

Properties of Modern Flowable Fill Incorporating Rapid-Setting Cements: Laboratory and Field Studies of Dry Placement Method

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Abstract

Timely maintenance and rehabilitation is critical to ensuring the long-term sustainability of transportation infrastructure. Full-depth pavement repairs represent a significant investment of both time and money, but such repairs become necessary where localized pavement failures have occurred as a result of inadequate performance of the underlying support system. Subsurface layers are traditionally repaired using compacted lifts of aggregate. While this approach is relatively inexpensive, it is labor-intensive, time-consuming, and can lead to premature repair failure if the layer is not adequately constructed. Rapid-setting (RS) flowable fill provides a backfilling material option that flows under gravity to fill subsurface voids, self-consolidates, and sets rapidly to facilitate the early placement of surfacing material. The dry placement method is a novel technique in which the blended RS flowable fill is placed in its dry state and water is added without mixing. The performance of three commercially available RS flowable fill materials placed using the dry method was investigated using both laboratory and accelerated full-scale vehicle trafficking. Results from these experiments indicate that reduced repair time and in-place cost, as compared to traditional repair techniques, can be achieved when flowable fill containing RS cement is employed using the dry placement method.

Introduction

Facilities such as interstate highways and high volume airfields require rapid methods of repairing damaged pavements due to the high lost opportunity cost created by closure. In these situations, the time required to remove and replace the weakened sub-layer materials will increase the time and cost required to complete the repair. To reduce facility closure and worker exposure times, an expedited method that yields high quality repairs at competitive cost is desired. Modern rapid-setting (RS) cements have been used for developing RS concretes that require minimal cure times and exhibit good performance for pavement surface repairs [Priddy et al. 2009, Vaysburd et al. 1999, Shoenberger et al. 2005]. Flowable fills incorporating modern RS cements placed using the dry method provide an alternative to compacted aggregate to speedily repair damaged subsurface pavement layers.

The dry placement method saves time as well as equipment and labor cost compared to traditionally placed flowable fill by eliminating the mixing process. The constituent materials of flowable fill are typically batched individually, vigorously mixed using a rotating drum or volumetric mixer, and dispensed into a prepared excavation. When using the dry method, the pre-blended dry material is placed directly into the prepared excavation in thin lifts. Mix water is applied to the surface of each lift and allowed to percolate through the dry particulate matrix, hydrating the cementitious materials.

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The experimental program for this study consisted of testing three commercially available proprietary RS flowable fill materials placed using the dry method in a series of laboratory characterization tests. To verify laboratory performance data and to develop rapid repair techniques, a series of full-depth patches were placed in an experimental runway pavement consisting of a subsurface layer of dry-placed rapid-setting (DPRS) fill capped with a 25.4-cm thick RS concrete surface layer. After a short cure time of two hours, each repair was trafficked with load carts simulating McDonnell Douglas F-15C/D Eagle and Boeing C-17 Globemaster III heavy aircraft loads. During trafficking, the performance of the repairs was evaluated by monitoring surface damage, foreign object debris (FOD) generation, and permanent vertical deformation. This paper summarizes the results of the laboratory testing as well as the construction, loading, monitoring, and performance of full-scale pavement repairs. Additionally, the time and cost efficiency of DPRS fill is examined through comparisons with traditional compacted aggregate base and wet mixed RS flowable fill. Pertinent conclusions from the testing are summarized, and recommendations for future research are provided.

Research Significance

This study proposes a new method for repairing the base layer in rapid pavement repair operations. The study has three major features including: introduction of the dry placement method, laboratory characterization of the physical properties of materials placed using the dry method, and the performance evaluation of full-depth pavement repairs using DPRS fill. DPRS fill reduces repair time, as compared to traditionally compacted aggregate or wet mixed flowable fill, while providing a high quality base on which to place the surfacing material. DPRS fill results from the combination of flowable fill containing modern commercial RS cements and the dry placement method in an effort to advance rapid pavement repair methodology.

Background

Flowable fill is a fluid-like, cementitious backfill material that can be used in-lieu of traditional compacted aggregate. Flowable fill is commonly composed of portland cement, fine aggregate, and water. Other materials such as fly ash, slag, foundry sand, bottom ash, and chemical admixtures are also commonly employed in flowable fill blends [ACI 229R 2008]. Commonly used names for flowable fill include controlled low-strength material (CLSM), controlled density fill, soil-cement slurry, soil-cement grout, flow fill, unshrinkable fill, and K-Krete. RS cements can be substituted for traditional Type I or Type II portland cement to expedite the hardening time and short-term strength development of the material. Flowable fill containing RS cements, such as Type III portland or modern proprietary cementitious blends, is referred to as RS flowable fill.

