A REVIEW OF FULL-DEPTH RECLAMATION AND ITS ROLE IN SUSTAINABLE ROAD INFRASTRUCTURE

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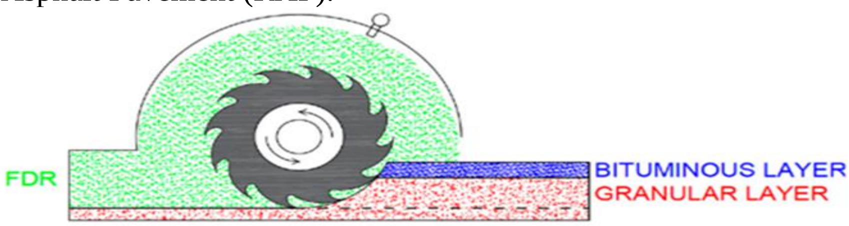
Abstract
Full-depth reclamation (FDR) is a method of rehabilitating asphalt pavement by recycling existing materials into a new base layer. The FDR process involves using a road reclaimer to pulverize the existing asphalt pavement and a portion of the underlying layers. The pulverized material is mixed with a stabilizing material, such as cement, to create a uniform and upgraded blend. The stabilized material is compacted in place using rollers to create a stiff and stable base. The most of the researchers aims to explain the details of FDR, including its basic principles, advantages, challenges, and recent progress. By carefully examining various studies, this review paper provides insights into different aspects of FDR, considering factors like the environment, economic impacts, and its potential to transform traditional road construction. The review also identifies gaps in current knowledge, offering a guide for future research and promoting a more informed use of FDR. The focus is on exploring materials, such as rice husk and Recycled Asphalt Pavement (RAP), and their impact on the environment. This reflects a shared commitment to constructing environmentally friendly pavements. Shifting to clayey soils, another study investigates how adding high calcium fly ash and cement can strengthen these soils for road construction. These enhanced soils perform well under traffic, with positive changes observed at a molecular level. This innovative approach addresses various soil-related challenges, from improving durability in saline environments to adopting eco-friendly solutions in road construction. As FDR gains popularity, researchers are working to refine and expand its applications, aligning with contemporary sustainability goals. A crucial advancement is the identification of a reliable test for predicting field modulus, allowing more accurate assessments of FDR materials in different conditions. However, there are still gaps in understanding, highlighting the need for further research to enhance our knowledge of FDR's behavior in various scenarios. The use of naturally occurring materials like rice husk and recycled asphalt pavement aligns with sustainability goals, showcasing a creative way to utilize available resources. This review emphasizes the transformative potential of FDR in road construction, not just for economic benefits but also as a champion of sustainability. It demonstrates that effective construction methods can coexist harmoniously with environmental stewardship. The identified gaps in knowledge pave the way for future research, ensuring that the adoption of FDR is based on a thorough understanding of its implications. As FDR becomes more widespread, its role in creating a greener, more sustainable future for road construction becomes increasingly significant.

Keywords: Full-depth reclamation (FDR), Road, Eco-friendly method, Environmental effects, Rice husk, Recycled Asphalt Pavement (RAP).



Source : H. Gonzalo-Orden, A. Linares-Unamunzaga, H. Pérez-Acebo, and J. Díaz-Minguela[1]
Figure 1 : full depth reclamation section[1]

