REVIEW OF PRECAST PORTLAND CEMENT CONCRETE PANEL TECHNOLOGIES FOR USE IN EXPEDIENT PORTLAND CEMENT CONCRETE AIRFIELD PAVEMENT REPAIRS

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ABSTRACT
Currently, there is a resurgent interest in the use of precast portland cement concrete (PCC) technologies for pavement construction and repairs. Precast PCC slabs or panels using conventional materials have been utilized at irregular intervals for the last 50 or more years and can offer similar reductions in field installation time as cast in-place PCC with rapid strength gaining materials. This paper documents the history of precast pavement panels around the world for airfield and highway pavements for both repair and new construction work. This information will be used to assist in the development of a methodology for use in rapid full-depth airfield repairs ranging from temporary patches to permanent replacement slabs for rehabilitation. Specific challenges related to military airfield pavement repairs using precast PCC panels are also presented for optimization of a repair panel system for emergency airfield repairs.
BACKGROUND

Airfield repair personnel require expedient methods for conducting full-depth repairs in damaged portland cement concrete (PCC) airfield pavements. Damaged areas must be replaced quickly to restore flight operations in the shortest timeframes possible. Damage requiring a full-depth repair can either result from traditional pavement distresses (i.e., from repeated traffic or overloading by heavy traffic, as-built construction errors, and environmental conditions) or from explosive blasts. Typical PCC pavement damage, including blowups from thermal expansion, shattered slabs, corner breaks, durability cracking, deep spalling (past mid-depth), punch-outs, deteriorating patches, and utility cuts have the potential to damage aircraft even if moderately severe. Damage from explosive blasts may include deep spalls, craters, or camouflets. In some situations, damaged airfields may contain both traditional and explosive distresses. Regardless of the cause of damage or the repair environment, these distresses are normally repaired by full-depth patches that require the removal and replacement of the damaged PCC with repair to sublayers performed as needed.

The most broadly used materials for repairs to PCC pavements are conventional PCC, high early-strength concrete, and proprietary rapid-setting repair materials. Current military guidance for conducting full-slab replacement and full-depth repairs on PCC airfield pavements suggest using conventional PCC. Generally, conventional PCC provides the best results when conducting permanent repairs in PCC airfield areas because the replaced material has similar mechanical properties to that of the adjacent pavement. Disadvantages of using conventional cast-in-place PCC include the long curing duration required to gain sufficient strength to open to traffic and the inability to place the material in all weather conditions. Both of these situations conflict with airfield operations, particularly in wartime scenarios. Over the past several years, the performance of proprietary rapid-setting rigid repair materials has improved, and their use is acceptable for a wide range of repair procedures including emergency, temporary, and permanent airfield repairs.

Proprietary rapid-setting repair materials have been successfully used for partial- and full-slab replacements for airfield repairs; however, these materials are expensive and can be a logistical burden to transport to remote locations. Military repair teams may have limited quantities of these materials; thus, these costly materials may be applied only to smaller repair areas or the most critical airfield repairs. Numerous products have been identified and certified for various categories and sizes appropriate for military airfield repairs.

High early-strength concretes have gained acceptance in the commercial and military airfield repair communities in recent years. The combination of high cement content and the use of accelerating admixtures results in repairs that can be reopened to traffic within 4 to 8 hours. High early-strength concretes may be more costly compared to traditional PCC but usually significantly less expensive than proprietary rapid-setting repair materials. In addition to cost, durability is a concern due to the high cement contents required.

A promising alternative repair method is the use of precast PCC panels for full-depth patches. This repair method has been explored for both highway and airfield repair as early as the 1930’s. A recent resurgence in precast panel repair research indicates that this technology may be applied beyond highway pavements. One main advantage to using precast PCC panels is that the panels may provide a higher quality patch, since the panels can be prepared with traditional PCC and constructed in a controlled environment with fewer time limitations than those encountered during narrow construction windows on highly trafficked airfield pavements. Hasty patching, regardless of material or construction practice used, may result in a poor quality
Precast panels can be fabricated in a controlled manner with less demanding environmental constraints that allow for good standard concreting practices to be followed. Panels made can be reserved and stored off-site for later use when needed. Another advantage is that the use of conventional PCC with local materials may be more economical than using the expensive proprietary materials for cast-in-place repairs. Both of these advantages require further exploration to understand the installation time requirements and the cost required to use this repair technology compared to current expedient and permanent repair methods already used for airfields.

**RESEARCH OBJECTIVE**

The paper presents the first step in a comprehensive study to understand the current state of practice in the U.S. and world in using precast PCC panels for airfield pavement repairs. The intent was to gain a better understanding of current best practices and design methods to apply for precast panel repairs on military airfields, particularly those in remote environments. Information was gathered pertaining to precast concrete panel systems to select a system for expedient airfield repairs in remote locations. The paper briefly presents relevant precast pavement experiences in the U.S. and the world that were reviewed to understand the history and challenges in precast panel fabrication and placement. The methods available (or best applicable) for the expedient pavement airfield repairs were determined, and unique challenges to applying a selected method for the repair situation are also presented.

