Comparative Study of Full-Depth Reclamation Pavement Performance Using Different Cement Types

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Abstract. This study evaluates the performance of Full-Depth Reclamation (FDR) with cement stabilization using seven Egyptian cement types. Unconfined Compressive Strength (UCS) tests were conducted on samples with cement ratios ranging from 0.5% to 5.5% following ASTM D1633-2017. Results indicate that Al-Sahm Beni Suef cement (CEM I 42.5N) achieved 250 psi and 300 psi UCS at 1.5% and 2.2% cement ratios. The optimal cement ratio for 250 psi UCS varied between 1.20% (Al-Sahm Beni Suef cement) and 2.58% (Suez Sulfate-Resistant Cement) and the optimal cement ratio for 300 psi UCS varied between 2.20% (Al-Sahm Beni Suef cement) and 3.47% (Suez Sulfate-Resistant Cement). These findings provide actionable insights for selecting cost-effective and durable cement types for FDR projects in Egypt.

1. Introduction

According to Asphalt Recycling & Reclaiming Association (ARRA), Full Depth Reclamation (FDR) is defined as: "A pavement rehabilitation technique in which the full flexible pavement section and a predetermined portion of the underlying materials are uniformly crushed, pulverized or blended, resulting in a stabilized base course."(1) In general, it is preferred to maintain the roads and make the necessary periodic maintenance at acceptable intervals to save the performance of the road according to the design age and if periodic maintenance is not carried out early enough and if there are base/subbase/subgrade problems, it is likely that the road will reach a high state of deterioration that needs major rehabilitation. When flexible pavements fail, we have three main choices for fixing failures.

- First choice: A simple asphalt overlay
- Second choice: mill and fill
- Third choice: recycling the failed flexible pavement through a process (FDR)

Full-Depth Reclamation (FDR) is a sustainable pavement rehabilitation technique that recycles existing materials. While cement stabilization enhances FDR performance, the variability in cement types and their ratios significantly impacts outcomes. This study addresses the gap in standardized guidelines for cement selection in Egypt by comparing seven locally available cement types.

1.1 Problem Statement

Full-depth reclamation (FDR) is an increasingly common technique that is used to rehabilitate flexible pavements. The practice involves blending the surface asphalt course with the underlying base course material. Portland cement can be added during the blending process to improve the properties of the new base (3).

Implementation of FDR on rehabilitation projects produces several desirable benefits. Recycling of the asphalt surface course into base material yields a reduction in waste material that must be hauled out initially, as well as a reduction in new material that must be brought to the site. The reduction in material movement results in faster construction as well as lower project costs; reduced material movement also leads to fewer truck trips made and an overall decrease in the environmental impact of a rehabilitation project (4).

The selection process for stabilizing agents for FDR projects requires rigorous laboratory experiments. This process requires large quantities of reclaimed materials for extensive analyses of all contributing factors to pavement performance.

Decisions made by many agencies and stakeholders are usually limited in scale of stabilizing agents, and this limits the number of benefits derivable from the rehabilitation projects.

Case Study is the selection process between different cement types in Egypt.

1.2 FDR Application

FDR can be used under the following conditions:

-The pavement is high damaged and simple resurfacing cannot be Impactful.
-The pavement distress indicates that the problem may be in the base or subgrade.
-The existing pavement distress requires full depth patching over more than (15 to 20) % of the surface area.
(Although patching is often necessary to keep a road serviceable, it can be expensive. In fact, once the area of full depth patching exceeds 15 to 20 percent, simple math proves it less expensive to use FDR than to perform the patching. Of course, the final product achieved with FDR is far superior to a road that is severely patched). (2)
-Inadequate structural capacity for the current or future traffic

1.1.1 *Examples of where FDR can be used:*

1- High-traffic roads:

FDR is a popular choice for rehabilitating high-traffic roads because it can provide a long-lasting, cost-effective solution.