Introduction

Full-depth reclamation (FDR), a method for building and maintaining roads, has become more well-known in recent years thanks to its affordability, effectiveness, and sustainability. [2] The procedure entails recycling the preexisting base and pavement components to produce a brand-new, stronger road base. [3] A fresh layer of asphalt or concrete is then put down to create a smooth driving surface. We shall discuss the FDR method, its benefits and drawbacks, and its different applications in this post. We'll also look at the various FDR variations and the variables that affect its effectiveness. Using sophisticated machinery, the existing pavement and base materials are first ground up during the FDR process. The material is ground into a powder and then combined with a stabilizing substance, like cement, lime, or asphalt emulsion, FDR also reduces the carbon footprint of road construction and promotes a sustainable built environment. The FDR procedure is adaptable and can restore a variety of road types, including city streets, interstates, and airport runways. It works particularly well to fix roads that have considerable structural damage or need a lot of upkeep. FDR can enhance the performance of parking lots and dirt roadways [3]. There are various FDR processes, including full-depth reclamation with cement stabilization, hot in-place recycling, and cold in-place recycling full-depth reclamation with cement (FDR-C). While hot in-place recycling (HIR) employs heat to recycle the base and pavement components, cold in-place recycling (CIR) recycles these materials at room temperature. With cement, FDR-C stabilizes the recycled materials to produce a more robust and long-lasting road basis.[4] However, several factors, including the caliber and condition of the existing pavement, affect how well the FDR procedure turns out.[1] Careful management and execution of these factors are necessary for FDR to result in a durable and long-lasting road base. In summary, FDR is a sustainable and cost-effective road construction and maintenance process that has become increasingly popular in recent years. It offers several advantages, including reduced construction time and costs, improved road durability, and enhanced sustainability.[2]However, its success depends on several factors, including the quality of existing materials, the type and amount of stabilizing agent used, and the construction crew's skill and experience. With careful planning and execution, FDR can create stronger, more durable, and sustainable roadways that can withstand the test of time.[3][1][4]The coarse aggregate in cementitious composites not only enhances mechanical properties but also reduces cement demand, thereby decreasing production costs for concrete infrastructure. The Researchers focuses on understanding the effects of different coarse aggregate types and contents on the compressive and flexural properties of ultra-high-performance fiber-reinforced cementitious composite (UHPFRC).[5] By investigating four types of aggregates (granite, basalt, limestone, steel slag) and varying content levels (0%, 15%, 30%, 40%), the findings reveal a substantial increase in compressive strength and elastic modulus with a moderate addition of coarse aggregate. This improvement comes at a marginal expense, namely a slight reduction in flexural strength and post-peak ductility. [5], [6]Significantly, the review study emphasizes the effectiveness of different aggregate types in either enhancing compressive strength or improving post-peak ductility, a trend that extends to increased aggregate content. Concerning flexural behavior, the type of aggregate notably influences flexural strength and equivalent flexural strength ratio, while minimal variations are observed in first crack strength. In conclusion, the research proposes an analytical model for generating comprehensive compressive stress-strain curves for (UHPFRC). To summarize, this study provides insights into optimizing UHPFRC for cost-effectiveness and mechanical robustness through strategic incorporation of coarse aggregate.[5], [7], [8]

Material & methods

In most of the research road had high-float and micro-surfacing layers on top of the granular base and sub-base layers. [11] For the new base in the FDR process, a blend of 40% Recycled Asphalt Pavement (RAP) from chip seal and micro-surfacing and 60% granular material was used.[12] Granular material with a chip seal coating makes up the foundation and sub-base of another research road. FDR involved blending 80% granular material and 20% RAP (chip seal material). [13] however, included a foundation and sub-base made of granulated material with a covering of asphalt concrete.[10], [11], [12]

Common mix Design In FDR

FDR usually uses a mixture of two thirds granular material and one third asphalt, while there are many different possible mixes of granular and bituminous materials. Researchers decided to investigate this mixture, which has a 20 cm granular material thickness and a 10 cm asphalt mix thickness. [14], [15] When building roads, this mix design which offers a well-balanced combination of strength and stability is widely used. Full Depth Reclamation uses an old road mix of in various ratios to build a new, sturdy base. [16] The selection of materials is determined by the distinct features of each road, guaranteeing durability and flexibility. Additionally, the rejuvenation process has a standardized but helpful touch because to the homogeneous mix formulation.[13], [14]

NaoH- Sodium Hydroxide AE- Asphalt Emulsion CR- Crushed Rock
FA-Fly Ash HL-Hydrated Lime
Source : T. Bualuang, P. Jitsangiam, and T. Tanchaisawat,[9]

Figure 2 : Different Additives & Stabilizers [9]

2.1. Soil

The Full Depth Reclamation (FDR) approach incorporates soil in a multi-step process that creates a strong basis for new road surfaces by removing current pavement and underlying layers, including soil.[15][10], [11]