These materials flow under gravity and do not require compaction or leveling. Flowable fill is traditionally used in place of compacted aggregate in backfill, utility bedding, void fill, erosion control, and pavement base applications. Despite the advantageous engineering properties, cure times approaching 24 hours have limited the widespread application of flowable fill in pavement repair applications [Pierce and Ihekweazu 2004]. Flowable fill incorporating RS cement eliminates extended cure times and is an ideal backfill material due to the high-early bearing capacity development, low potential for shrinkage and compression, low economic impact, low construction labor intensity, excavatability, and resistance to changes in moisture [Pons et al. 1998].

Flowable fill provides equivalent or greater strength, consistency, and reduced potential for settling as compared to traditional backfilling methods [Lundvall and Turner 2007]. Savings in project cost can be realized when using flowable fill due to reduced construction requirements (equipment and labor) [ACI 229R 2008]. RS flowable fill is an alternative to both compacted aggregate and traditional flowable fill that reduces facility closure time, and therefore, the operational cost of loss of use [Pierce and Ihekweazu 2004]. Reductions in cost can be further increased through the employment of DPRS fill that has minimal equipment and labor requirements. A summary of the descriptive characteristics of compacted aggregate, traditional flowable fill, RS flowable fill, and DPRS fill is presented in Table 1.

Table 1: Flowable Fill Characteristic Summary

	Compacted Aggregate	Traditional Flowable Fill	Rapid-Setting Flowable Fill	DPRS Fill
Ideal Applications	Commonly used backfill; new construction	Backfill; structural fill; utility bedding; void fill; bridge approaches; erosion control; pavement base	Backfill; structural fill; utility bedding; void fill; bridge approaches; erosion control; pavement base	Backfill; structural fill; utility bedding; bridge approaches; pavement base
Constituent Materials	Well-graded aggregate	Fine aggregate, Type I portland cement, water, fly ash, slag, chemical admixtures	Fine aggregate, Type III portland cement or proprietary rapid-setting cement, water, fly ash, slag, chemical admixtures	Fine aggregate, Type III portland cement or proprietary rapid-setting cement, water, fly ash, slag, chemical admixtures
Mixing Method	NA	Externally mixed in drum or volumetric mixer with required mix water	Externally mixed in drum or volumetric mixer with required mix water	No mixing required
Placement Method	Aggregate is placed and graded in 4 to 6-in. lifts	Discharged from mixer into excavation	Discharged from mixer into excavation	Placed and graded in 2 to 6-in. lifts; required water is added evenly to the surface of each lift
Compaction Requirement	Vibratory compaction using plate, hammer, or roller	No compaction required	No compaction required	No compaction required
Time to Place 0.76 m³ (minutes)^a	90 - 150	60 - 240	30 - 60	10 - 15
Minimum Curing Time (minutes)^b	NA	180 - 300	30 - 120	15 - 30
28-day UCS (kPa)^c	NA ^d	689 - 8,274	1,724 - 8,274	1,034 - 6,895
Advantages	Material is relatively inexpensive; readily available; method commonly used	Easy to place; versatile; minimal settlement; all-weather construction; reduces equipment needs; faster return to service	Same as traditional flowable fill; rapid return to service	Same as traditional flowable fill; fastest repair and shortest closure time; least equipment requirement
Disadvantages	Equipment requirements; settlement; relative labor intensive; takes longer to place	Lack of experience; hardening time; sloped final surface	Lack of experience; sloped final surface; cost	Lack of experience; cost; inconsistent hydration
Cost / 0.76 m³ (\$) ^e	20 - 50	75 - 150	250 - 450	250 - 450

^a Construction time estimates based upon 2010 RS Means CostWorks data [RSMeans 2010]

^b Average curing time values presented in literature [Pierce and Ihekweazu 2004]

^c Average compressive strength values presented in literature [ACI-229R 2008]

^d 100% California Bearing Ratio (CBR) equivalent to 345 - 689 kPa

^e Cost estimates based upon 2010 RS Means CostWorks data

Dry Placement Method. The cost of purchasing, renting, and operating mixing equipment contributes greatly to the total cost of utilizing flowable fill. The ability to harness the beneficial properties of flowable fill including high bearing capacity, rapid hardening time, and self-consolidation without the additional expense of using external mixing equipment presents a significantly improved employment scenario.