**PRECAST SLAB EXPERIENCES**

Precast construction of PCC elements such as concrete columns, beams, piles, highway barriers, and railroad ties are used extensively in construction industries. Off-site fabrication and storage of these elements benefit the user by reduce job site congestion, and a controlled manufacturing process results in increased quality and minimized costs. The use of precast concrete slabs in conventional road and airfield pavements for either new construction or repair is not a recent innovation; several precast pavement studies have been conducted over the last 50 to 80 years. Researchers report that one reason widespread pavement use has lagged behind other precast elements is that precast panels used to repair a pavement require more effort to place and level bedding materials than other precast construction elements when installed. Careful grading of bedding materials is required to provide full contact of the slabs with the underlying base, but the process can be time consuming and requires experienced field crews and heavy or specialized equipment. Placement of precast panels generally requires the use of a crane, which in turn requires additional experienced operators and equipment on the jobsite compared with traditional PCC placement. As a result, this repair method was not necessarily applicable to emergency or contingency repair efforts where experienced crews or heavy equipment were not available.

Another reason reported in literature that precast pavement repairs have lagged behind other repair techniques is the lack of consistent, documented design and construction techniques for using precast panels. While proprietary and non-proprietary panels exist and have been explored in recent years, there has been a hesitancy to use them on an extensive basis due to the lack of documentation for their successful use, particularly for airfields. Finally, the use of panels may be more expensive compared to other repair or construction techniques due to the need for heavy construction equipment, proprietary systems, and specially trained crews.
A review of literature revealed numerous instances of the use of precast PCC slabs for a variety of single and multiple panel repairs as well as rapid pavement construction in North America, Europe, the former Soviet Union, and Asia as early as the 1930s. Early use of precast panels was primarily for airfield construction in the former Soviet Union as early as the 1930s and in Europe from 1947 through 1958 (12). Infrequent studies were conducted in the U.S. from 1970 to 2000; however, there has been a resurgence of investigations of this technology in the past 10 years (11,15). Until recently, the precast PCC panel systems were periodically studied for “technical feasibility” (15) with the exception of the former Soviet Union, which used these systems extensively. In recent years, additional countries including Japan, the Netherlands, France, and Indonesia, have used precast PCC slabs for roadway, highway, and in some cases, airfield applications. A summary of early precast panel use in U.S. and foreign projects (12) and more recent applications are documented (11,14-17). The following sections summarize early and current use of precast panels in the U.S. and other countries for pavement repairs and/or construction.

Earlier Experiences

Soviet Union
Perhaps the earliest instance of PCC precast panel construction for airfields was in the former Soviet Union during the early 1930s (12,16). The authors report that the panels were useful for “construction in regions where swelling or settlement caused construction problems, where rapid construction was required, where pavements could be overlaid by panels to strengthen the pavement, or in below freezing applications.” Airfield precast panels were slightly over 6 ft wide and varied in length from 13 to 20 feet with a length-to-width ratio of 2 to 3. In addition to airfield construction, the Soviet Union also used precast PCC panels extensively for road construction. By the 1980s, the Soviet Union had a sophisticated precast concrete industry for both airfield and road construction (12).

Europe
Additional airfield construction was conducted in Europe in the late 1940s through the late 1950s. The first precast, prestressed concrete slabs in airfield construction took place at Orly Airport in Paris, France in 1947 (12,16). The slabs were 3.3-ft wide, 3.3-ft long, and 6.3-in. thick. Another instance is reported to have taken place in London in 1949. Additional pavement construction with precast, prestressed slabs occurred in 1956 at Finningley, England and in 1958 at Melsbroek, Belgium. The slabs at Finningley were 9-ft wide, 30-ft long, and 6-in. thick; and the slabs used at Melsbroek were 4.1-ft wide, 39-ft-long, and 3-in. thick. Emergency airfield repairs of simulated munitions blasts using precast concrete slabs were conducted in Germany in the 1980s. The slabs were 6.6-ft wide, 6.6-ft long, and 4.7- to 5.9-in. thick. No application of test traffic was reported (16).

Japan
Precast concrete panels designed for DC-8 aircraft traffic were constructed and tested in Japan prior to 1981 (16). These panels were 3.2-ft long, 7.5-ft wide, and 7.9-in. thick. Other reported instances of precast panel use in Japan were precast concrete panels used in the 1970s for container yards and airports (17). Panels were also used for roadway pavements in Japan after
1991. Panels for road repairs were 3.3 ft by 6.6 ft, 6.6 ft by 6.6 ft and 9.8 ft by 6.6 ft, and were approximately 5.9 in. thick. No load transfer devices were used between these panels.

