A Comparative Environmental Assessment of Pavement Rehabilitation Strategies: Full-Depth Reclamation Vs. Mill and Fill

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Abstract : This study provides a comprehensive comparative environmental assessment of two pavement rehabilitation strategies: Full-Depth Reclamation (FDR) and Mill and Fill (M&F). The analysis includes two FDR treatments, each containing bitumen emulsion in combination with a distinct hydraulic binder (active filler). Life Cycle Assessment (LCA) methodology principles were applied to quantitatively assess advantages and disadvantages associated with these techniques. The system boundaries considered in the assessment cover the base layer rehabilitation process of a pavement road after its service life. The comparative analysis is based on greenhouse gas emissions (GHG) and energy consumption. Results indicate that FDR significantly outperforms M&F, with a 51% reduction in GHG emissions and a substantial 64% decrease in energy consumption. In FDR solution, the absence of the heating process at the asphalt plant is essential for achieving this performance since it constitutes 53% of GHG emissions in the M&F solution. Sustainable material choices may also improve the environmental impact of the FDR opting for a stabilized material with bitumen and low clinker binder. This may lead to even more substantial reductions compared to M&F.

Keywords: Full-Depth Reclamation, Mill and Fill, Pavement Rehabilitation, Life Cycle Assessment (LCA), Greenhouse Gas Emissions, Sustainability.

1 Introduction

Facing climate change emergency, VINCI Group is actively getting involved in the environmental transition and has set ambitious goals for 2030, with a focus on three main actions: reduce CO_2 emissions, optimizing resources thanks to the circular economy, and preserving natural ecosystem. To achieve these objectives, Vinci Construction Road Division has been prioritizing efforts to reduce energy consumption and the use of natural resources in its construction, maintenance, and road rehabilitation activities.

In the context of an ageing European road network, the search for sustainable rehabilitation strategies has contributed to a growing interest in full-depth reclamation (FDR), a process that rebuilds damaged asphalt by recycling the existing pavement at ambient temperature. This process has been successfully used as a rehabilitation strategy within Vinci Construction, with experiences of cold recycling techniques dating back to the 1990s [1]. FDR has gained popularity due to technical advancements that have improved our understanding of its mechanical behavior and durability [1,2,3,4], and, especially, due to its environmental benefits. These benefits include preserving natural resources by recycling materials already present in the pavement and reducing energy consumption, particularly when compared to the mill and fill (M&F) process of the base layer [2,5,6].

To quantitatively assess the theoretical environmental benefits associated with rehabilitation techniques, several researchers have conducted studies using Life Cycle Assessment (LCA) methodology [7,8,9]. LCA is a popular method described in the ISO 14040 series, which addresses the environmental aspects and potential environmental impacts throughout the life cycle of a product [10]. However, studies on the environmental performances of FDR, is relatively new in the field of pavement LCA literature, especially when compared to other rehabilitation techniques.

The present study combines LCA principles with road pavement design to compare the environmental impact of FDR rehabilitation process versus conventional rehabilitation process of base layer. In order to provide valuable insights into the environmental effects of this technique.

This study is structured into six sections, including the introduction. The second section defines the scope of the study (i.e., functional unit, and physical dimensions) according to its goals. The third section focuses on the life cycle inventory, containing data collection, the quantification of inputs and outputs, and the modeling of the system. In the fourth section, the potential environmental impacts are presented. Then, the major findings and conclusions of this study are summarized in the last section.

2 Methodology

2.1 Goal

The primary objective of this study is to conduct a comparative analysis of the potential environmental impacts of the FDR strategy versus the conventional mill and fill of the base layer. Advantages and disadvantages associated with these techniques were investigated by following the recommendations of the LCA methodology [10]. The comparative results from this study are intended to be used to provide a more informed basis for assessing the pros and contras associated with the use of the FDR rehabilitation technique instead of the conventional methods.