The dry placement method examined in this study involved placing the pre-blended dry RS flowable fill material without the use of external mixing equipment. Thin lifts (5.1 to 15.2-cm) of dry material are placed directly into the prepared excavation, and the required amount of mix water is metered over the surface of each lift. The water is allowed to percolate through the granular structure, hydrating the cementitious materials, forming a bound backfill with the properties of traditionally placed flowable fill. Once the surface water has dissipated, the process is repeated until the target backfill depth is achieved. Figure 1 illustrates the major steps in the dry placement method. This process is simple, does not require experienced labor or specialty equipment, and reduces backfill and repair construction time.

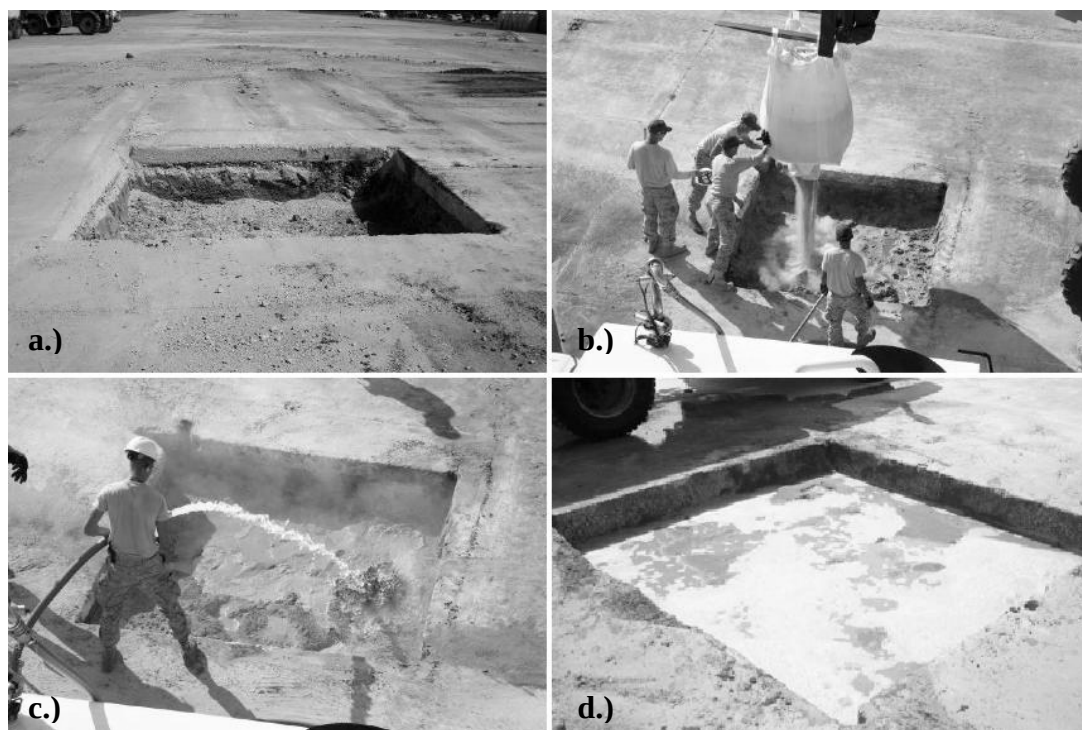


Figure 1: Dry Placement Method: a.) prepare repair area for backfill operations, b.) fill excavation with dry pre-blended RS flowable fill, c.) add required mix water to surface and allow to percolate completely, d.) repeat until final elevation is reached then observe necessary curing time prior to placing surfacing material.

Performance Criteria. The primary performance measures for flowable fill include compressive strength, flowability, hardening time, and excavatability [ACI 229R 2008]. Other characteristics such as subsidence potential, permeability, shrinkage, corrosiveness, and thermal conductivity are potential material design factors in select engineering applications. Performance criteria for RS flowable fill were established in this study based upon guidance provided in American Concrete Institute (ACI) 229R-99 [2008], U.S. Army Technical Manual 5-822-14 [1994], and operational assessments in U.S. Army Engineer Research and Development Center (ERDC), Geotechnical and Structures Laboratory (GSL), technical report TR-09-12 [2009]. In accordance with the referenced guidance, the performance criteria were established as follows:

- Minimum unconfined compressive strength (UCS)
 - 1,700 kPa after 30 minutes
 - 5,400 kPa after three hours

- No flowability requirement due to use of dry placement method
- Open to traffic within 30 minutes
- No excavatability requirement for permanent pavement repair

Laboratory Testing

The objective of the laboratory investigation was to determine the principle material characteristics of three commercially available RS flowable fill materials placed using the dry method and compare the performance to the same material placed using the traditional wet mix method. The primary performance measures of unconfined compressive strength and hardening time were evaluated in this study. Flowability is not a property possessed by flowable fills placed using the dry placement method and therefore was not included in this investigation. Additionally, the focus of this study was pavement base applications where long-term excavatability is not a factor, and therefore, it was not evaluated.