**United States**

A review of the literature reveals several repair efforts in the U.S. using precast panel technologies for highway repairs during the 1960s and 1970s. Additional panel studies were conducted in the 1970s and 1980s for airfield repair applications. Table 1 presents a summary of the U.S. experiences with precast panels for both highway and airfield repairs from the 1960s through the 1980s as reported in the literature. As can be seen in the table, panel designs, seating methods, load transfer mechanisms, and reinforcement type varied greatly among the reported efforts.

<table>
<thead>
<tr>
<th>Time period</th>
<th>Location</th>
<th>Pavement Type</th>
<th>Dimensions</th>
<th>Comments</th>
<th>References</th>
</tr>
</thead>
<tbody>
<tr>
<td>1960s</td>
<td>South Dakota</td>
<td>Highway</td>
<td>6-ft wide, 24-ft long, and 4.5 in. thick</td>
<td>Panels were overlaid with 1.5 to 3.5 in. of AC. Panels were prestressed.</td>
<td>12</td>
</tr>
<tr>
<td>1970s</td>
<td>Michigan</td>
<td>Highway</td>
<td>6- to 12- ft wide, 10- to 11-ft long, and 8- or 9- in. thick</td>
<td>Doweled and undoweled panels</td>
<td>12, 18, 19</td>
</tr>
<tr>
<td></td>
<td>New York</td>
<td>Highway</td>
<td>12- to 13- ft wide, 20- to 30 ft long, and 9-in. thick</td>
<td>Pretensioned precast panels</td>
<td>20</td>
</tr>
<tr>
<td></td>
<td>Florida</td>
<td>Highway</td>
<td>12-ft wide, 20-ft long, and 8-in. thick</td>
<td>Panels raised into place using slab jacking. Used to conduct interstate repairs.</td>
<td>21</td>
</tr>
<tr>
<td></td>
<td>California</td>
<td>Freeway</td>
<td>11.4-ft wide, 12.3- to 17.4-ft long, and 8-in. thick</td>
<td>Grout bedding and grout filled joints</td>
<td>22</td>
</tr>
<tr>
<td></td>
<td>Virginia</td>
<td>Highway</td>
<td>1- to 2- ft wide, 1- to 3-ft long, and 2-in. thick</td>
<td>Conducted 68 partial depth patches using precast panels seated on epoxy grout</td>
<td>23</td>
</tr>
<tr>
<td></td>
<td>South Dakota</td>
<td>Highway</td>
<td>Unknown</td>
<td>Partial depth precast panels</td>
<td>12</td>
</tr>
<tr>
<td></td>
<td>New York</td>
<td>Airfield</td>
<td>12-ft wide, 30-ft long, and 9 in. thick</td>
<td></td>
<td>24</td>
</tr>
<tr>
<td>1980s</td>
<td>Wisconsin</td>
<td>Highway</td>
<td>6-ft wide, 6-ft long and 8.5 in. thick</td>
<td>Panels were placed on 0.5 in. of mortar grout.</td>
<td>25</td>
</tr>
<tr>
<td></td>
<td>California</td>
<td>Airfield</td>
<td>116 panels were replaced, and each panel was custom built to the slab requiring replacement. The panels were overlaid with 8-in. of AC.</td>
<td>12, 16</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Florida</td>
<td>Airfield</td>
<td>6-ft wide, 6-ft long, and 8- to 12-in. thick</td>
<td>Placed on grade and bonded with polymer concrete and or covered with polymer concrete</td>
<td>16</td>
</tr>
<tr>
<td></td>
<td>Mississippi</td>
<td>Airfield</td>
<td>Predicted repair times for continuous repairs to repair bomb craters of size 20- to 50- ft wide and 20- to 50-ft long, and 6- to 8- in. thick</td>
<td>16</td>
<td></td>
</tr>
</tbody>
</table>
Recent U.S. experiences

Testing of “Soviet-style” Slabs
The U.S. encountered precast panel airfield pavements in former Soviet Union occupied countries during recent military operations in Afghanistan and Iraq. Research was conducted in the U.S. to understand the load-carrying capacity of the panels to predict damage caused by U.S. aircraft (26). A precast panel runway using “Soviet-style” prestressed, precast slabs was constructed in 2007 and 2008. Panels were connected by welding deformed rebar near the corners of each slab. During this time, another study was conducted to understand the Soviet precast panel manufacturing and design process to determine if the technology could be applied for U.S. efforts (27). To date only preliminary information is available on field testing.