2.2 System boundaries

The system boundaries outline the unit processes considered in the assessment and were defined to cover only the rehabilitation stage of a pavement road after its service life. The analysis boundaries include three phases : (1) material production, consisting of the acquisition and processing of raw materials needed to produce the mixtures used in the rehabilitation solutions ; (2) transportation of materials, accounting for the transportation from the facilities to the asphalt plant and, as well as the transportation from the facilities and from asphalt plant to the construction site ; (3) In situ operations, including all the rehabilitation operations at the job site.

Within these boundaries, two rehabilitation systems were assessed. The reference solution involves the removal of the old pavement (milling operations), replacement of the base layer with a Hot Mix Asphalt (HMA) produced at the asphalt plant, and compaction of the base layer (filling operations). A flowchart of this process is illustrated in Fig. 1.

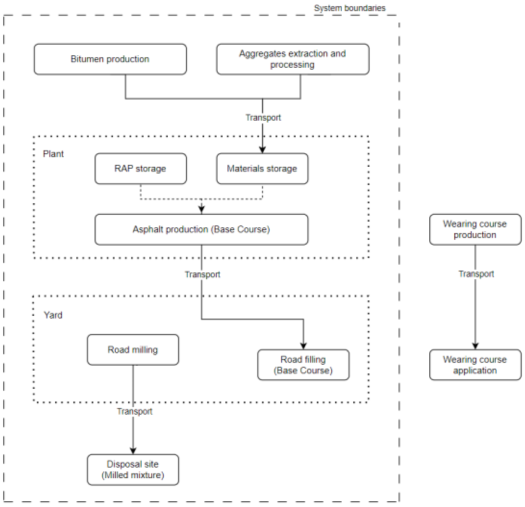


Fig. 1. System of the reference solution (mill and fill)

In contrast, the alternative rehabilitation solution involves pulverizing the old pavement, mixing it with a composite binder (bitumen emulsion and an active filler), and compaction. A flowchart of this process is illustrated in Fig. 2. The details of these rehabilitation process are described in section 2.3.

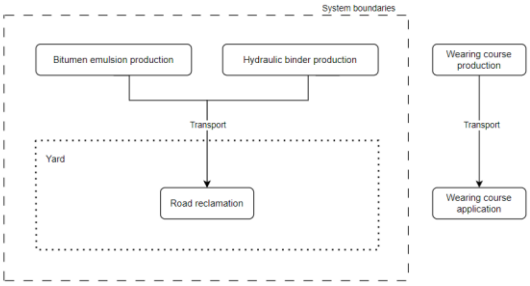


Fig. 2. System of the alternative solution (FDR)

The old pavement construction, as well as the processes occurred during its service life, are not included in this analysis. They were assumed to be the same, independently of the solutions analyzed here and were not considered to avoid adding uncertainty to the inventory.

Regarding the rehabilitated pavement, the wearing course and its maintenance plan were estimated to be the same for all the pavement rehabilitation strategies analyzed. Therefore, the operations associated with the surface layer were not considered to avoid adding uncertainties to the inventory. Additionally, for clarity, no additional rehabilitation activities were considered during the project analysis period of 20 years.

2.3 Functional unit

The functional unit (FU) of any LCA study serves as the criteria for comparisons between different systems with the same utility for the same function [10]. In the pavement field, the FU represents a surface of pavement that can safely and efficiently (same damage level) carry the same traffic over the same project analysis period. Then, it is defined by their geometry, service life, and levels of traffic supported [8].

A) Traffic, service life, pavement structure

For this study, the functional unit was defined as 1-kilometer length, composed of two lanes with a 3.5 meters width. The average annual daily traffic (AADT) was set at 200 heavy vehicles/day/lane, with an arithmetic traffic growth rate of 2.5% per year. The project analysis period is 20 years.

These features were based on compatible FDR traffic. This technique is more widely used on roads with low and medium traffic intensity [1,2] which represents approximately 98% of the French road network [11].