FDR is ideal for high-traffic roads like highways because it offers several advantages:

•Durability: FDR creates a long-lasting, strong pavement that can withstand heavy traffic loads for years to come. This leads to lower maintenance costs. (5)
•Cost-effectiveness: Compared to traditional pavement replacement, FDR can be a more cost-effective solution. It uses existing pavement materials, reduces waste, requires less time and labour. (6)
•Sustainability: FDR is an environmentally friendly option as it recycles existing materials and reduces the need for virgin resources. (7)

2- Airports:

FDR is often used to rehabilitate airport runways and taxiways because it can withstand the heavy loads and stresses of aircraft.

Airports demand pavements that can handle the immense weight and stress of airplanes. FDR comes to the rescue with its:

- High load capacity: FDR can withstand the heavy loads of airplanes without cracking or rutting. (8)
- Quick turnaround: FDR can be applied relatively quickly, minimizing downtime for airport operations. This is important for maintaining air travel schedules. (9)
- Resistance to jet fuel: FDR is formulated to resist the damaging effects of jet fuel spills, protecting the pavement and ensuring long-term performance. (10)

3- Local roads and streets:

FDR can be used to rehabilitate local roads and streets of all types, from residential streets to major arterial roads.

The benefits of FDR extend to local roads and streets of all types:

- Improved ride quality: FDR creates a smoother, more even pavement surface, leading to a more comfortable driving experience for motorists. (11)
- Reduced maintenance: FDR's durability minimizes the need for frequent repairs and maintenance, saving time and resources. (12)
- Versatility: FDR can be adapted to various pavement thicknesses and conditions, making it suitable for a wide range of local road applications. (13)

4- Parking lots:

FDR is a good option for rehabilitating parking lots because it can create a strong, durable surface that is resistant to cracking and rutting.

Parking lots also benefit from the advantages of FDR:

- Crack and rut resistance: FDR creates a strong, stable surface that resists cracking and rutting caused by heavy vehicles and harsh weather conditions. (14)
- Improved drainage: FDR can be formulated to enhance drainage, preventing water accumulation and reducing the risk of potholes and surface deterioration. (15)
- Aesthetics: FDR can be finished with various textures and colours, allowing for the creation of aesthetically pleasing parking lot surfaces. (16)

1.1.2 Some of the most common applications of full-depth reclamation:

1- Rehabilitating cracked and rutted asphalt pavements: FDR is the most effective choice to repair pavements that have been damaged by cracking and rutting. through removing asphalt and base layers and replaces them with a new stable and stronger base layer that provide more resistance to cracking and rutting.

2- Improving the load-bearing capacity of pavements: FDR can be used to increase the load-bearing capacity of pavements that are not strong enough to handle the traffic they are exposed to. The new stable base layer is much stronger than the original pavement and can support heavier loads.

3- Reducing pavement maintenance costs: FDR can be a cost-effective way to extend the life of pavements and reduce the need for frequent maintenance. The new, stabilized base layer is much more durable than the original pavement and requires less maintenance.

4- Recycling existing pavement materials: FDR is a very environmentally friendly process because it recycles the existing pavement materials instead of sending them to a landfill. This leads to more reduction of the amount of waste made by pavement construction and maintenance.

In addition to these general applications, FDR can also be used for other purposes, such as:
-Paving new roads and parking lots
-Stabilizing shoulders and slopes
-Creating a base for overlays
-Repaving roads with limited access
Overall, full-depth reclamation is a cost-effective pavement rehabilitation technique that can be used for many applications. It is a sustainable and environmentally friendly option that can lead to extend the life of pavements and reduce maintenance costs.

1.3 FDR Benefits

FDR has been growing in popularity over the past eight to 10 years. its benefits include minimal traffic disturbance, environmental friendliness, minimal use of virgin material and being an economical alternative to some other pavement preservation methods. The benefits of FDR can be placed into three major categories:

1.2.1 Economical Benefits

Full-depth reclamation (FDR) offers significant economic benefits compared to traditional pavement replacement methods. Here are some key advantages:

1-Reduced Material Costs:

•*Recycling existing materials: FDR reuses the existing asphalt and base materials, minimizing the need for virgin materials like aggregates and bitumen. This can lead to cost savings of up to 50% compared to traditional methods. (17)*

•*Reduced hauling and disposal: FDR eliminates the need to haul away old pavement materials and dispose of them in landfills, further lowering transportation and disposal costs. (18)*

2-Lower Labor Costs:

•*Faster project completion: FDR typically requires less time and labour than traditional methods, as it doesn't involve extensive excavation and removal of existing materials. This can lead to quicker project turnaround and reduced labour costs.*

•*Simplified process: FDR involves fewer steps and equipment compared to traditional methods, requiring less manpower and simplifying project logistics. (19)*

3 -Extended Pavement Life:

•*Improved durability: The stabilized base layer created by FDR is stronger and more resistant to cracking and rutting, leading to a longer pavement lifespan. This can lead to reduce maintenance costs over time. (20)*

•*Delayed need for major repairs: By addressing underlying pavement issues and creating a robust base, FDR can postpone the need for major repairs for many years, further contributing to cost savings. (21)*

4 - Additional Economic Advantages:

•*Reduced traffic disruptions: Faster project completion with FDR minimizes traffic disruptions and associated economic losses for businesses and commuters. (22)*

•*Environmental benefits: FDR's recycling and reduced material usage translate to lower environmental impact and potential cost savings associated with carbon footprint reduction.*

Overall, the economic benefits of FDR are significant, which makes it a cost-effective option for pavement rehabilitation. By reducing materials and labour costs and extending pavement life. FDR offers a sustainable and economical solution for various infrastructure projects.

The specific cost savings achievable through FDR depend on various factors like project size, pavement condition, and local material and labour costs.

1.2.2 Technological Benefits

Full-depth reclamation (FDR) is a pavement rehabilitation technique that offers significant technological advantages over traditional methods. By pulverizing and stabilizing existing asphalt and base materials, FDR creates a stronger, more durable base layer with several key benefits:

1-Enhanced Structural Performance:

•*Increased Strength and Durability: The stabilized base layer significantly exceeds the original pavement's strength, resisting heavy loads and pavement distress like cracking and rutting for a longer lifespan.*

•*Improved Flexibility: Specific stabilizing agents or additives can enhance base layer flexibility, accommodating traffic movements and ground shifts, further reducing cracking risks.*

2-Efficient Material Utilization and Sustainability:

•*Reduced Virgin Materials: FDR primarily uses existing materials, minimizing reliance on scarce resources like aggregates and bitumen. This lowers environmental impact and promotes resource conservation.*

•*Minimized Construction Waste: Traditional methods generate substantial waste, while FDR significantly reduces it by recycling and reusing existing materials.*

3-Faster and More Efficient Construction Process:

•*Reduced Construction Time: Less excavation and material removal compared to traditional methods lead to faster project completion, minimizing traffic disruptions and inconvenience.*

•*Simplified Construction Process: Fewer steps and less equipment streamline the construction process, reducing project complexity and overall time.*

4-Improved Pavement Performance and Maintenance:

•*Reduced Maintenance Needs: The durable base layer requires less frequent maintenance compared to traditional pavements, translating to lower long-term costs and improved performance.*

•*Enhanced Skid Resistance: Incorporating specific materials or additives can improve skid resistance, particularly in wet or icy conditions, enhancing safety for drivers and pedestrians.*

5-Adaptability and Versatility:

•*Suitable for Various Pavement Types: FDR effectively rehabilitates different asphalt pavements like highways, airport runways, local roads, and parking lots.*

•*Customizable Mix Design: Stabilizing agents and additives can be adjusted to suit specific project requirements and site conditions, offering greater flexibility and customization.*

6-Additional Technological Benefits:

•*Reduced Noise Pollution: FDR's smoother surface can reduce tire noise, contributing to a quieter environment for surrounding communities.*

•*Improved Drainage: FDR can be designed to enhance pavement drainage, minimizing water accumulation and potential damage.*

•*Reduced Thermal Expansion and Contraction: Stabilized base layers experience less thermal expansion and contraction, leading to fewer cracks and improved pavement longevity.*

Overall, FDR's technological benefits make it a more likely choice for pavement rehabilitation. It offers a solution to improve the performance of our transportation infrastructure.