2.1.1. Pulverization

The first stage of FDR involves crushing the previous pavement and any underlying layers, including the soil, using large machines like pulverizes or reclaimers. This important step creates a homogenous mixture out of the current ingredients, which sets the stage for the rejuvenation process.[10]

2.1.2. Stabilization

The second step is essentially about shaping the dirt to fit the needs of the project. Depending on the project's objectives and the qualities of the existing soil, various additives are applied to increase certain attributes. These additives may consist of foamed asphalt, fly ash, cement, or lime. Their function is to increase the strength, resilience, and workability of the soil so that it can serve as a stable foundation for the newly installed road surface.[11], [16]

2.1.3. Mixing
After stabilization, the added additives and ground soil are well mixed. This careful mixing guarantees the production of a stabilized base material with the attributes required to support the future road surface.[2], [17]

2.1.4. Compaction
Achieving the required density and stability of the blended material requires compaction. To compact the mixture and ensure its stability and strength, heavy rollers or compactors are used. The foundation for the road's resilience to traffic and environmental stresses is laid during this phase.[12], [18][12], [13], [14]

2.1.5. Final Surface
The reclamation area is graded to create the appropriate road profile after compaction. The last step is to finish the road surface and prepare it for usage by placing a fresh layer of concrete or asphalt on top of the stabilized base.[13], [19]

The precise selection of soil and additives is essential to the success of FDR; this reviews decision is impacted by the particulars of the project, the local soil, and the intended road standards. [15] The main objective is to provide a solid, durable, and affordable foundation for the new road while reducing trash and the environmental effect by reusing existing materials. [21] FDR is still a crucial technology for building sustainable roads, but new developments in soil exploitation and continuous research, when combined with the right additives, should improve methods and increase their flexibility to a variety of soil types across the globe. As a result, FDR would be better positioned in the field of road engineering as a common and sustainable approach.[15], [16], [17]

2.2. Portland Cement
Portland cement's durability and versatility make it an essential part of modern construction. For this investigation, ordinary Portland cement (OPC Type I) that complied with ASTM C150 standards was acquired from Phoenix in Malaysia.[14], [18]

2.3. Rice Husk Ash
Rice husk ash, often thought of as a byproduct, became a greener choice during the FDR era. Though generally discarded, it shows potential as a pozzolanic material particularly in lime-pozzolana mixtures and could be used in place of Portland cement.[19], [20]

2.4. Asphalt Emulsion
When used in FDR, asphalt emulsion improves the reclaimed base material's qualities. Using this technique, old pavement is ground up, combined, and stabilized to create a new road base. As a binding agent, the emulsion a mixture of asphalt cement, water, and an emulsifying agent improves the functionality of the reclaimed foundation.[21], [22], [23], [24], [25]

2.5. Aggregates
Two soil types were considered, to be mixed with Recycled Asphalt Pavement (RAP). The first sample, SP-SC, from beneath an HMA layer, aligns closely with subbase material standards.[23], [25], [26] The second sample, GW-GC, from a material closely resembles base material standards. Both soils underwent rigorous testing, considering characteristics like optimum moisture content, maximum dry density, liquid limit, plasticity index, sand equivalent, and soaked CBR. [6], [7], [23]

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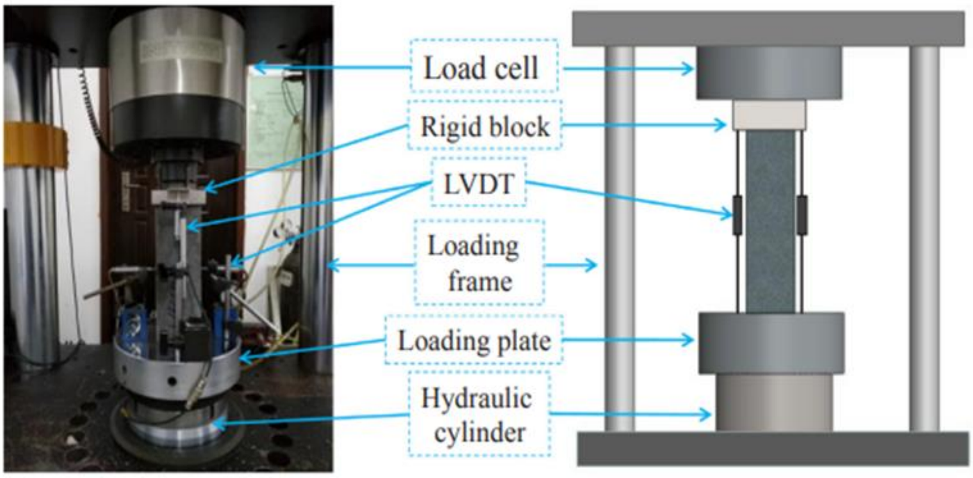
TEST CONDUCTED