Hardening Time. Hardening time is defined as the time required for a flowable fill mixture to transition from a plastic to a hardened state with sufficient bearing capacity to support the weight of a person [ACI 229R 2008]. Hardening time is a key material property and greatly influences construction time and project cost. Typical hardening times range from one to five hours, but can be accelerated by the use of set accelerator admixtures or the substitution of Type III portland or proprietary RS cement blends for Type I/II portland cement. The hardening time of flowable fill mixtures were determined in accordance with ASTM D 6024 [2007]. According to this method, the flowable fill surface is ready for load application when the average Kelly Ball impact diameter is 7.6-cm or less, with no bleed water rising to the surface.

Unconfined Compressive Strength. The strength or bearing capacity of flowable fill is commonly quantified by measuring the UCS. Flowable fills are defined by the ACI as having compressive strengths of 8,300 kPa or less, compared to compressive strengths of 350 to 690 kPa for high quality compacted aggregate [ACI 229R 2008]. Guidance on the preparation and testing of flowable fill material specimens is provided in ASTM D 4832 [2002]. This procedure was used for forming specimens blended using the traditional wet mix method. However, a modification to the method was required for the specimens formed using the dry placement method. The specimens generated using the dry placement method were formed by filling half of a 15.2 x 30.5-cm cylinder mold with the dry flowable fill blend, adding the manufacturer specified mix water to the cylinder, and repeating this process for the upper half of the cylinder. Nine specimens for each investigated material were formed using the traditional method, and nine were formed using the dry placement method. Three cylinders from each placement method were allowed to cure for 30 minutes, 3 hours, or 28 days prior to UCS testing. Each cylinder was capped with a steel cap with neoprene pad and axially loaded until the specimen reached failure.

Results. The laboratory characterization testing pursued in this investigation was driven by the performance requirements developed for the rapid repair of highway and airfield pavements. The results from the laboratory investigation are presented below in Table 2.

Table 2: Laboratory Testing Results for Studied Materials

Designation		Product A		Product B		Product C	
	Threshold	Wet Mixed	Dry Placed	Wet Mixed	Dry Placed	Wet Mixed	Dry Placed
Hardening Time (min)	30	45	15	30	15	105	30
30-minute UCS (kPa)	1,724	1,517	5,033	4,413	689	0	207
3-hour UCS (kPa)	5,171	4,964	5,861	6,343	1,999	1,310	827
28-day UCS (kPa)	5,171	8,481	4,413	14,755	3,447	5,102	3,585
Cementitious Component	NA	Modified Portland Cement		Calcium Sulfoaluminate Cement		Portland Cement	
Material Cost (\$/0.76 m³)	NA	435		400		266	

The hardening times ranged from 30 to 105 minutes when the traditional wet mix method was used and 15 to 30 minutes when the dry placement method was employed. Factors affecting the hardening time of a flowable fill mixture include type and quantity of cementitious material employed, permeability of confining material, water content of mixture, mixture proportions, mixture and ambient temperature, humidity, and depth of fill [ACI 229R 2008]. Both the traditional and dry placement methods provide a prepared backfill ready for surfacing in a fraction of the time a similar surface could be provided using traditional compacted aggregate. However, a significant savings in construction time is possible when the dry placement method is selected.

The compressive strength values measured for the three investigated RS flowable fill materials at 30 minutes, three hours, and 28 days range from 0 to 5,033 kPa, 1,310 to 6,343 kPa, and 3,447 to 14,755 kPa respectively. The type and amount of cement, type and amount of supplementary materials such as fly ash and slag, water to cement ratio, chemical admixtures, density, air content, aggregate fabric, and the mixing, construction, and curing techniques employed determine the strength developed in flowable fill materials [ACI 229R 2008]. A considerable reduction in ultimate compressive strength is obtained with employing the dry method versus the traditional wet mixing method. The reduction in strength may be due to the irregular hydration of cementitious materials in the blend. An average of 52% of the ultimate UCS is retained when employing the dry placement method for the materials used in this study, which is adequate for rigid surfacing applications.