The parameters for a Mechanistic-Empirical (ME) design according to the French method [12] are described in Table 1. The risk associated with the pavement design was set equal to 12 %, representing the maximum % of the project subjected to structural failure at the end of the service life (20 years) according to the French Mechanistic-Empirical design method [12]. For the FDR, fatigue and mechanical parameters are derived from French practices, with a more conservative value considered for ε_6 (90 instead of 97 *μdef)* [3,4,13]. For the RBA (EN 13108-1), the mechanical parameters are derived from the French standard [3].

Table 1: Mechanical properties

Solutions	**Modulus (MPa) (15°C, 10Hz)**	**Fatigue parameters**							
		Risk (%)	ε_6 *(μdef)*	*-1/b*	*Sh (cm)*	*SN*	k_θ	*ks*	*kc*
HMA – Road Base Asphalt (GB-3)	9000	12	80	5	2.5	0.3	1.148	0.83	1.3
FDR treatment	3500	12	90	5	2.5	0.3	1.157 [4]	0.95	1.7 [4]

Based on these data, the thicknesses of the pavement structures were carried out using the French software Alize v1.5 [14]. The solutions were designed to have the same mechanical performance and the results are presented in Table 2.

Table 2 Geometrical characteristics resulting from the pavement design according to NF P 98-086 for a 200 HV/day for 20 years and a risk failure of 12% (NB: The surface layer is considered for pavement design but is not included in the environmental analysis boundaries)

Structure	Reference solution, Mill and fill - RBA	Alternative solution, FDR
Surface Layer	5.0cm Wearing course	5.0cm Wearing course
Base Course	19 cm RBA (GB-3)	26 cm FDR treatment
Granular base course	Existing granular layer 50 MPa	Existing granular layer 50 MPa

B) Mix design

Three mixtures were considered in this study: i) one concerns a road base asphalt (HMA – GB-3), used in the reference solution; ii) and the other two are FDR mixtures, each containing bitumen emulsion in combination with a distinct hydraulic binder (active filler). The mixtures are assumed based on knowledge from Vinci Construction rehabilitation road projects in France and abroad (Canada, USA) and from industry practices [1,2,4,6]. These mixtures are as follows:

(1) Reference solution: HMA, comprising 19% reclaimed asphalt pavement (RAP) and 3.25% bitumen (both by weight of the mixture).
(2) Alternative solution A: FDR stabilized with 3.5% bitumen emulsion and 1% Portland Cement II (both by dry weight of the FDR material).
(3) Alternative solution B: FDR stabilized with 3.5% bitumen emulsion and 1% Hydraulic Road Binder (HRB) containing 30% of clinker (both by dry weight of the FDR material).

It's worth mentioning that the reference mixture composition was defined taking into consideration the practice of incorporating around 19% RAP (mean rate observed) into asphalt mixtures in France since 2016 [15]. Regarding the FDR, the selection of two types of hydraulic binders reflects the versatility of this technique, as it can be effectively implemented using either Ordinary Portland Cement (OPC) or Hydraulic Road Binders (HRB) without deteriorating the strength and the durability of the mixtures [5,6,16]. HRBs are specific hydraulic binders designed for road construction, also known to have a lower environmental impact compared to OPC [6,16].

C) Rehabilitation operations

In the reference solution, the reconstruction process consists of milling the entire (deteriorated) existing asphalt pavement using a milling machine. The RAP materials are then loaded into trucks for removal. After, a finisher is used to pave the new base layer (here a conventional Road Base Asphalt Layer – GB3) with HMA. The layer is properly compacted using two steel-rubber rollers with a smooth drum and a rubber-pneumatic roller, which compacts the lane with six passes. Regarding the thickness of RBA required (19 cm), laying in two layers will be necessary (10cm + 9cm) to achieve a good compaction, as well as a tack coat between the layers.