Unconfined Compressive Strength (UCS) Test

This test assesses the strength of treated or stabilized soil. It involves applying stress to samples using a machine and measuring the response. The samples are cured for specific periods (7 or 28 days), and UCS is determined based on the average of two measurements.[6], [7], [28]



Source : F. Wu, L. Xu, Y. Chi, Y. Zeng, F. Deng, and Q. Chen [7]

Figure 3 : Stress-Strain Test Setup [7]

California Bearing Ratio (CBR) Test

This test measures the strength and swelling of soil with different percentages of Recycled Asphalt Pavement (RAP). Samples are compacted, saturated, and subjected to specific conditions. The CBR value indicates the material's suitability as a base for road surfaces.[27][26]

Mechanistic Sensitivity Analysis

This study explores how variations in the FDR base modulus affect pavement performance. Using Win JULEA software, engineers model reactions in pavement sections to understand the impact of different FDR attributes.[29], [30]

Durability Test

FDR combinations undergo conditioning procedures – dry, soaking (wet), and vacuum saturation. These simulate real-world conditions and help evaluate the materials' durability under various circumstances.[11], [31]

Source: S. Gowthaman, K. Nakashima, and S. Kawasaki F. Wu, L. Xu, Y. Chi, Y. Zeng, F. Deng, and Q. Chen [7], [32]

Figure 4 : Durability sample (a) after wet-dry process (b) before wet-dry process [7], [32]

Asphalt Concrete Characterization Tests

Tests like dynamic modulus, IDT creep compliance, and IDT strength provide crucial material parameters for asphalt concrete characterization. These tests ensure that the asphalt mix meets the required standards for strength and performance.[21], [26], [33]

Unbound Granular Material Characterization Tests

The resilient modulus test characterizes unbound materials. It assesses their ability to recover shape after deformation, providing insights into the material's behavior under traffic loads.[14]

Modulus of Elasticity (MOE) Test

This test, following ASTM C469, measures the elasticity of chemically stabilized materials. It helps understand how materials deform under stress, aiding in designing stable and resilient road bases.[14], [34]

Indirect Tensile Strength (IDT) Test

The IDT test, following Austroads Technical Report AP-T101/08, assesses the tensile strength of stabilized materials. It helps in predicting low-temperature performance, crucial for roads in diverse climates.[35][12], [27]

X-ray Diffraction and SEM

These tests examine the influence of additives on soil structure. X-ray diffraction helps identify mineral composition, and scanning electron microscopy (SEM) visualizes the soil's microstructure.[14], [36]

Scanning Electron Microscopy (SEM)

SEM is an advanced imaging technique used in microscopy. It scans a focused beam of electrons across the surface of a specimen, creating detailed images with high magnification. SEM provides high-resolution, three-dimensional images of the surface morphology of materials, allowing scientists to examine structures at the nanoscale.[14], [37]

Energy-Dispersive X-ray Spectroscopy (EDS)

EDS is a technique for elemental analysis. It detects X-rays emitted by a sample when it is irradiated with a focused beam of electrons. EDS helps identify and quantify the elements present in a sample, providing insights into its chemical composition.[14], [37]

Unrestrained Shrinkage Test

Conducted according to French specification NF P 15-433, this test evaluates the shrinkage of mixes. It is particularly essential for mixes exceeding recommended compressive strength thresholds.[5], [6], [9]