Field Testing

Field testing was conducted during April and May 2009 on a portland cement concrete (PCC) experimental airfield runway at Tyndall AFB, FL. The existing rigid pavement was composed of 4.6 x 4.6-m slabs that were either 22.9 or 38.1-cm thick. Five full-depth patches were constructed using DPRS fill for the base layer and a RS concrete material for the surface layer. Product A, examined during laboratory characterization, was selected for demonstration during the field testing because it was the only material providing the threshold bearing capacity at both 30 minutes and three hours. The geometry of each repair is presented in Table 3. The process used to

create the prepared excavation is presented in Figure 2. The silty-sand subgrade was excavated to a depth of 61.0-cm to allow for 35.6-cm of flowable fill backfill and a 25.4-cm RS concrete cap. No compaction of the subgrade material occurred prior to backfilling operations.

Table 3: Description of Repairs

Repair Designation	Parent Slab Dimensions (m)	Location within Parent Slab	Repair Area Dimensions (m)
1	4.6 X 4.6 X 0.2	North Center	2.8 X 2.5
2	4.6 X 4.6 X 0.2	Center	2.1 X 2.8
3	4.6 X 4.6 X 0.4	Center	2.7 X 2.2
4	4.6 X 4.6 X 0.2	South Edge	2.3 X 2.4
5	4.6 X 4.6 X 0.2	North Center	3.3 X 3.1



Figure 2: Excavation Preparation Procedure: a.) saw cut damaged pavement and upheaval, b.) remove damaged pavement and excavate until sound subgrade is reached, c.) trim excavation using hand tools to ensure vertical walls and level floor, d.) clear debris from surrounding pavement prior to backfill operations.

Repair Procedure. The repair procedure began by dispensing 1,361-kg supersacks of dry RS flowable fill into the bottom of the prepared excavation. After dispensing the contents of each supersack, hand rakes were used to quickly spread and level the dry material. The target lift thickness for the dry RS flowable fill was 7.6-cm. Three hundred three (303) liters of water were applied to the surface and allowed to percolate through the material. The time required for the mix water to percolate through the dry material matrix is controlled by the lift thickness and the gradation of the material. The percolation time observed in this field study ranged from 1 to 3

minutes. This procedure was repeated until the target depth of backfill was achieved. The personnel used to complete each repair included three laborers, one heavy equipment operator, and one crew foreman.

Once three of the five repairs were backfilled, placement of the RS concrete surfacing began using a second repair team. This allowed the repairs to be completed as quickly as possible while providing approximately 10 to 15 minutes of backfill cure time prior to capping. The capping material selected for these field tests was previously identified in tests by researchers at the ERDC as applicable for rapid airfield pavement repairs [Priddy et al. 2009, Shoenberger et al. 2005, Vaysburd et al. 1999]. The RS concrete material had a 28-day UCS of 41,369 kPa and was composed of proprietary RS cement, sand, and 1.0-cm pea gravel. The capping material was placed in accordance with manufacturer's specifications using a volumetric type mixer. After capping, each repair was struck level, finished using concrete hand tools, and air cured. The capping procedure using RS concrete is presented in Figure 3.



Figure 3: Capping Procedure using RS Material: a.) dispense material into excavation after observing required backfill curing period, b.) level surface using straight edge and finish using minimal handwork. Delay application of traffic until completion of manufacturer specified curing period.

The time required to backfill and cap each repair was recorded and is provided in Table 4. With the exception of Repair 1, the time required to backfill each repair ranged from 6 to 17 minutes. Repair 1 required 39 minutes to backfill due to repair team inexperience with the dry placement method and the employed equipment set. Based on actual backfill volumes and using a team of 5 people, the average backfill rate was 0.23 m^3 per min when Repair 1 is not considered and 0.20 m^3 per min when Repair 1 is included. The average time for capping a repair with RS concrete was 25 minutes including finishing activities. Therefore, the total repair time using a five-person repair team ranged from 42 to 91 minutes including preparation of the excavation, backfill, and capping activities.