1.2.3 Environmental Benefits

Full-Depth Reclamation (FDR) offers a range of significant environmental benefits compared to traditional pavement replacement methods. By reusing existing materials, FDR minimizes environmental impact in several keyways:

1-Reduced Resource Consumption:

•*Minimized Virgin Materials: FDR primarily relies on existing pavement materials, significantly reducing the need for virgin aggregates, bitumen, and other resources. These lowers quarrying and mining activities, conserving natural resources and minimizing environmental damage associated with their extraction and processing. (23)*

•*Reduced Transportation Emissions: By minimizing the need for virgin materials, FDR reduces the need for transportation, leading to lower greenhouse gas emissions and air pollution. (24)*

2-Decreased Waste Generation and Disposal:

•*Recycling Existing Materials: FDR recycles and reuses nearly 100% of the existing asphalt and base materials, significantly minimizing construction waste generated. This reduces landfill burden and associated environmental impacts, including land use, methane emissions, and leachate contamination.*

•*Lower Disposal Costs: Reduced waste generation translates to lower costs associated with waste transportation and disposal, further minimizing the environmental and financial burden.*

3-Reduced Energy Consumption:

•*Simplified Construction Process: FDR's simplified construction process requires less energy-intensive equipment and processes compared to traditional methods. This translates to lower overall energy consumption and associated greenhouse gas emissions.*

•*Faster Project Completion: By reducing construction time, FDR minimizes the need for equipment operation and fuel consumption, further contributing to energy savings and environmental benefits.*

4-Enhanced Pavement Longevity and Durability:

•*Improved Pavement Performance: The stronger and more durable base layer created by FDR extends pavement lifespan, reducing the need for frequent rehabilitation and replacement. This translates to fewer construction projects and associated environmental impacts over time.*

•*Reduced Maintenance Needs: The robust nature of the FDR-treated pavement minimizes the need for maintenance activities like patching and crack sealing. This reduces the environmental footprint associated with materials and energy consumption required for maintenance.*

5-Potential for Carbon Footprint Reduction:

•*Reduced Embodied Carbon: By reusing existing materials, FDR avoids the embodied carbon associated with extracting, processing, and transporting virgin materials. This can significantly contribute to lower overall carbon footprint compared to traditional methods.*

•*Improved Pavement Reflectivity: FDR can incorporate materials that improve pavement reflectivity, potentially reducing the need for artificial lighting and its associated energy consumption and emissions.*

Overall, FDR's environmental benefits are more, making it a sustainable and eco-friendly solution for pavement rehabilitation. By reducing resources, waste, energy consumption, and extending pavement life, FDR contributes to a cleaner and greener environment for future generations.

1.4 Research Objectives

Determine optimal cement ratios for target UCS values (250 psi and 300 psi), Compare the performance of seven Egyptian cement types and develop a decision-making framework for Egyptian road agencies.

2. Methodology

2.1 Materials

- Reclaimed Asphalt Pavement (RAP)
  Tests were carried out on (RAP), and the findings are outlined in Table No. 1.
- Cement Types Used: As shown in Figure 1 ,These are types of cement which used with (RAP)
  1. Misr Beni Suef cement (CEM II/A-P 42.5N)
  2. Al-Sahm Beni Suef cement (CEM I 42.5N)
  3. Suez Sulfate-Resistant Cement (CEM IV/A-P 42.5 SR)
  4. Tourah Pozzolanic Cement (CEM II/A-P 42.5N)
  5. Assiut Portland Pozzolanic Cement (CEM II/B-P 42.5N)
  6. El-Arish Cement (CEM I 42.5N)
  7. El-Arish Road Cement (Type C additives)
- Specimen Preparation:
  As shown in Figure 2, Specimens compacted using Proctor Molds (ASTM D1557).
  Curing Conditions: "Samples were cured at 25°C and 60% relative humidity for 7 days (ASTM D1633-17)."
  Moisture Control: "Moisture content was maintained using sealed containers and periodic weighing (ASTM D1557)."
- Test Protocol:
  - UCS tests conducted by ASTM D1633-17.
  - Cement ratios: 0.5%, 1.5%, 2.5%, 3.5%, 4.5%, 5.5%.
  - Three replicates per cement type and dosage.
  - Curing period: 7 days.

Figure 1. cement types which used with (RAP)

Figure 2. Specimens compacted using Proctor Molds (ASTM D1557).