Flexural Strength Test

A Universal Testing Machine (UTM) with a 300 KN capacity was used to test the bending strength of UHPFRC samples. Using a four-point bending test, flexural behavior was evaluated. On each side of the sample, two 50 mm gauge length LVDTs (Linear Variable Differential Transformers) were positioned using a specially made aluminum structure. This configuration made it possible to capture mid-span deflection. There were two supports, spaced 300 mm apart. A constant rate of 0.5 mm/min was used throughout the displacement control mode of the flexural test. This technique sought to fully capture UHPFRC's post-peak behavior. The load and displacement sampling modes matched those employed in stress-strain experiments.[5], [6]

Literature Review

Sabry A. Shihata and Zaki A. Baghdadi (2001)

Assess the durability of soil-cement mixtures exposed to salty water. Conducted tests on three soil types, measuring mass loss and strength over 270 days. Used compressive strength as a key indicator. Results: The introduction of Natural Rubber Latex (NRL) to cement-stabilized soil led to higher compressive strength, and optimal replacement ratios were identified. Conclusion: NRL addition not only enhanced performance but also reduced cement input, significantly lowering the carbon footprint. NRL showed promise for sustainable improvement of cement-stabilized soil in tropical regions.[28]

S.Kolias, V. Kasselouri-Rigopoulou, A. Karahalios (2005)

Investigate the effectiveness of high calcium fly ash and cement in strengthening clayey soils. Added fly ash and cement to soil samples, and conducted tests on compression, tension, and flexure. Evaluated performance under construction and traffic.

Results: The addition of high calcium fly ash and cement to clayey soils enhanced strength, with tests revealing improved performance under traffic.

Conclusion: The study suggests that using fly ash and cement for soil improvement, indicated by molecular-level changes, is a beneficial practice for constructing resilient and durable pavements.[29]

Mewade R3 (2017)

Explore low-cost and eco-friendly methods for soil improvement. Used enzymes as a biological solution, engaging in catalytic reactions with soil particles. Evaluated improvements in shear strength, stiffness modulus, water resistance, and load-bearing capacity.

Results: Enzymes, as a biological solution, improved various soil properties, including shear strength and water resistance, offering a cost-efficient and eco-friendly alternative.

Conclusion: Enzymes' catalytic reactions with soil particles presented an effective and environmentally friendly technique for enhancing sub-grade soil properties.[30]

Thanon Bualuang, Peerapong Jitsangiam,(2021)

Enhance road construction eco-friendliness using industrial by-products.

Used fly ash (FA) and hydrated lime (HL), enhanced with sodium hydroxide (NaOH) and asphalt emulsion (AE). Evaluated mechanical properties, structure, and durability of the FA-HL binder.

Results: The addition of NaOH and AE to FA and HL for road construction improved strength and durability, meeting requirements for an eco-friendly flexible pavement base.

Conclusion: The study proposes this approach as a sustainable solution for eco-friendly road construction, utilizing industrial by-products.[9]

Apinun Buritatum, Suksun Horpibulsuk,(2021)

Improve the performance of cement-stabilized soil in tropical regions. Added Natural Rubber Latex (NRL) to cement-stabilized soil, and examined factors like soil type, NRL characteristics, replacement ratio, and cement content. Proposed a predictive equation for compressive strength.

Results: The introduction of NRL to cement-stabilized soil led to higher compressive strength, and optimal replacement ratios were identified.

Conclusion: NRL addition not only enhanced performance but also reduced cement input, significantly lowering the carbon footprint. NRL showed promise for sustainable improvement of cement-stabilized soil in tropical regions.[31]

Advantages

1. The initial strength improvement followed by weakening after about 90 days raises concerns for long-term durability. The study's focus on saline water exposure limits the direct applicability of findings to other environmental conditions.[28], [36]
2. While strengthening clayey soils, the formation of hydraulic compounds poses potential long-term implications that warrant further investigation. The study's effectiveness may be soil-type-dependent, and monitoring the long-term impacts of hydraulic compounds is crucial.[9], [37]