Commercial Airfield Investigations
During the early 2000’s investigations were conducted at La Guardia International Airport, NY, and Dulles International Airport, Washington, DC (40,41). In 2001, precast panels were used to replace repairs were conducted at Dulles International Airport. Panel sizes utilized included 12.5 x 12.5 ft and 6.5 ft x 10 ft panels to repair damaged slabs on two taxiways. The repairs utilized the Uretek Method described later in this paper using foam injection leveling and fiberglass ties for load transfer restoration. The repairs conducted at La Guardia were conducted in test sections on Taxiway D-D using two types of precast panels, including 16-in.-thick conventionally reinforced panels and 12-in.-thick pretensioned precast panels. Both panels had dimensions of 12.5 ft x 25 ft and were each used to construct 100 x 50 ft test sections. Panels included male-female connections to establish load transfer using grouted dowel receptacles formed in the surface of a panel. Two unique aspects of the panel installation used were the use of setting bolts to minimize surface elevation differences and the use of a fast setting cement bedding grout. As of 2007, these sections were performing satisfactory, but no information has been published regarding the long-term performance (42).

Highway Repairs
In addition to the study of Soviet-style precast panels, numerous other studies have been conducted in the U.S. in recent years, but the major focus has been for highway repairs. A summary of precast panel initiatives since 1995, which resulted in a resurgence of interest and investigations into precast panels for highway repairs, has been published (15); thus, only a brief summary is provided here.

In the late 1990’s the FHWA sponsored research at Michigan DOT to investigate the use of precast PCC panel systems for full-depth PCC repairs. This work led to the “Michigan” method of precast slab repair discussed later in this paper. This method is one of the major repair methods available today for highway repairs using precast PCC panels (15,28). More recent activities include AASHTO promoted technology transfer of precast PCC repair and construction activities including precast panel design, fabrication, and repair installation specifications during 2006-2008 (15). In addition to the FHWA and AASHTO efforts, precast panel technology investigations have been conducted since 2000 by numerous agencies including Caltrans, Illinois Tollway Authority, Iowa DOT, New Jersey DOT, New Jersey Turnpike, New York State DOT, and the New York State Thruway Authority, among others. Other users reported include Colorado, Delaware, Florida, Hawaii, Indiana, Michigan, Minnesota, Missouri, Texas, and Virginia (15,29).
Strategic Highway Research Program 2 (SHRP 2)
From 2008 through 2012, SHRP2 Project R05-Modular Pavement Technology focused almost exclusively on precast panel technologies to develop and evaluate the use of modular pavement systems. As part of this research, various precast panel systems in the U.S. and abroad were investigated. Results (14) indicate that as long as the panels were installed with care including adequate bedding material and dowel alignment during installation, they have the potential to provide long-term service for pavement repairs of 15 to 20 years for highway applications. This projected long-term service life on highway pavements makes the use of precast panels for airfield repairs more promising.

Common Precast Panel Systems in the U.S.
Currently, the most common methods of precast panel repairs in the United States are the Fort Miller Super-Slab Method, the Michigan Method, and the Uretek Method or some variation of these three methods. Additional commercial systems have been developed recently including the Kwik Slab system (30) and the Roman Road System® by the Roman Stone Construction Company (31). The main differences between repair methods are the base support, panel size, and spacing and number of dowels. The following sections present a summary of each method and recent experiences with each method.

Fort Miller Super-Slab Method
Since 2002, Fort Miller Super-Slab® method has been used by several agencies in the U.S. with the most use occurring in New York, New Jersey, and California (14,32). The method consists of placing factory fabricated slabs on a carefully graded aggregate bedding material. Standard sizes can be produced; however, individual panels fabricated to fit the exact area (or warped to fill volume) to be replaced can be made. Panels are tied together through dowel receptacles that are manufactured in the bottom of the slabs to tie to existing or retrofitted dowels in the adjacent slabs (parent slabs). The dowel receptacles are grouted after placement with rapid-setting cementitious grout to provide slab interlock and allow load transfer using predrilled or manufactured grout holes. The panels also have grout holes that allow a bedding grout to be pumped under a slab through precast channels on the underside of the slab to fill voids and level the panels (33). If precast panels are connected, then dowel bars are cast on one side of the precast panel with dowel receptacles precast in the other side.

Michigan Method
In 2003, 21 precast panels were installed for a full-depth patching effort along two interstates in Michigan using the Michigan method. The panels were typically 12-ft long, 12-ft wide, and 10-in. thick, with three 1.5-in. diameter dowel bars cast into the precast panel wheel paths to provide load transfer across the joints (28). This method uses precast panels that are seated on a layer of flowable fill or alternatively leveled in place using injected high-density polyurethane foam through preformed or drilled holes. Dowel bars cast into the panels are connected to the surrounding pavement through dowel slots that are sawcut and excavated using a jack hammer. After the dowel slots or receptacles are prepared, the panels are lowered into place, leveled, and then the dowel slots are filled with a rapid-setting grout. The final step in the process is to seal the joints. Time-consuming repair activities include the preparation of the dowel slots, the sawcutting, demolition, and removal of the existing PCC, and the adjustment of the panel elevation with respect to the surrounding slabs (28).
Uretek Method
Uretek USA, Inc. developed a repair method for raising in-place slabs in the late 1990s. The method requires the injection of high-density polyurethane foam through holes drilled through the PCC surface into the sublayers to lift settled slabs to the elevation of the surrounding pavement. Recently, this method has also been applied for precast panel leveling using both the Michigan method and the Air Force method that will be described in a following section. For precast panels, the foam injection method is combined with surface mounted fiberglass ties to restore load transfer in jointed concrete pavements. In this repair method, a precast panel is lowered into the area where damaged pavement has been removed with little or no bedding preparation. The slab is then leveled by injecting the foam under the slab. Either injection ports are preplaced during panel construction, or they can be drilled after the slabs seated. Once the slabs are leveled, then the ties are used to provide load transfer between the precast panel and the surrounding pavement (15,34). The ties are inserted and grouted into slots that extend from the existing slab to the precast panel or precast panel to precast panel.