Table 1. Results of Tests were carried out on (RAP)

specifications							Metadata					
							FDR Machine Product Materials				Sample Type	
							Sample1	Sample2	Sample3	Sample4	Sample Number	
							First: Visual inspection Materials of the output of recycling existing paving layers using FDR machine					
PCA 2019	FHWA-RD-97-148		ASTM D8038		ECP-2020		A mixture of stones resulting from crushing crushers and stones resulting from crushing asphalt layers				Visual inspection	
							Second: validity tests (gradation - type)					
							A- General Gradation Test					
							Passing Percentage					Sieves
100	-		-		-		100.0	100.0	100.0	100.0	AASHTO T27 ASTM C136/ C136M	3"
Not less than 95%	-		100		100		99.8	100.0	99.3	100.0		2"
-	100		100	95	100	70	93.4	93.8	96.0	90.3		1.5"
-	100	95	-		85	55	83.9	84.9	88.3	78.6		1"
-	100	84	92	70	80	50	72.9	72.4	79.5	66.7		¾"
-	100	70	-		-		56.5	55.6	64.5	49.5		½"
-	98	58	70	50	70	40	47.1	45.0	53.7	42.7		⅜"
Not less than 55%	75	38	55	35	60	30	44.0	39.0	45.0	41.0		4 #
-	60	25	-		-		26.5	24.2	27.9	26.5		8 #
-	-		-		50	20	28.1	26.4	33.1	24.9		10 #
-	40	17	-		-		23.0	23.3	25.4	20.0		16 #
-	35	10	-		-		21.0	20.0	22.0	17.0		30 #
-	-		-		30	10	18.0	18.0	20.1	15.0		40 #
-	25	5	25	13	-		15.2	15.5	18.5	13.5		50 #
-	20	3	-		-		9.7	8.2	13.5	10.5		100 #
-	15	2	8	0	15	5	7.6	4.8	10.2	7.9		200 #
B-Type Tests												
							Inelastic	Inelastic	Inelastic	Inelastic	ASTM D 4318 AASHTO T 89	Liquidity limit Plasticity limit Field of plasticity
							A-1-A	A-1-A	A-1-A	A-1-A	AASHTO M145 ASTM D 3282	Material classification
C. Proctor Test												
							2.11	2.09	2.13	2.10	"ASTM D-1557 AASHTO T-180"	Maximum dry density (t/m3)
							5.67	5.60	5.90	5.50		Fundamentalist water percentage (%)

3. Results and Discussion

Optimal Cement Ratios (%) for Achieving 250 psi and 300 psi Unconfined Compressive Strength (UCS) in Full Depth Reclamation (FDR)(See Table 2)

Table 2. Optimal Cement Ratios (%) for Achieving 250 psi and 300 psi Unconfined Compressive Strength (UCS) in Full Depth Reclamation (FDR) using Seven Different Cement Types, Including R-squared Values for Model Fit.

Cement Type	Cement Ratio for 250 psi	Cement Ratio for 300 psi	R^2 Value
Type 1	2.37	3.23	0.803
Type 2	1.5	2.2	0.917
Type 3	2.58	3.47	0.715
Type 4	2.4	3.29	0.583
Type 5	2.3	3.15	0.832
Type 6	2.45	3.3	0.772
Type 7	2.4	3.15	0.857

[a] Note: UCS = Unconfined Compressive Strength. Cement ratios are expressed as percentages. R^2 values represent the coefficient of determination for the relationship between cement ratio and UCS.

As shown in Table 2: Type 2 cement exhibits the lowest cement ratios for both 250 psi and 300 psi UCS. This suggests that Type 2 cement is the most efficient (among those tested) in terms of strength development per unit of cement used. It requires significantly less cement (1.5% for 250 psi and 2.2% for 300 psi) compared to other types. This could translate to cost savings and potentially environmental benefits due to reduced cement consumption.

Type 3 Requires Highest Cement Ratio for 300 psi: For achieving 300 psi, Type 3 cement requires the highest cement ratio (3.47%). This indicates that Type 3 is the least efficient for achieving this specific strength target among the cements tested.