In the case of the alternative solution, the reconstruction process begins with a cold recycler machine pulverizing the top 26 centimeters of the existing pavement (including usually untreated granular materials). Next, a seeder spreads hydraulic binder into the pulverized material, and the recycler thoroughly mixes the material. The recycler, connected by a rigid line to a water tank (and a tank containing bitumen emulsion), injects the emulsion while mixing all the constituents of the new base layer. After, it is necessary to level out the surface with a grader, as the material is significantly loosened. The layer is then properly compacted using one heavy steel-rubber roller with a smooth drum and a heavy rubber-pneumatic roller, which compacts the lane in three passes.

3 Life cycle inventory

The life cycle inventory (LCI) stage includes data collection and modeling of the system. Inventory data was categorized into two types: primary and secondary data. Primary data refer to specific system under study, while secondary data includes generic or average information for the system [8].

Primary data sources were selected to ensure the representativeness of the French industry practices. Primary data mainly includes information on (1) composition of the mixtures, (2) transportation distances, and (3) manufacturing conditions. Secondary data relies on the French software SEVE v.4.0 [17] based on the principles of EN 15804 standard [18], a tool to compare the environmental impacts of the construction and maintenance solutions of road and highways. SEVE provides an environmental database for materials, equipment, and products aligned with the French industry [17].

3.1 Material Production

Mix design used for assessing the production of the Road Base Asphalt (HMA)at the asphalt plant are shown in Table 3. Mixing temperature of the HMA was set at 160° C and the asphalt plant was powered by natural gas (French industry average practices). The energy consumption of the process relies on SEVE asphalt plant thermodynamical modelling [17].

Table 3 Hot asphalt mixture production

Solution	HMA	Percentage by ton of mixture	Water content	Environmental data
Reference solution, Mill and fill	Bitumen 35/50	3,35%	-	Eurobitume, 2012 [19]
	Aggregate	77,65%	4 %	UNPG, 2017 [20]
	RAP	19,00%	3 %	NF EN 15804+A2/CN, 2022 [21]

The quantities of materials entering and leaving the construction site was assessed by considering 1km long stretch of road, composed of two lanes, 3.5 m each. The RBA density was set at 2344 kg/m^3 and for the FDR solution a density of 2198 kg/m^3 was considered.

Tableau 4 Materials movements on the construction site

Solution	Product	Quantity	Environmental data
Reference solution, Mill and fill	HMA	3117.50 ton	Modelized on SEVE [17]
	Disposal material	984.60 ton	SEVE Methodology, 2022 [17]
Alternative solution 1, FDR-EPC	Emulsion 65%	140.00 ton	LCA, Routes de France, 2022 [22]
	Portland Cement II	16.50 ton	LCA, ATILH, 2017 [23]
Alternative solution 2, FDR-EHRB	Emulsion 65%	140.00 ton	LCA, Routes de France, 2022 [22]
	HRB: clinker 30 %	40.00 ton	SEVE Methodology, 2022 [17]

3.2 Transportation of materials

All materials and mixtures were assumed to be transported using heavy-duty vehicles powered by diesel fuel. Additionally, the transportation includes a return trip with an empty backhaul. The SEVE data process "Transport par semi TR2+SR2 24t" [17] was used to assess the environmental impacts associated with transportation of materials. The transportation distances considered for each material and mixture used in this study are representative of typical conditions in France and are presented in Tableau 5. It should be noted that, as RAP are usually stored in the asphalt plants, no supply distance is assigned to them.

Tableau 5 Transportation of materials

Solution	Material	One-way trip distance (km)
Transport to the plant	Bitumen	234
	Aggregates	50
	RAP	0
Transport to the yard	Asphalt mixture	30
	Bitumen emulsion	30
	Hydraulic Road Binders	120
	Portland Cement	120
Transport to disposal site	Disposal material	30

It's important to note that these distances represent national French averages and might vary depending on the region. The distances could vary based on the proximity of production plants and should be adjusted to reflect specific site conditions.