3. Despite suggesting improvement in various soil properties, specific enzyme-soil interactions and potential ecological impacts require further exploration. The effectiveness of enzymes can vary with soil conditions, emphasizing the need for thorough, long-term environmental impact studies.[10], [34]
4. While enhancing strength and durability, potential drawbacks include the environmental impact of solid NaOH and uncertainties about the long-term behaviour of asphalt emulsion. Applicability hinges on factors like traffic load and environmental conditions, highlighting the need for careful consideration.[28], [31]
5. The addition of coarse aggregate significantly enhances the compressive strength and elastic modulus of UHPFRC, ensuring structural integrity. Incorporating coarse aggregate reduces cement demand, promoting cost-effective concrete production for sustainable construction.[5], [7]
6. Exploration of four aggregate types allows tailoring of concrete properties based on project requirements and local material availability. Varying mortar replacement volumes provide insights into optimizing UHPFRC mix designs for different applications[5], [6]

Disadvantages

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Conclusions

1. Soil-cement mixtures exposed to saline water exhibit durability over time.[38]
2. Initial weakening is followed by stabilization of strength.[15], [39]
3. Compressive strength is a valuable indicator for durability assessment. Relevant for designing structures or pavements in saline water-exposed areas.[7]
4. The addition of fly ash and cement strengthens clayey soils significantly. The formation of hydraulic compounds at a molecular level suggests durability. Valuable for resilient and durable pavement construction.[19], [29]
5. Enzymes offer a low-cost and eco-friendly alternative for soil improvement. Catalytic reactions enhance various engineering properties.[33], [40]
6. Effective in improving shear strength, stiffness modulus, water resistance, and load-bearing capacity.[37]
7. Promising for geotechnical engineering in areas with poor-quality sub-grade soil.[29]

8. Sodium hydroxide (NaOH) and asphalt emulsion (AE) enhance the mechanical properties of road construction materials.[30], [33]
9. Improved strength and durability for eco-friendly flexible pavement bases. Sustainable solution using industrial by-products. Promising for environmentally conscious road construction.[36], [41]
10. NRL improves compressive strength in cement-stabilized soil. Enhances cohesion and reduces carbon footprint by allowing a reduction in cement input.[36]
11. The proposed predictive equation for compressive strength under wetting and drying cycles.[31]
12. Sustainable solution for cement-stabilized soil in tropical climates. The addition of coarse aggregate results in a slight reduction in flexural strength and post-peak ductility, requiring careful consideration in structural designs.[5], [6], [23]
13. The stiffness of coarse aggregates significantly influences various properties, emphasizing the need for careful aggregate selection.[23]
14. Limited variations in first crack strength raise considerations about the implications for structural design.[8], [42]
15. A significant increase was observed after moderate coarse aggregate addition. Offers improved mechanical properties crucial for structural applications.[6], [25]
16. Slight reduction in flexural strength and post-peak ductility with coarse aggregate addition. Aggregate types and content impact flexural strength and equivalent flexural strength ratio.[5], [7]
17. Different stiffness of aggregate types influences compressive strength and post-peak ductility. Flexural behavior is significantly affected by aggregate type. Inclusion of coarse aggregate curbs cement demand, lowering production costs Aligns with sustainability goals in concrete infrastructure.[5], [6].

References

[1] Amarh, e. A., w. Fernandez-gómez, g. W. Flintsch, b. K. Diefenderfer, and b. F. Bowers. 2017. “nondestructive in situ characterization of elastic moduli of full-depth reclamation base mixtures.” Transp res rec, 2641: 1–11. National research council. Https://doi.org/10.3141/2641-01.

[2] Attom, m. F., and m. M. Al-sharif. 1998a. Soil stabilization with burned olive waste. Appl clay sci.
B, s. Y., p. S. R, y. Patil, r. Rayate, and a. Professor. 2018. Cement treated sub-base for bituminous pavement.

[3] Bahmani, s. H., n. Farzadnia, a. Asadi, and b. B. K. Huat. 2016. “the effect of size and replacement content of nanosilica on strength development of cement treated residual soil.” Constr build mater, 118: 294–306. Elsevier ltd. Https://doi.org/10.1016/j.conbuildmat.2016.05.075.

