a biennial basis and provide an update for the SLF staff on areas in need of immediate repair, as well as tracking the overall deterioration patterns and planning for future maintenance efforts. The SLF is a tremendous example of how to maintain a pavement network in excellent condition for as long as possible.

Introduction

The quest of the National Aeronautics and Space Administration (NASA) to expand the realm of mankind in space begins with considerations on how to safely return a shuttle orbiter and its crew at the end of a mission. During the landing phase the orbiter is unlike conventional aircraft in that it cannot perform a "missed approach" since it has no propulsion, and it also has a much faster landing speed around 343 kilometers per hour (220 mph) (NASA Facts Online, 2000). Operational decisions involving a wet runway and/or crosswinds at the SLF must be made nearly 90 minutes prior to a planned landing, thus making the friction characteristics extremely important. From a logistics standpoint, the KSC offers the best option for end-of-mission landings, as well as the possibility of an emergency landing soon after launch. The prime alternate site is on the expansive dry-lake beds of Edwards Air Force Base (EAFB) in California, but this necessitates the added costs and potential dangers of a cross-country ferry trip atop NASA's modified B-747 Shuttle Carrier aircraft to return the shuttle to the SLF (NASA Facts Online, 2000). The many unique aspects of the orbiter had to be considered in designing the landing surface.

[1] Senior Engineer, Applied Research Associates, Inc., 505 W. University Avenue, Champaign, IL, 61820, email: wweiss@ara.com
[2] SLF Manager, Space Gateway Support, P.O. Box 21237, SGS-346, Kennedy Space Center, FL 32815-0237 email: Robert.Bryan-1@ksc.nasa.gov

This paper focuses on the SLF in Florida and presents specific pavement information for the following areas:

- Construction history
- Maintenance history
- Condition measurements
- Analysis and repair recommendations

Construction History

The SLF has the distinction of being designed and constructed well before the intended design "aircraft" was even completed. Constructed in 1975-76, the primary role of the SLF is to provide a safe and smooth surface for shuttle orbiter landings and other NASA operations, but it wasn't until 1984 that a mission actually returned to SLF without first landing at EAFB (NASA Facts Online, 1995). The SLF consists of a runway 4,572 meters by 91.4 meters (15,000 ft by 300 ft), a small connector taxiway, apron area, overruns, and paved shoulders along the runway. The runway, taxiway, and apron areas are comprised of over 455,000 square meters (4.9 million sf) of PCC pavement containing 9,864 slabs. The typical slab size is 7.62 m (25 ft) wide and 6.1 m (20 ft) long and contains no reinforcing steel. The typical cross-section is 40.6 cm (16 in) of PCC on top of a 15.2-cm (6-in) soil cement layer; the outer 30.5 m (100 ft) of the runway is 38.1 cm (15 in) of PCC on top of the soil cement layer. Load transfer is provided along the longitudinal construction joints using keyways, with the exception of the centerline and outermost joints, which are tied. The transverse joints rely on aggregate interlock for load transfer, with the exception of the last two transverse joints on the runway, taxiway, and apron, which are doweled. Expansion joints were constructed 19 mm (¾ in) wide and used thickened edges with no reinforcement.

Like much of Florida, the area is very flat around the SLF with swamps in the vicinity, making drainage a challenge. To promote positive drainage away from the runway, it was constructed at a slightly higher elevation than the surrounding land with canals running the full length along both sides. The runway has a 1% crown and is grooved transversely to help expedite the water away from aircraft tires.

Shoulders were added along the edge of the runway in 1992 and were designed to serve as service roads for the various support vehicles that frequently operate at the SLF. The shoulders are composed of 2.5 cm (1-in) asphalt, over 15.2 cm (6-in) of lime rock, over 15.2 cm (6-in) soil cement. Moving the vehicular traffic off the runway helped to reduce the potential for creating additional foreign object debris/damage (FOD) on the runway surface. The shoulders also help facilitate surface drainage away from the edge of the runway (Weiss, 2004).

Operational Specifications. Operational considerations of the Orbiter also factored into the design of the SLF. The original specifications for flight operations included the capability to land in 20-knot crosswinds. Achieving this magnitude of crosswind would not only increase the margin of safety for normal end-of-mission landings, but also increase the chances of meeting short launch-window opportunities when Space

Station rendezvous are planned. The SLF runway surface was designed with a texture that would provide high friction performance despite heavy rainfall and/or crosswind conditions (Daugherty, 1997). The dimensions of the runway are nearly double those of a conventional runway, making the SLF one of the largest runways in the world. The added width and length of the runway provide some room for error on the one-time high-speed final approach. Although the orbiters resemble a DC-9 in size, the weight per tire during landing is much higher than any aircraft (Sotham, 2004). Structurally speaking, this would usually mean a thicker cross-section due to the high stresses caused by the lack of weight distribution across more landing gear. However, excessive loadings are not as critical when the number of overall operations of the orbiters at the SLF is only a handful per year.