3.3 Rehabilitation operation

In the rehabilitation phases, the environmental impacts are mainly due to the combustion-related emissions from the machinery usage [8,7]. The fuel consumption of the equipment relies on SEVE database [17] and the information about the operations are shown in Tableau 6.

Tableau 6 - Rehabilitation operations

Solution	Equipment used	Performance
Reference solution, Mill and fill	Milling machine	12m/min
	Truck	
	Finisher (paver)	6 m/min
	Roller	60 m/min
Alternative solution FDR	Recycler machine	12 m/min
	Emulsion applier	12 m/min
	Hydraulic binder spreader	120 m/min
	Grader	120 m/min
	Roller	120 m/min

4 Life cycle impact assessment

The purpose of the life cycle impact assessment (LCIA) is to assign the LCI results to different impact categories based on the potential effects that the several substances have on the environment [9,10]. In this study, the environmental footprint of the technical solutions was calculated using SEVE v.4.0 [17]. The Climate Change (CC) impact category expresses the Greenhouse Gas (GHG) emissions in tons of CO2 [17]. Furthermore, an energy analysis was conducted based on the consumption of energy resources, in MJ, as the sum of primary renewable and non-renewable energies used by the solutions [17].

4.1 Results and discussion

Based on the impact assessment results of the solutions used for rehabilitating the base layer [Fig. 3], the percentage of GHG emissions reduction (tCO2eq) of the alternative solutions compared with M&F is -51% for FDR-EPC and -63% for FDR-EHRB. These findings align with previous studies comparing in-place recycling activities to conventional reconstruction activities reported a potential greenhouse gas savings ranging from 54% to 62% [7,9].

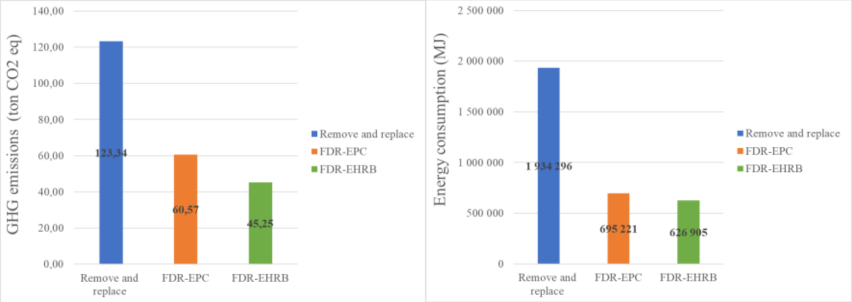
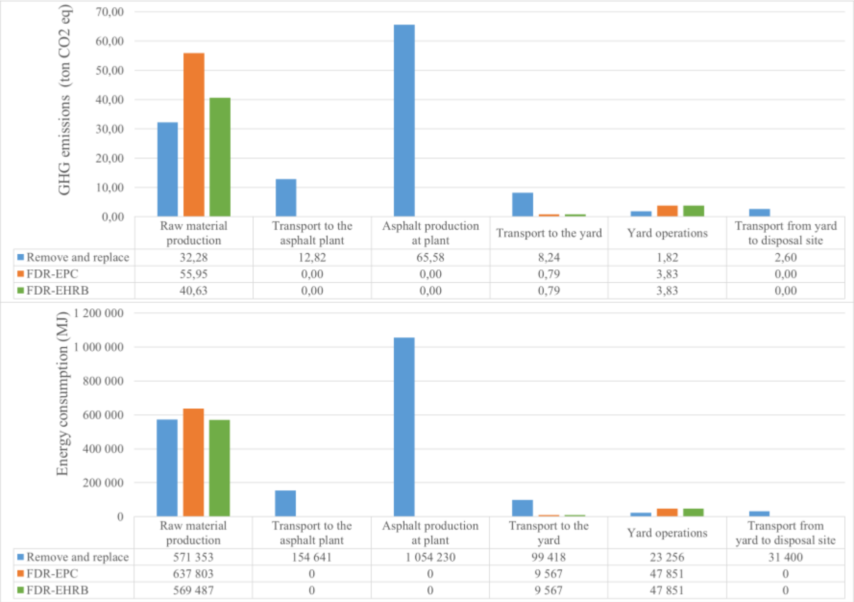


Fig. 3 Total GHG emissions (left) and Energy consumption (right) of the pavement rehabilitation solutions.