3.1 UCS Performance by Cement Type

1. Superior Performance of Al-Sahm Beni Suef Cement (CEM I 42.5N):
   - Demonstrated the highest efficiency in stabilizing Full-Depth Reclamation (FDR) pavement layers, achieving an Unconfined Compressive Strength (UCS) of 250 psi at a cement ratio of 1.5% and 300 psi at 2.2% (lower ratios compared to other cement types). See Figure 3, for cement ratios results for both 250 psi and 300 psi UCS for cement type 2 (Al-Sahm Beni Suef cement (CEM I 42.5N))
2. Optimal Cement Ratios:
   - To achieve 250 psi UCS: Ratios ranged from 1.20% to 2.58%, depending on cement type.
   - To achieve 300 psi UCS: Ratios ranged from 2.20% to 3.47% (see Figure 3).
3. Impact of Cement Type:

- Other Egyptian cement types showed significant performance variability, highlighting the need for careful material selection.

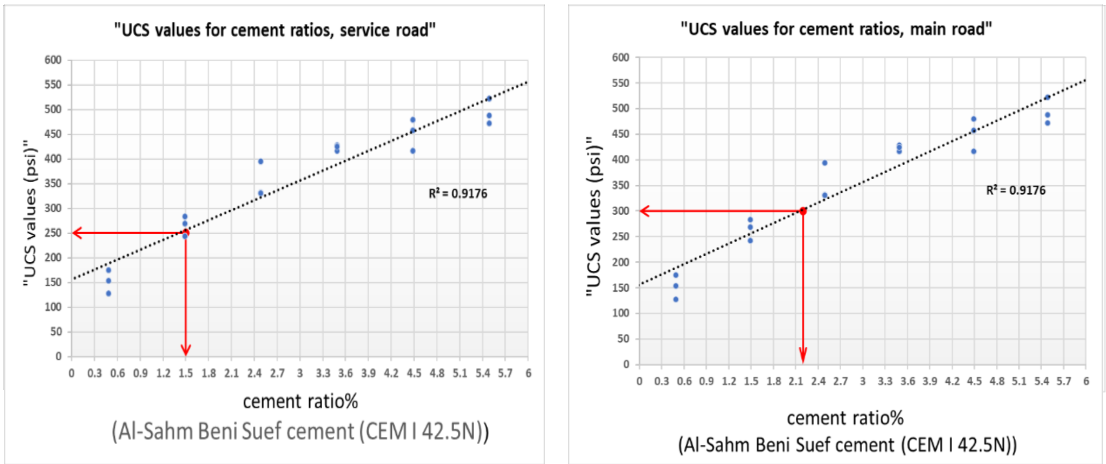

Figure 3. cement ratios for both 250 psi and 300 psi UCS for cement type 2 (Al-Sahm Beni Suef cement (CEM I 42.5N))

3.2 Statistical Analysis

R^2 values were calculated to assess the goodness-of-fit for regression models, with 95% confidence intervals applied to ensure result reliability (see Table 2).

4. Conclusions

1. Cement Type and Optimal Ratios:
   - Selecting the appropriate cement type (e.g., CEM I 42.5N) and its optimal ratio is critical for achieving cost-effective durability in FDR projects.
2. Cost Efficiency:
   - Al-Sahm Beni Suef cement's lower required ratios reduce consumption by up to ~30% compared to other types, while maintaining performance.
3. Practical Recommendations for Egyptian Construction:
   - These findings provide engineering benchmarks to guide cement stabilization decisions in Egyptian infrastructure projects, particularly for large-scale, budget-constrained initiatives.
4. Alignment with Global Standards:
   - The study confirms that the proposed optimal ratios align with international road pavement standards (e.g., ASTM, AASHTO)

References

[1] ARRA. (2001). Basic Asphalt Recycling Manual. Asphalt Recycling & Reclaiming Association.
[2] FHWA. (2017). Full-Depth Reclamation with Cement Stabilization. FHWA-HRT-17-089.
[3] Guthrie, W. S., et al. (2001). Selecting Optimum Cement Contents. Texas Transportation Institute.

[4] ASTM International. (2017). Standard Test Method for Compressive Strength of Molded Soil-Cement Cylinders (ASTM D1633-17).

[5] Luhr, J. D., Adkisson, L. D., & Gress, D. L. (2014). Guide to full-depth reclamation (FDR) with cement. Portland Cement Association. This document provides a comprehensive overview of FDR with cement, including its benefits for high-traffic roads.