The U.S. Air Force evaluated the Uretek method without the fiberglass ties for leveling precast panels in 2007. Results of the study indicated that the Uretek method provided better load transfer between single panel repairs and the surrounding pavement than poured flowable fill seating preparations. However, the researchers did not recommend this procedure for expedient airfield repair applications due to the precision and training that would be required to properly use the foam injection system (34).

Kwik Slab System
The Kwik Slab System is a newer precast panel repair system developed and marketed in Hawaii and Singapore. The system relies on the placement of precast panels that are connected using steel couplers that are precast in one or more panel ends. The couplers are then grouted with a high-strength grout. The panels are lifted into place using polyurethane injection, through plastic leveling shims, or grout leveling pads (30).

Roman Road System®
The Roman Road System® is a newer precast panel repair system that was developed by the Roman Stone Construction Company in 2009. Panels are placed in the prepared repair area then lifted into place using injected polyurethane foam in the same manner as the Uretek or Michigan seating methods. The load transfer is provided by sawcutting through both the parent PCC and the precast panel and installing load transfer devices following the leveling of the panel. Dowels are placed in locations of expected truck traffic similar to the Michigan Method. The panels are typically 1-in. thinner than the existing pavement (14,31).

Air Force Method
Recently, the U.S. Air Force developed a method of airfield pavement repair using single precast panels. The panels were designed such that deployed personnel could assemble prefabricated forms in the field and cast and stockpile panels on-site for future use. Precast panels were prepared on site using specially designed forms made by the Air Force. The precast panels were 9 ft-10.5 in. long, 9 ft 10.5 in. wide, and 11-in. thick. Load transfer was provided by 10 1.0-in.-diameters, 22-in.-long dowels precast into the slabs on both sides of the panel in the direction of traffic. Similar to the Michigan method, dowel slots were sawcut and prepared in the surrounding
PCC as dowel receptacles. Following the placement of each panel, the dowel slots were filled with rapid-setting proprietary repair material.

In the study conducted by the Air Force, two single panel repairs were conducted using foam injection for leveling, and a third single panel was seated on a layer of flowable fill backfill. Each repair was trafficked using an F-15E load cart for 1,508 passes. Load transfer was monitored for each repair before, during, and after trafficking (34). Although the foam injected repairs provided better load transfer compared to the third repair, the flowable fill backfill provided sufficient support for the design traffic and was deemed suitable for contingency (emergency) repairs (34). Currently the U.S. Air Force Research Laboratory (AFRL) and the U.S. Army Engineer Research and Development Center (ERDC) are working together to refine the panel design and repair process so that single and multiple panel repairs can be conducted.

**Recent International Experiences**

In addition to the recent U.S. experiences, a resurgence of precast panel research has occurred around the world. Recent worldwide experiences with precast panels have also been reported (17). Several pilot studies were conducted in the Netherlands during the period 2004-2006 as part of a “Roads to the Future” contest by the Dutch Ministry of Transport. One precast panel concept investigated included ModieSlab. ModieSlab is a modular pavement structure where precast concrete panels are used to construct pavements that rest on concrete piles or are embedded in the existing pavement. A pilot study and accelerated pavement testing study were conducted using ModieSlab (among other technologies). In the pilot study, the ModieSlabs were constructed on a motorway in the Netherlands with reported problems such as smoothness, raveling, and polished aggregate (35-36).

A study was also conducted in France using hexagonal shaped panels (similar to the early Soviet precast airfield slabs) placed over a granular bedding material (17). This precast panel research was part of an ongoing Removable Urban Pavements research project coordinated by the Laboratoire Central des Ponts et Chaussees. This study focused on new road construction methods using modular precast concrete elements where small hexagonal panels were connected together to form a pavement surface that can be quickly removed and replaced when damaged. A modular road design allows repair teams to make repairs to the sublayers by removing the panels. Once sublayer repairs are complete, the panels may be reused or only the damaged panels replaced, potentially reducing costs of repaving the entire pavement section (37). Each slab was 8 in. thick and had an equivalent diameter of 5 ft.