As with any airfield pavement, FOD is always a concern for the airport operators, but it is even more critical at the SLF. FOD is any free object on the pavement surface that could cause damage to a passing aircraft, either by striking the aircraft or getting ingested in the engines. The main concern for the shuttle is FOD damaging the fragile outer layer of the orbiter, thereby compromising the structural integrity of the inner layers. The Space Shuttle Columbia accident of 2003 served as a harsh reminder that the orbiters are unique vehicles that experience extreme conditions, yet are even more susceptible to FOD than other aircraft. With this in mind, the surface of the SLF must be maintained at a high standard with little or no FOD potential.

Maintenance History

As pavements deteriorate from their initial condition, properly applied maintenance treatments often help to slow the overall deterioration rate. Although there are numerous studies to show that it is more cost-effective and easier to maintain a pavement that is in good condition, maintenance is often deferred until more expensive rehabilitation is the only option for a pavement in poor condition. From its inception, the SLF has been maintained at a very high standard in regards to operational condition, which has been made possible in large part by a very proactive approach to maintenance. The three major types of maintenance at the SLF have been partial-depth patching, joint seal replacement, and texture modifications. The first two maintenance items are common treatments for any PCC pavement, yet the texture modification was unique to the SLF.

Partial-depth Patching. As a PCC pavement expands with daily and seasonal temperature changes, the PCC joints will experience higher stresses if restrained from also moving with the expansion due to incompressible material in the joints. In addition, the edges of a PCC slab are more susceptible to higher stresses caused by a load since the PCC is weakest at the edges of the slab. Both of these scenarios often result in a spall—a portion of the PCC that has separated from the rest of the slab. Initially, the spalled piece of concrete will often remain tightly compressed by the surrounding PCC, but over time will loosen and become a greater FOD consideration. The pavement at the SLF has spalled along the joints and at the corners of slabs and represents the most common reason for patching. What is fairly unique at the SLF is the size of the potential repair is often very small and would generally be considered too small of an area to repair at most airports. For example, of the 1,453 documented patches on the SLF there is only 1 patch that is larger than 0.46 square meters (5 square feet); the remainder can be measured in square inches. The typical size of repair that is feasible at the SLF indicates the level of concern a spall represents. Throughout the years the patching repairs at the SLF have been made with a variety of materials and techniques. The current practice is to saw cut the boundaries of the repair area, and then use a cementitious patching material that reaches acceptable compressive strengths within hours.

Joint Seal Replacement. When the SLF was originally constructed, the joint sealer was of the compression variety. After 21 years of good service, the hardened joint seals were replaced with a liquid silicone-based product. Although simple in task, replacing all of the joint seals at the SLF is a major budget item, considering that there are nearly 119 km (74 miles) of joints on the runway alone. One of the advantages of using liquid sealants is that small spalled-out areas and irregularities along the joint can be filled in with sealant, thus reducing any FOD potential. Considering the small dimension of some spalls, filling the spalled area with silicone instead of a patching material is the most appropriate repair.

Texture Modifications. After the first several orbiter landings at the SLF, it was discovered that the original surface texture of the PCC was causing excessive wear on the orbiter tires, potentially leading to a blown tire and subsequent loss of control during rollout. Improvements were made to the tire composition and the braking system, but additional landings and tests still concluded that the original texture was too abrasive. This situation is rather unique in that most pavements with texture issues lack certain friction characteristics, and any modifications seek to improve friction levels. Fortunately for the SLF, the PCC surface was adaptable to the necessary modifications to reduce the friction levels but still maintain good wet friction characteristics.

The original texture on the SLF was an extremely rough surface produced by a brush dragged longitudinally through the plastic concrete creating numerous peaks and valleys. This texture represents the macrotexture that can be felt by rubbing one's hand across the surface of the pavement. In addition, the entire runway was grooved transversely (see figure 1, left side). The original thinking was that most of the tire wear occurred during the spin-up phase when the tire first contacted the pavement. In 1988, the nominal touchdown regions of the runway were diamond ground deep enough to remove the original transverse grooves (figure 1, right side). These regions are the first 1,067 m (3,500 ft) at each end of the runway and now resemble corduroy with its texture aligned with the centerline of the runway.

Figure 1. Original texture on runway (left), corduroy texture after milling (right).