Table 4: Backfill Volume and Timing Data

Repair Designation	Repair Activity	Activity Volume (m ³)	Time to Complete (minutes)	Total Repair Time (minutes)
1	Prepare Excavation	4.4	26	90
	Backfill Repair	2.5	39	
	Cap Repair	1.8	25	
2	Prepare Excavation	3.7	23	42
	Backfill Repair	2.1	6	
	Cap Repair	1.5	13	
3	Prepare Excavation	3.6	53	91
	Backfill Repair	2.1	17	
	Cap Repair	1.5	21	
4	Prepare Excavation	3.4	28	62
	Backfill Repair	2.0	9	
	Cap Repair	1.4	25	
5	Prepare Excavation	6.4	32	73
	Backfill Repair	3.7	16	
	Cap Repair	2.7	25	

Simulated Aircraft Loading. The constructed repairs were trafficked by simulated aircraft loadings to verify the performance of the repair materials. The F-15C/D load cart was designed to simulate the main gear of a McDonnell Douglas F-15C/D Eagle aircraft. The single-wheel F-15 C/D load cart was equipped with a 91.4-cm diameter, 27.9-cm wide, 18-ply tire inflated to 2,241 kPa. Lead weights were used to achieve a gross single wheel load of 11,204 kg representing a 25,855 kg F-15 C/D aircraft. A multiple-wheel C-17 load cart was designed to match one full main gear of a Boeing C-17 Globemaster III. The multiple-wheel C-17 load cart was equipped with six 127-cm diameter, 53.3-cm wide, 20-ply tires inflated to 979 kPa. The cart was loaded with lead weights to achieve a loaded weight of approximately 102,512 kg, resulting in estimated individual wheel loads of 17,463 kg representing a 227,703 kg C-17 aircraft. Figure 4 depicts both the F-15 C/D and the C-17 load carts used in this study.

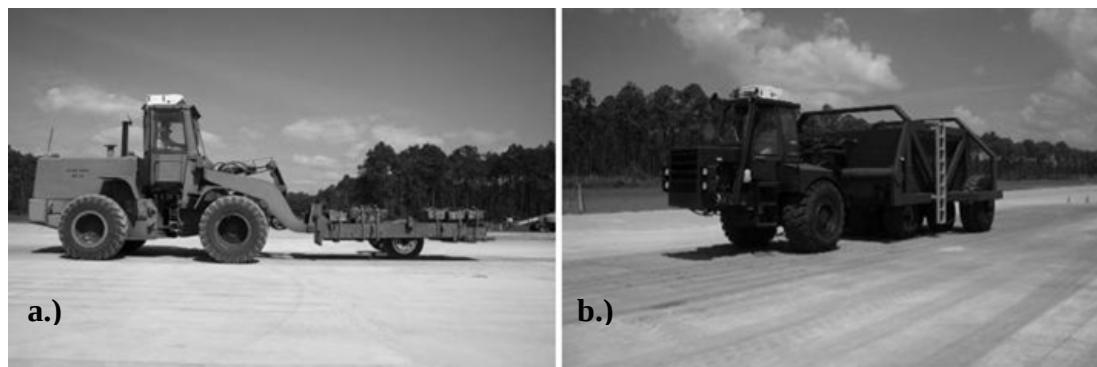


Figure 4: Traffic Testing Load Carts: a.) single wheel F-15 C/D
b.) multiple (6) wheel C-17.

Trafficking procedure. Traffic testing was conducted on Repairs 1, 3, and 5 using the F-15 C/D and C-17 aircraft load carts. Repairs 2 and 4 were not trafficked due to potential safety hazards associated with the proximity to damaged pavement near the

repairs. For Repairs 1 and 5, F-15 C/D traffic was first applied for 112 passes after 2 hours of curing. Additional F-15 C/D traffic was continued after 24 hours of cure until 1,800 passes were applied. Upon completion of the F-15 C/D trafficking, 500 C-17 passes were applied. For Repair 3, 112 passes of F-15 C/D traffic were applied, followed by 2,000 passes of the C-17 load cart. The different trafficking pattern was used because Repair 3 was constructed in an area of thicker pavement (38.1 versus 22.9-cm), and the parent slabs could withstand the heavier trafficking operations from the C-17 load cart with minimal damage. Traffic was applied by driving the load carts forward and back in the same wheel path, then moving laterally approximately one tire width, 22.9-cm for the F-15 C/D and 45.7-cm for the C-17. Each repair surface was periodically inspected for damage; however, maintenance was not conducted during or after the traffic testing process.