[4] Bahmani, s. H., b. B. K. Huat, a. Asadi, and n. Farzadnia. 2014. “stabilization of residual soil using sio2 nanoparticles and cement.” Constr build mater, 64: 350–359. Elsevier ltd. Https://doi.org/10.1016/j.conbuildmat.2014.04.086.

[5] Basha, e. A., r. Hashim, h. B. Mahmud, and a. S. Muntohar. 2005. “stabilization of residual soil with rice husk ash and cement.” Constr build mater, 19 (6): 448–453. Https://doi.org/10.1016/j.conbuildmat.2004.08.001.

[6] Braham, a. 2016. “comparing life-cycle cost analysis of full-depth reclamation versus traditional pavement maintenance and rehabilitation strategies.” Transp res rec, 2573: 49–59. National research council. Https://doi.org/10.3141/2573-07.

[7] Bualuang, t., p. Jitsangiam, and t. Tanchaisawat. 2021. “sustainable flexible pavement base stabilization with pozzolanic materials incorporating sodium hydroxide and asphalt emulsion.” Transportation engineering, 6. Elsevier ltd. Https://doi.org/10.1016/j.treng.2021.100094.

[8] Buritatum, a., s. Horpibulsuk, a. Udomchai, a. Suddeepong, t. Takaikaew, n. Vichitcholchai, j. Horpibulsuk, and a. Arulrajah. 2021. “durability improvement of cement stabilized pavement base using natural rubber latex.” Transportation geotechnics. Elsevier ltd.

[9] Tennessee department of transportation, s., and s. By federal highway administration. N.d. Performance evaluation of full depth reclaimed (fdr) pavements in tennessee.

[10] California bearing ratio test. N.d.
[11] Choobbasti, a. J., and s. S. Kutanaei. 2017. "microstructure characteristics of cement-stabilized sandy soil using nanosilica." Journal of rock mechanics and geotechnical engineering, 9 (5): 981–988. Chinese academy of sciences. Https://doi.org/10.1016/j.jrmge.2017.03.015.
[12] Dang, l. C., b. Fatahi, and h. Khabbaz. 2016. "behaviour of expansive soils stabilized with hydrated lime and bagasse fibres." Procedia eng, 658–665. Elsevier ltd.
[13] Dixon, p., w. Guthrie, and d. Eggett. 2012. "factors affecting strength of road base stabilized with cement slurry or dry cement in conjunction with full-depth reclamation." Transp res rec, (2310): 113–120. Https://doi.org/10.3141/2310-12.
[14] Euch khay, s. El, s. El euch ben said, a. Loulizi, and j. Neji. 2015. "laboratory investigation of cement-treated reclaimed asphalt pavement material." Journal of materials in civil engineering, 27 (6). American society of civil engineers (asce). Https://doi.org/10.1061/(asce)mt.1943-5533.0001158.
[15] Fedrigo, w., w. P. Núñez, and a. T. Visser. 2020. "a review of full-depth reclamation of pavements with portland cement: brazil and abroad." Constr build mater. Elsevier ltd.
[16] Ghanizadeh, a. R., m. Rahrovan, and k. B. Bafghi. 2018. "the effect of cement and reclaimed asphalt pavement on the mechanical properties of stabilized base via full-depth reclamation." Constr build mater, 161: 165–174. Elsevier ltd. Https://doi.org/10.1016/j.conbuildmat.2017.11.124.
[17] Gidley, j. S., a. M. Asce, w. A. Sack, and m. Asce. N.d. Environmental aspects of waste utilization in construction.
[18] Gonzalo-orden, h., a. Linares-unamunzaga, h. Pérez-acebo, and j. Díaz-minguela. 2019. "advances in the study of the behavior of full-depth reclamation (fdr) with cement." Applied sciences (switzerland), 9 (15). Mdpi ag. Https://doi.org/10.3390/app9153055.
[19] Gowthaman, s., k. Nakashima, and s. Kawasaki. 2022. "effect of wetting and drying cycles on the durability of bio-cemented soil of expressway slope." International journal of environmental science and technology, 19 (4): 2309–2322. Springer science and business media deutschland gmbh. Https://doi.org/10.1007/s13762-021-03306-1.
[20] Guthrie, w. S., a. V. Brown, and d. L. Eggett. 2007. "cement stabilization of aggregate base material blended with reclaimed asphalt pavement." Transp res rec, (2026): 47–53. Https://doi.org/10.3141/2026-06.
[21] Hasan, h., l. Dang, h. Khabbaz, b. Fatahi, and s. Terzaghi. 2016. "remediation of expansive soils using agricultural waste bagasse ash." Procedia eng, 1368–1375. Elsevier ltd.
[22] Kaseer, f., e. Arámbula-mercado, j. Epps, a. E. Martin, and r. Ceccovilli. 2020. "full-depth reclamation (fdr) mix design: proposed revisions to the indirect tensile strength thresholds." Constr build mater, 254. Elsevier ltd. Https://doi.org/10.1016/j.conbuildmat.2020.119283.
[23] "kearney1999full-depth reclamation process." N.d.
[24] Kolias, s., v. Kasselouri-rigopoulou, and a. Karahalios. 2005. "stabilisation of clayey soils with high calcium fly ash and cement." Cem concr compos, 27 (2): 301–313. Https://doi.org/10.1016/j.cemconcomp.2004.02.019.
[25] Kwon, j., y. Seo, j. Yang, and a. Kaplan. 2021. "field and numerical investigation of full depth reclamation with portland cement in georgia." Transportation geotechnics, 27. Elsevier ltd. Https://doi.org/10.1016/j.trgeo.2020.100465.
[26] Linares-unamunzaga, a., h. Pérez-acebo, m. Rojo, and h. Gonzalo-orden. 2019. "flexural strength prediction models for soil-cement from unconfined compressive strength at seven days." Materials, 12 (3). Mdpi ag. Https://doi.org/10.3390/ma12030387.
[27] Lothenbach, b., k. Scrivener, and r. D. Hooton. 2011. "supplementary cementitious materials." Cem concr res.
[28] Lv, s., c. Xia, h. Liu, l. You, f. Qu, w. Zhong, y. Yang, and s. Washko. 2021. "strength and fatigue performance for cement-treated aggregate base materials." International journal of pavement