The diamond ground ends helped to reduce the spin-up wear on the tires, but it was discovered after additional landings and tests that the rollout phase (the distance between the main gear down and the orbiter coming to a complete stop) still added unacceptable tire wear. Further, it was discovered that the diamond ground surface had little or no effect in reducing tire wear during the rollout, so simply milling the remainder of the runway would not have corrected the issue. At this point, despite the improvements in tires and texture modifications, the runway was still short of the operational goal to handle landings with 20-knot crosswinds. However, the limiting factor was now known to be excessive tire wear during the rollout, whether induced by the pilot maneuvering the orbiter or a crosswind, both of which produce tire side energy. Extensive studies focused on the rollout phase and how additional texture modifications could satisfy operational goals, yet offer enough texture during wet conditions. A second and final texture modification was performed in 1994 over the entire runway surface using a Humble Equipment Company Skidabrader™ shootpeening machine. This device uses pressurized air to propel small steel shot at the pavement, basically rounding off the sharp peaks and reducing the average texture depth. After impact, the shot and any debris were vacuumed up, and the SLF was finally in full compliance operationally (Daugherty, 1997).

Condition Measurements

The pavements at the SLF have been inspected thoroughly approximately every 2 years since 1990. The inspection serves a number of purposes, the main one being the identification of any new distresses that will need to be repaired. On a bigger scale, the overall deterioration trends can be studied since the inspections are designed to be repeatable and occur on a regular basis. The inspection of the runway, taxiway, and apron at the SLF used two separate and distinct survey techniques. The first survey was conducted in accordance with FAA AC 150/5380, *Guidelines and Procedures for maintenance of Airport Pavements,* and ASTM D5340, *Standard Test Method for Airport Pavement Condition Index Surveys,* in which the pavement condition index (PCI) procedures were applied. The second survey was more thorough, where individual spalls and patches were identified, located, and examined for debonding from the adjacent concrete. Together, the two surveys constituted a complete examination of the current condition of the SLF airside pavement network and provided a basis for predicting future pavement performance and for making repair recommendations. Finally, a third inspection was performed to track the texture depth on the runway.

PCI Survey. The PCI procedure has become the universally accepted means of rating airfield pavements for operational and structural integrity. Prior to conducting the PCI survey, the pavement network at the SLF was divided into units referred to as branches, sections, and sample units. This definition is intended to identify unique characteristics, such as construction history and traffic patterns, that may influence the performance of the pavement in the future.

During a PCI inspection, inspectors walk over the surface of the pavement and identify visible signs of deterioration or distress. Each distress type is identified, and then classified as low, medium, or high severity, generally depending on FOD potential. For the SLF, every sample unit (20 slabs ± 8 slabs) on the runway, taxiway, and apron was inspected, and the recorded distresses were entered into MicroPAVER, a software program specifically designed for managing a pavement network. The calculated PCI is a number between 0 and 100, with 100 representing a pavement with no visible signs of distress and 0 representing a totally failed pavement. A PCI is calculated for each sample unit within a section, and the average of these sample units is the section's PCI.

Based on the latest inspection, the section PCI values of the PCC at the SLF range from 90 to 98, which is very high (any PCI > 85 is considered "excellent"), taking into account the age of the pavement. The overall PCI of the SLF has remained not only very high, but also remarkably consistent, with an area-weighted average of 95.9 ± 0.7 since 1992. The high PCI after nearly 3 decades of service speaks to the quality of the initial product (design, materials, construction), and the consistency points to a sound and persistent maintenance approach.

Intensive Pavement Inspections. In addition to the PCI survey, a detailed inspection was conducted at the SLF where each spall and patch was located, checked for debonding, and prioritized as to the potential level of repair. Normally the PCI procedure would provide enough detailed information to extrapolate future maintenance type and work effort. However, when the level of detail requires the specific location, type of repair, and quantity, more intensive inspections are necessary.

All of the 9,864 slabs at the SLF were checked for loose or fragmented pieces of pavement typically represented by spalling along a joint or corner of a slab or an existing patch. Each spall and patch was identified by the FOD potential and the location on the slab. The FOD potential of each spall and patch was critiqued visually and confirmed by sounding using a rubber mallet. The level of debonding from the rest of the slab is heard (and felt) by the sound when struck by the mallet—the looser the spall or patch, the duller the response. Based on this, each spall and patch was categorized by FOD potential as either fully or partially debonded, or fully bonded with little or no FOD potential.

Also identified during the intensive inspections were holes found at the surface of the pavement that were created by the presence of deleterious material, such as wood or clay balls, and that had deteriorated over time, leaving a void. In most cases, the holes found during the inspection do not pose a FOD problem; however, many of the holes contained small particles, which increase the FOD potential (Weiss, 2004).