[6] Federal Highway Administration. (2018). Pavement Rehabilitation Manual. Chapter 5: Full-Depth Reclamation. This manual outlines the technical aspects of FDR and its applications for various pavement types. https://www.fhwa.dot.gov/pavement/

[7] American Road & Transportation Builders Association. (2023). Pavement Sustainability Report. This report highlights the environmental benefits of FDR compared to traditional pavement replacement methods.

[8] Airport Cooperative Research Program. (2014). Guide for Pavement Rehabilitation of Existing Airport Runways. ACRP Report 126 page 38 . This report provides guidance on choosing appropriate rehabilitation techniques for airport pavements, including FDR. https://www.nationalacademies.org/trb/transportation-research-board.

[9] Airport Cooperative Research Program. (2014). Guide for Pavement Rehabilitation of Existing Airport Runways. ACRP Report 126 page 39 .

[10] Airport Cooperative Research Program. (2014). Guide for Pavement Rehabilitation of Existing Airport Runways. ACRP Report 126 page 40 .

[11] National Center for Asphalt Pavement Technology. (2020). Full-Depth Reclamation (FDR) for Local Roads and Streets. This document provides information on FDR applications for local pavements, including its cost-effectiveness and improved ride quality.

[12] American Society of Civil Engineers. (2018). Journal of Infrastructure Engineering. Volume 24, Issue 3: Full-Depth Reclamation for High-Traffic Urban Arterials. This article presents a case study of FDR on a busy urban arterial street, showcasing its performance and benefits.

[13] American Public Works Association. (2023). Public Works Magazine. Article: FDR: A Sustainable Option for Local Road Rehabilitation. This article discusses the positive environmental and economic impacts of FDR for local roads.

[14] National Concrete Pavement Association. (2019). Pavement Design Guide for Parking Lots. Chapter 8: Full-Depth Reclamation. This guide provides design recommendations for using FDR in parking lot pavements.

[15] Asphalt Institute. (2018). Manual Series No. 23: Asphalt Pavements for Parking Lots. This manual discusses various pavement construction techniques for parking lots, including FDR.

[16] International Parking & Transportation Association. (2022). Parking Magazine. Article: FDR: A Durable and Sustainable Solution for Parking Lot Rehabilitation. This article highlights the advantages of FDR for parking lot surfaces, including its crack and rut resistance and aesthetic appeal.

[17] "Recycling and Rehabilitation of Pavements: A Review" by J.L. Zhou (2017), Department of Civil and Environmental Engineering, North Carolina State University. This study found that FDR can lead to cost savings of up to 50% compared to traditional methods due to the reuse of existing materials.

[18] Full-Depth Reclamation Saves Money and Resources" by the Asphalt Recycling and Reclaiming Association (ARRA, 2018). This report highlights the significant reduction in hauling and disposal costs associated with FDR due to the avoidance of landfill waste.

[19] "Full-Depth Reclamation: A Contractor's Guide" by the Federal Highway Administration (FHWA, 2015).

[20] "Long-Term Performance of Full-Depth Reclamation Pavements" by M.O. El-Basyouny and D.L. Allen (2010), Department of Civil and Environmental Engineering, University of Illinois at Urbana-Champaign. This study found that FDR pavements exhibit improved durability and resistance to cracking and rutting compared to traditional pavements, leading to reduced maintenance costs

[21] "A Pavement Preservation Primer" by the American Road & Transportation Builders Association (ARTBA, 2021). This document emphasizes how FDR addresses underlying pavement issues, creating a stronger base and delaying the need for major repairs for several years.

[22] "The Economic Benefits of Pavement Preservation" by the National Center for Asphalt Technology (NCAT, 2019). This report highlights the economic benefits of minimized traffic disruptions associated with faster completion times of FDR projects.

[23] Federal Highway Administration (FHWA), "Full-Depth Reclamation (FDR) with Cement Stabilization," 2017 https://www.fhwa.dot.gov/pavement/sustainability/

[24] FHWA, "Life-Cycle Cost Analysis of Full-Depth Reclamation (FDR) with Cement Stabilization," 2013.