Results. Data collected during trafficking included periodic surface condition assessments (distress data), and pavement surface elevation measurements. Data collection was performed after the initial 112 passes of the F-15 C/D load cart and then every 500 passes of either load cart until trafficking was complete or repair failure occurred. Failure in this study was defined as greater than 3.2-cm permanent surface deformation, crack widths exceeding 2.5-cm or generation of FOD in excess of 0.64-cm.

Repairs 1 and 5 performed well under trafficking. After 1,800 passes of the F-15 C/D load cart, only minor spalling was noticed on Repair 1, and a hairline longitudinal crack developed on Repair 5. After the application of 500 C-17 load cart passes, neither repair failed, and surface distresses included light spalling along the approach and departure edges of the repair. Repair 3 performed well under trafficking as well. After 112 passes of F-15 C/D load cart, no changes in the repair surface condition were noticed. Following 2,000 passes of the C-17 load cart, the repair exhibited only minor spalling along the approach and departure edges of the repair.

Spalling along the edges of the repairs was most likely due to poor construction methods. A raveled edge was observed on the parent slab following saw cutting; however, because these repairs were conducted in an expedient manner, some spalling of the parent slab during saw cutting was permitted. When the repair was capped, a thin layer of material was feathered over the construction joint and onto the surrounding pavement when screeding and finishing the surface. This weakly bonded material was easily crushed under the heavy load carts creating FOD.

The change in elevation under traffic loads was measured periodically during trafficking to monitor settlement of the repair. The maximum amount of vertical deformation across the surface of each repair is presented in Table 5.

The final measured elevation changes are far below the U.S. Department of Defense maximum allowable elevation change requirements of 3.2-cm and 7.6-cm for the F-15 C/D and C-17 respectively. The measured values indicate that little settlement occurred in the DPRS fill base layer during trafficking.

Table 5: Deformation Data at Selected Traffic Intervals

F-15 C/D Passes	C-17 Passes	Permanent Surface Deformation (cm)		
		Repair 1	Repair 3	Repair 5
0	0	0.00	0.00	0.00
1,800	0	0.20	^a	0.13
1,800	192	^b	0.15	^b
1,800	288	^b	0.20	^b
1,800	384	^b	0.25	^b
1,800	480	0.46	0.23	0.38
1,800	1,000	^c	0.13	^c
1,800	1,500	^c	0.28	^c
1,800	2,000	^c	0.23	^c

^a Repair not subjected to F-15 C/D loading^b Data not collected^c C-17 trafficking discontinued due to tire hazard

Upon the conclusion of trafficking, three dynamic cone penetrometer (DCP) tests following ASTM D 6951 [2003] were conducted in each of the repairs (including the repairs not trafficked) to estimate the as-placed backfill strength using the dry placement method. DCP measurements were not collected prior to trafficking to ensure minimal cure times prior to capping and trafficking. The average DCP estimated California Bearing Ratio (CBR) for all of the repairs was 84 percent. The lowest estimated CBR was for Repair 3 at 50 percent with 70 percent measured for Repair 1. The remaining repairs resulted in refusal of the test device (100 percent CBR). The test results indicate that sufficient backfill strength can be achieved and retained under high load trafficking using DPRS fill.

Analysis and Discussion

The performance benefits of RS flowable fill as compared to traditional compacted aggregate backfill include material uniformity, increased bearing capacity, and reduced potential for settlement. However, operational benefits including construction time, worker exposure, labor intensity, and in-place cost are key factors that should be considered when selecting a backfill technology. In addition to the DPRS fill repairs presented previously, repairs using compacted aggregate and wet mixed RS flowable fill were conducted simultaneously using identical testing procedures for companion projects. This data will be presented in the following sections to allow for comparisons in rate of backfill and in-place cost to be conducted between the methods.

Construction Time Comparison. Total backfill time encompasses all the time required from batching the material to finalizing placement and varies on the material used. Placing, grading, and compacting are required for the conventional aggregate backfill. Batching, mixing (wet mixed only), placing, hydrating (dry placed only), and hardening time are required for flowable fill technologies. To measure the total backfilling time required by each method considered, five repairs of various geometries were backfilled using well graded granular crushed limestone and RS wet mixed flowable fill. The granular base was compacted in 15.2-cm lifts using

traditional soil construction techniques. The wet mixed RS flowable fill was batched into a 6.8 m³ rotating drum mixer following manufacturer's specification, mixed for five minutes, and discharged into the prepared excavation. The total time to backfill each repair was recorded, and the backfill rate was calculated by dividing the backfill volume by the placement time.