**CANDIDATE REPAIR METHOD FOR AIRFIELD REPAIRS**

The literature reviewed revealed numerous investigations in recent years that show promise for widespread acceptance or use of precast panels for highway or roadway repair applications. Despite the amount of research applied to the topic of pavement repair, a single repair method or system has not been established in the U.S. or world-wide. As part of this research, the current methods of precast panel repairs were reviewed to select a single repair method that can be applied in current or modified form for contingency (emergency) airfield repairs anticipated in remote locations. In these locations, repair teams would not necessarily have access to proprietary repair materials or high-early strength concrete for cast-in-place repairs. Figure 1 presents several precast panels presented in the literature. Differences in the size of panels and number and spacing of dowels can be seen in this figure. Methods presented outside the U.S. were eliminated from consideration due to the lack of performance and design information available.
For repairs on permanent civilian or military airfields, commercial or generic systems could be used to prepare panels for placement; however for contingency repairs in remote locations, the needs of both situations must be considered to create an optimal system. Remote locations will most likely not be within suitable transport distance from precast yards with well established routes. Panel fabrication would be required on-site from locally available materials to decrease production and transport costs and ensure the panels would arrive without damage. Quick, efficient, and correct installation by available personnel that may not be completely familiar with this construction concept demands a system that requires limited training to operate and uses basic supplies and equipment a typical operator could use with little experience or little learning curve. For this reason, most commercial systems discussed in the literature are

FIGURE 1  (a) Soviet Style precast slab placement (26), (b) Super-Slab® installation (32), (c) Michigan method slab installation (28), (d) Roman Road Slab installation (31), (e) Kwik slab precast panel (30), and (f) Air Force method panel (34).
not applicable to this specific set of conditions. Commercial systems may be best applied for non-emergency repairs where repair window and transportation constraints are less stringent. Further investigation into the applicability of commercial systems intended for traditional airfield repairs utilized in non-emergency airfield repairs is recommended.

Other systems presented in the literature rely on prestressing panels before installation. Due to the nature of contingency repairs, these type panels are also not applicable for contingency repairs, because they require additional equipment and training that would not necessarily be available for troops tasked with repair in remote environments. Post-tensioning considerations would be the most difficult to implement for quick, small repairs, since multiple slabs are typically tied together, and significant work is required to complete post-tensioning efforts after the panel is placed on grade. By eliminating prestressed panels, several previously used systems were eliminated from further consideration.

The use of injected polyurethane foam has been investigated for use in multiple repair methods including the U.S. Air Force, Uretek Method, Michigan Method (injection method), Kwik Slab, and Roman Road. The injection of foam requires the use of highly trained personnel to inject the foam to prevent cracking of the panels, excessive lifting, and damage to surrounding pavements (38). While this process worked well in previous field investigations for precast panel leveling, it would be best applied for non-contingency environments. This step in the repair process also requires additional equipment and materials that may be difficult to maintain and store in remote locations. Due to the risk of failing to install the panels properly and equipment demands on an installation and personnel, methods that rely on injected foam leveling are not recommended for contingency airfield pavement repairs using precast slabs.

Backfilling options that remain include compacted aggregate and flowable fill. Compacted aggregate backfill is used in the Fort Miller method, where either a lightweight laser screed or customized spreading equipment is used to place the base and provide the correct cross-section shape. Heavy equipment is a necessity for this backfilling option, due to the area covered, quantities installed, and to achieve the acceptable tolerances required; however, using heavy equipment for small repair areas may be difficult and may damage the existing pavement. Additionally, previous studies conducted by the ERDC regarding different repair strategies for airfield repairs have shown repairs with aggregate bases take considerably more time to construct than flowable fill and foam, reducing the attractiveness of this option (39).

After eliminating repair methods for the various reasons stated above, only the Michigan method and Air Force method using flowable fill bedding remained for further examination. Both options are fairly the same in terms of ease of fabrication and use of commonly available materials. The Air Force method was only designed for single panel repairs, and the panels could not be connected to repair larger areas. The dimensions and doweling of both systems are also different, but this is not surprising since the panels were designed for different pavement applications. The Michigan Method size is suited for a replacement of a typical single highway lane slab measuring 12 ft wide and 12 ft long with dowels only in the wheel path, whereas the Air Force method is suited for a partial airfield slab replacement with an area of roughly 10-ft by 10-ft with dowels spaced at regular intervals across the panel. The lack of dowels and vehicle traffic sized slabs make implementation of the Michigan method very difficult for airfield use; thereby leaving the Air Force method as the most applicable for contingency airfield repairs.
COMPARISON OF PRECAST PANEL REPAIRS TO TRADITIONAL FULL-DEPTH AIRFIELD REPAIRS

In selecting a repair material or method to repair a damaged airfield pavement, one must consider the repair speed, cost, and performance. For contingency repairs, faster repair speeds and longer lasting repairs may come at a higher cost compared to traditional PCC repairs that require longer curing durations. Because of this, the speed, cost, and performance of precast panel repairs reported in the literature was compared to other repair methods.