Texture Depth. Texture depth is a measurement of the visible peaks and valleys on the surface of the concrete, also know as macrotexture. The primary function of macrotexture is to provide paths for water to escape from beneath the aircraft tires. The depth of the valleys can vary due to a build up of contaminants such as rubber or other foreign matter. Mechanical wear from aircraft traffic can also distort the pavement's surface texture. As mentioned previously, the challenge to the SLF staff is to keep the runway surface smooth enough to prevent excessive tire wear on the orbiter, yet abrasive enough to prevent hydroplaning.

The NASA Grease Smear Method (FAA AC 150/5320-12C, 1986) was used to measure the average texture depth of the pavement at 48 spots along the runway. The individual tests are grouped by paving lane (centerline or an offset from centerline), and by milled versus non-milled pavement sections. The averages can then be compared to past averages to see if changes in texture depth may warrant more sophisticated testing.

Analysis and Repair Recommendations

Pavement Performance. The SLF is a high-profile facility that has nearly 3 decades of high pavement performance to back it up. It is hard to say how long this pavement will last, but we can say the following are currently true:

- There are no load-related distresses (corner breaks, linear cracks, or shattered slabs) on the runway, taxiway, or apron area. Traffic patterns, so far, have not influenced the condition of the pavement.
- The spalling is occurring fairly uniformly across the runway, despite concerns that the diamond grinding would cause additional spalling. In addition, the spalling at the SLF is most likely caused by incompressible material in the joints since there is no other load-related distress to relate it to.
- The consistently high PCI of the SLF indicates the initial design, materials, and construction were well selected, and persistent maintenance activities have adequately maintained the condition levels.
- The useful life of some of the early partial-depth patches is coming to an end. 12.1% of the existing patches were partially or fully debonded.
- After modifications in 1988 and 1994, the surface texture of the runway appears to satisfy the existing operational specifications set forth by NASA.

Repair Recommendations. The future repair recommendations for the SLF were presented in two ways—a priority-based systematic approach to repair all defects and a summarized list of the most immediate repairs required at the SLF. The priority-based approach relies on the section definitions that were utilized during the PCI inspection, and the state of debonding for the spall or patch. Differences in traffic for a section can influence whether a repair should be done immediately or can wait until later. Table 1 presents the four-level priority scheme setup for repairing the spalls and debonded patches at the SLF.

Table 1. Priority matrix for repairing spalls and debonded patches.

Priority	Traffic level	Condition
1	High traffic	Fully debonded, high FOD potential
2	Low traffic	Fully debonded, high FOD potential
3	High traffic	Partially debonded, moderate FOD potential
4	Low traffic	Partially debonded, moderate FOD potential

The results of the intensive pavement inspections are presented and summarized in several ways so that a variety of users can obtain useful information. For example, the results are sorted by priority level so that a patching crew can systematically repair all priority one and two level defects, locating the individual slabs by map or table form. For an even faster repair schedule, the most immediate repairs required at the SLF were marked in the field and reported in a separate table. The recommended repairs are also summarized across the entire SLF so a manager can estimate the total level of time and materials to budget for the next year.

Conclusion

Although the SLF is unique in a number of ways, the overriding purpose is still to provide a safe and smooth surface for orbiter landings. The PCC pavement has been well constructed using good materials and a sound design. The time and expense of maintenance on the SLF is viewed as a necessary and beneficial step in providing the highest possible condition level for the longest possible time. The SLF is an excellent example of a quality product being well maintained.

Acknowledgement

The authors would like to thank Space Gateway Support and NASA for their support provided during the preparation of this paper.

References

Daugherty, R. H., and Yager, T. J. (1997). *Texture Modification of the Shuttle Landing Facility Runway at Kennedy Space Center*, National Aeronautics and Space Administration, Hampton, Virginia.

Federal Aviation Administration Advisory Circular 150/5320-12 (1986). “Measurement, Construction, and Maintenance of Skid Resistant Airport Pavement Surfaces.”

NASA Facts Online (1995). "Landing the Space Shuttle Orbiter at KSC." http://www-pao.ksc.nasa.gov.kscpao/release/1992/1-92.htm (Jan. 30, 2005).

NASA Facts Online (2000). "Countdown! NASA Launch Vehicles and Facilities." http//www-pao.ksc.nasa.gov/kscpao/nasafact/count3slf.htm (Jan. 26, 2005).

NASA Facts Online (2000). "Landing the Space Shuttle Orbiter at KSC." http//www-pao.ksc.nasa.gov/kscpao/nasafact/landing.htm (Jan. 26, 2005).

Sotham, J. (2004). "How the Rubber Meets the Runway." *Air&Space,* http://www.airandspacemagazine.com/asm/web/site/QT/bigfoot.html (Jan. 26, 2005).

Weiss, W. R. (2004). "Biennial Inspection of the Shuttle Landing Facility (SLF) at Kennedy Space Center, FL." *Final Report.*