engineering, 22 (6): 690–699. Taylor and francis ltd. Https://doi.org/10.1080/10298436.2019.1634808.

[29] Melese, e., h. Baaj, s. Tighe, s. Zupko, and t. Smith. 2019. "characterisation of full-depth reclaimed pavement materials treated with hydraulic road binders." Constr build mater, 226: 778–792. Elsevier ltd. Https://doi.org/10.1016/j.conbuildmat.2019.07.317.

[30] Mewade, r. 2017. Issue 8 www.jetir.org (issn-2349-5162). Jetir1708094 journal of emerging technologies and innovative research. Jetir.

[31] Rahane, prof. A. B. 2022. "a comparative study of cement-treated sub-base and granular sub-base." Int j res appl sci eng technol, 10 (5): 4736–4740. International journal for research in applied science and engineering technology (ijraset). Https://doi.org/10.22214/ijraset.2022.43487.

[32] Recommended construction guidelines for full depth reclamation (fdr) using cementitious stabilization fdr102. N.d.

[33] Reeder, g. D., d. S. Harrington, m. E. Ayers, and w. Adaska. 2017. Title and subtitle guide to full-depth reclamation (fdr) with cement 5. Report date 13. Type of report and period covered guide/manual.

[34] Sal haji alii, f. A. N.d. Nii-electronic library service stabilization of a residual soil.

[35] Sarma, p., s. Singh, and m. Kaur. 2019. "optimization of sisal fibre and rice husk ash usage on lateritic soil for construction of roadway." Mater today proc, 1720–1726. Elsevier ltd.

[36] Scullion, t., s. Sebesta, c. Estakhri, p. Harris, c.-s. Shon, o. Harvey, and k. Rose-harvey. 2012. Full-depth reclamation: new test procedures and recommended updates to specifications 5. Report date 13. Type of report and period covered unclassified.