Speed
Complete timing data for precast airfield repairs was only available for the Air Force method. For the Air Force method using flowable fill bedding material, a total repair time was reported to be 4 hours, however; this did not include curing of dowel slot material (34). A realistic return to service time for the Air Force method repairs would be 6 hours including a minimum 2 hour cure for a typical rapid-setting grout. Repairs conducted at Dulles International Airport took place over 6 nights with 7 hour work windows. The work was staged over several nights, and total time per repair was not reported (40). At LaGuardia Airport, test section timing data indicated that construction could be completed within a 36 hour timeframe (41).

Because of the lack of airfield repair timing data, highway work was also reviewed for additional information. Highway repairs using precast slabs may be installed in a single night (8 hour work window) or in two or more days when the repair process is completed in phases to minimize traffic disruptions (11, 15, 28). An FHWA study reported total precast panel repair times for several repairs in Michigan and Colorado of less than 4 hours, but these reported times did not include dowel slot material curing or joint sealing in the total repair time (11). Considering these reported times, the Air Force method is similar to those reported in literature for highway repairs.

If precast panels are selected for airfield repair work, filling the dowel is an essential work task that must be completed before reopening. Due to the loads and tire pressures aircraft have compared to automobiles, significant care must be taken to minimize damage to aircraft tires. High speed movements over multiple unfilled dowel slots, such as those required for the Air Force panels, would not be recommended. Traffic traversing precast repairs with open dowel slots may be more appropriate for road repairs using precast panels.

In comparing the Air Force panel method with rapid-setting repair techniques, the Air Force panel method requires more time than a cast in place rapid-setting material repair. ERDC testing has shown these repairs can be completed in less than 4 hours from identification of damage to reopening to traffic (39). Recent ERDC testing revealed slightly longer curing durations for non-proprietary rapid-setting or high-early strength PCC repairs. For these repairs, 4 to 8 hours were required prior to reopening to traffic (9).

Cost
The Air Force method panels cost approximately $2,500 (2011) each or $25/ft² including the panel, rapid-setting grout, joint sealant, miscellaneous disposable materials and flowable fill bedding materials. This cost does not include forms, labor, or equipment costs. The Minnesota DOT (2005) reported the lowest bid cost $9,040 per panel using the Fort Miller Method or $63/ft² (43). This is over 150% more costly than the Air Force method; however, it is unknown how
the MnDOT value was developed. Precast panel costs have decreased since this project and range from $27 to 56/ft$^2$ (14).

While the Air Force method appears to be similar in cost to current precast systems, its cost compared to cast-in-place methods for emergency repairs may not. The average cost for an emergency repair using proprietary rapid-setting repair materials in 2011 was $440-500/yd$^3$ depending on repair material utilized and $140-200/yd$^3$ for high-early strength PCC based on Vicksburg, MS PCC vendor pricing. For comparison purposes, the cost of conventional airfield PCC mixture was $125/yd$^3$. Based on an 18 in. full-depth PCC pavement repair (the maximum depth the Air Force method will replace—11 in. panel plus 7 in. of flowable fill), prices for these three cast in place repair methods (proprietary rapid-setting, high-early strength PCC, and conventional PCC) are $24 to 28/ft$^2$, $8$ to $11/ft$^2$ and $7/ft$^2$, respectively. The precast panel repair cost ($25/ft$^2$) is similar to proprietary rapid-setting repair materials but has a sizable cost difference to high-early strength or conventional PCC. This cost difference comes from the additional materials needed to construct the panel so it can be lifted into place, which account for approximately 67% of the total panel cost.

Performance
The only recent performance data reported in the literature using precast panels for airfield repair are from the Soviet style construction project and the Air Force Method research. The Soviet style panels were intended for airfield construction or pavement overlays. Simulated traffic testing with F-15E (35,000 lb single wheel load at 325 psi) and C-17 traffic (6 wheels with 38,500 lb tire load at 141 psi each) revealed the most cracking around joints and corners (26). The Air Force Method field testing resulted in the three panels trafficked not failing after 1,508 applications of F-15E traffic (34). The overall condition of the panels and surrounding pavement following traffic was good with minor spalling noted in the dowel grout near the joints.

Other reported performance of precast panels includes accelerated pavement testing in California indicating a repair life of 25-37 years for highway traffic for sections constructed using Fort Miller slabs (13). This life is based upon traffic data conducted with both simulated truck and aircraft loadings. The test section trafficked with simulated aircraft testing withstood over 1,500,000 load applications (approximately 34,000 lb single wheel load at 209 psi). Corner breaks, spalling, and cracking were noted at failure.