This data is presented in Table 6. As shown in this table, the compacted aggregate and wet mixed RS flowable fill backfill methods had similar average backfill rates of 0.06 m³ per minute. The DPRS fill placement method had an average backfill efficiency of 0.20 m³ per minute, allowing almost 0.14 m³ per minute more material to be placed using the dry placement method.

Table 6: Backfill Technology Production Rate Comparison

Repair Designation	Backfill Material	Repair Volume (m ³)	Repair Time (minutes)	Backfill Rate (m ³ /minute)
1	Limestone	2.4	43	0.06
2	Limestone	2.5	42	0.06
3	Limestone	2.5	38	0.07
4	Limestone	2.7	49	0.06
5	Limestone	3.9	57	0.07
	Average	2.8	46	0.06
6	RS Flowable Fill	2.5	41	0.06
7	RS Flowable Fill	2.3	51	0.05
8	RS Flowable Fill	1.5	63	0.02
9	RS Flowable Fill	4.0	64	0.06
10	RS Flowable Fill	4.9	53	0.09
	Average	3.1	54	0.06
11	DPRS Fill	2.5	39	0.07
12	DPRS Fill	2.1	6	0.36
13	DPRS Fill	2.1	17	0.12
14	DPRS Fill	2.0	9	0.22
15	DPRS Fill	3.7	16	0.23
	Average	2.5	17	0.20

In-place Cost Comparison. Reduced labor, equipment, and total construction time results in reduced in-place cost for a repair completed with DPRS fill versus compacted aggregate or traditional flowable fill. National average values for labor wages and equipment rental costs as published in the 2010 RS Means Construction Cost Data Book [RSMeans 2010], and the actual material costs were used to determine the cost of conducting each of the simulated full-depth pavement repairs. Material costs for aggregate are inexpensive as compared to the RS flowable fill materials. However, rapid setting times and reduced equipment requirements allow for lower labor and equipment costs for the flowable fill technologies.

Examination of the total cost per 0.76 m³ of backfill shows DPRS fill is the most cost effective of the backfill technologies examined. The in-place cost of the compacted aggregate, traditional wet mixed RS flowable fill, and DPRS fill using U.S. national average values were \$1,350, \$3,430, and \$2,940 respectively. The difference in cost between the compacted aggregate and RS flowable fills is due to the significant difference in material cost, \$25 per 0.76 m³ of crushed aggregate versus

\$435 per 0.76 m³ of Product A flowable fill. However, the economic impact of loss of use incurred by users due to construction activities can range from \$50,000 to \$75,000 for interstate highways and \$300,000 to \$500,000 for high volume airfields per half hour of closure time [Hu 2008, Hansen et al. 2009]. When considering the total economic impact of repair activities, DPRS fill has a high initial cost but provides the lowest total economic impact of the backfill technologies investigated in this study.

Conclusions and Recommendations

The objective of this investigation was to evaluate the performance of commercial RS flowable fills placed without use of external mixing equipment for the rapid repair of pavement base layers. Laboratory material characterization and field performance under simulated aircraft loads were investigated. The results of this study indicate that DPRS fill presents a promising new backfill alternative that reduces operations and total economic impact while providing sufficient performance for rapid pavement repair. Conclusions and recommendations from this investigation include:

- DPRS fill reduces the required number and skill set of laborers, eliminates the need for compaction and mixing equipment, and rapidly provides a base layer capable of withstanding construction traffic.
- In this investigation, approximately 0.06 m³ per minute of backfill could be placed using compacted aggregate or traditional wet mixed flowable fill; three times as much backfill (0.20 m³ per minute) could be placed using DPRS fill.
- RS flowable fill hardening times ranged from 30 - 105 minutes while DPRS fill materials were ready for load application 15 - 30 minutes after completion of backfill placement.
- Opening to construction traffic using DPRS technology was accomplished 15% faster than compacted aggregate base technology. The rapid opening time minimizes interruption of operation and exposure of workers to traffic hazards.
- On average, 52% of the ultimate compressive strength is retained when employing the dry placement method; the reduction in strength may be due to irregular hydration of cementitious materials.
- Pavements repaired with DPRS fill are capable of withstanding a minimum of 2,112 passes of heavy aircraft traffic with minimal surface settlement or distress development.
- Further research is required for the development of acceptance and quality control tests for DPRS fill that can be easily and rapidly conducted in the field.
- Caution should be observed when working with RS materials. Consult the manufacturer for guidance on performance, handling, and safety requirements prior to use.

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