OPTIMIZATION OF SELECTED PRECAST PANEL METHOD
The Air Force method has a few drawbacks that require system modification or verification of specific design elements before implementation. Additional research will be required to thoroughly review the selected method’s precast panel design, fabrication methods, and field placement techniques to optimize critical items for a future field placement study:

- The panels were developed for installing a single panel into an existing damaged slab for repairs. Repairs not requiring replacement of an entire slab could be made using these panels; however, the current panel design does not allow for tying multiple slabs together for full-slab replacements.
- A review of typical airfield pavement slab sizes is required for selecting the appropriate panel size. A single set of panel dimensions will be selected to standardize prefabricated, reusable formwork, and construction methods. This design is very stringent and limits panel optimization at the project level from its “one size fits all” mentality; however, the
system will reduce storage, transport, and lifting challenges that could arise from multiple sized panels. This option eliminates the need to design sturdy, reusable formwork that is flexible enough to allow casting multiple different panel dimensions. Formwork designed for this task may not be cost effective for a few small jobs.

- The reinforcement design needed should be sufficient for all phases of the panel’s lifecycle and follow typical structural concrete design guidance. The panels should be lifted, transported, and stockpiled without damage.
- Lifting capabilities at remote locations are variable and are a design challenge. The dimensions of the panels and large removed mass sections of damaged pavement must allow for safe and efficient operation. Airfield pavements are generally thicker than roadway pavement since the loading per pass is significantly higher for aircraft. If lifting capabilities are limited, then thicker panels will require smaller panel dimensions for installation. Integrating a minimum crane size available at typical installations should be considered.
- Streamlining the work tasks required by personnel to fabricate panels and install into pavement is required to ensure panel quality and performance. Adapting existing or using common, commercially available equipment and disposable supplies is needed as well to limit the training or learning curve required for personnel with little construction related background knowledge and operation in various work environments.
- Techniques for prompt demolition of the damaged existing pavement should be explored since this is expected to be the most time consuming work task. Current methodologies focus on breaking the pavement into smaller, manageable pieces or removal of intact slabs. Removal of intact slabs shows the most promise for efficiency, speed, and mitigating existing pavement damage.
- Specifications for selecting flowable fill material and its expeditious placement as bedding material are needed. Strength requirements should revolve around preventing damage of this material under the various aircraft loads expected.
- The timing data reported for each individual work task used for installing the panels should be assessed to ascertain inefficient tasks. Modifications to the equipment or procedures should be used to reduce the overall installation time for minimal airfield downtime.
- The major failure modes precast panels experience under aircraft traffic require identification. Modifications to the materials used and panel design should be made to mitigate potential sources of foreign object debris damage and tire hazards.
- A cost-benefit analysis of the finalized precast system should be completed where the system is compared against other commonly used repair methods.

**SUMMARY AND CONCLUSIONS**

There has been resurgence in the use and study of precast PCC slabs for highway and airfield construction in recent years. The majority of research in the U.S. has focused on highway applications of precast PCC panels. This paper summarized worldwide experiences using precast PCC slabs for pavement repairs. For over 80 years, various procedures have been developed and investigated around the world, and these procedures are still evolving as more experience is gained. The advantages of using precast pavement technology include better quality concrete repairs through use of precision fabrication and reduced delay in reopening a pavement to traffic.
The main disadvantages of precast panel repairs include panel size restrictions due to lifting capabilities in the field, seating and leveling issues, and the uncertainty of the long-term performance of the current systems.

Based on the current methods and systems available, the Air Force method of precast panel repair was selected for further investigation for military contingency airfield repairs. Flowable fill was selected for the bedding material due to the cost, equipment, and operational concerns. Modifications will be required to tailor the system to best construct panels on-site, increase installation rates, determine the most efficient supplies and materials for use, and expand the system to allow for larger repairs with multiple panels. A cost-benefit analysis of the modified system is underway to compare this method against other accepted repair methods to assist with making proficient and justified decisions when conducting pavement repairs. Continued research is required to refine the current processes. Performance testing of single and multiple panel repairs under simulated aircraft loads is required to understand the life of the repairs under aircraft traffic.

FUTURE RESEARCH

The next step in this research effort is to optimize and investigate the field performance the selected Air Force method precast panel system. Optimization will focus on determining the most efficient panel dimensions based on projected slab sizes encountered, reinforcement needs, and lifting considerations. A standard listing of disposable supplies and small equipment needed to perform rapid airfield repair of PCC pavements with precast panels will be developed along with guidance to construct and install the panels. Supplies and small equipment recommended will encompass all aspects of the precast pavement job, from construction and storage of panels on the project site using local materials to installation of the cured panels.

Once all initial modifications are made, a full-scale field investigation will be conducted using the optimized system to determine the performance of partial- and full-slab replacements using precast panels in a PCC test section constructed at the ERDC. Panels will be trafficked to failure under simulated, accelerated C-17 aircraft loads. Data regarding the repaired pavement’s surface deterioration and mechanical properties will be collected during trafficking. In addition to performance, the required installation work tasks will be timed to assist with identifying required equipment or manpower requirements to complete repairs in less than 6 hours. Results of the field investigations will be used to make further improvements to the panel design, construction, and installation tasks. Additional field testing will be required to verify and finalize the panel design, construction, and installation procedures.

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