The savings achieved in terms of CO_2eq are also confirmed in terms of energy consumption in the case of the FDR-EPC (64% savings) and the FDR-EHRB (68% savings) alternative solutions [Fig. 3].



	Raw material production	Transport to the asphalt plant	Asphalt production at plant	Transport to the yard	Yard operations	Transport from yard to disposal site
■ Remove and replace	32,28	12,82	65,58	8,24	1,82	2,60
■ FDR-EPC	55,95	0,00	0,00	0,79	3,83	0,00
■ FDR-EHRB	40,63	0,00	0,00	0,79	3,83	0,00

	Raw material production	Transport to the asphalt plant	Asphalt production at plant	Transport to the yard	Yard operations	Transport from yard to disposal site
■ Remove and replace	571 353	154 641	1 054 230	99 418	23 256	31 400
■ FDR-EPC	637 803	0	0	9 567	47 851	0
■ FDR-EHRB	569 487	0	0	9 567	47 851	0

Fig. 4 Contribution of the different life cycle phases to GHG emissions (top) and Energy consumption (bottom)

The energy consumption reflects the results of CO_2 emissions along the different lifecycle phases, except for raw material production [Fig. 4]. In this phase, the reduction in GHG achieved by the FDR alternatives is less pronounced compared to the energy consumption, notably, due to the decarbonization of limestone during the clinker production process that releases GHG independently of the amount of energy consumed during the cement manufacturing.

The impact reduction of the FDR is mainly based on the absence of heating process at the plant (asphalt production). This stage represents the highest impacts along the lifecycle of the reference solution (53% of the total GES impact). The GHG emissions in this stage is 21 kgCO2eq/ton (calculated considering the HMA amount needed by this solution) and is comparable to data found in literature of 25 kgCO2eq/ton [7].

However, there is an increase in the impact associated with the FDR raw material production stage (which includes the production of bitumen emulsion and hydraulic binder) counting the highest impacts along its lifecycle (90% of the impact). This percentage is slightly lower for FDR-EHRB due to the use of hydraulic road binder, which implies substituting the clinker with alternative materials (such as fly ashes, natural pozzolans, blast furnace slags, etc.) and consequently reducing its production impacts [6].

In the case of the reference solution, the raw material production stage (including bitumen production, aggregates extraction, and processing) has significant importance in CO2eq emissions (26% of the impact), mainly due to the high weight assumed by the production of bitumen (21% of the total GES impact based on a bitumen production impact of 0.247 kgCO2/ton [17,19]).

Contributions of yard operations are considerably lower than other phases for the three options. Yard operations of FDR solutions have higher impacts, due to major fuel consumption by the cold recyclers. Meanwhile, approximately 20% of the GHG emissions in the reference solution are due to the transportation of materials (upstream and downstream). Therefore, defining an average distance to the supply-chain-related impacts may result in underestimating the life cycle environmental footprint of the pavement systems.

5 Conclusions

The present study aims to provide a comparative environmental assessment of Full-Depth Reclamation (FDR) and Mill and Fill (M&F) strategies, focusing on the life cycle stages of the base layer rehabilitation. The results reveal a substantial reduction of 51% in greenhouse gas (GHG) emissions and a significant 64% decrease in energy consumption when opting for FDR. A key factor contributing to this impact reduction is the absence of heating processing at the asphalt plant, accounting for 53 % of GHG in the M&F solution. Additional reduction could be achieved in the FDR solution by selecting a low clinker binder, especially for GHG emissions (-63%).

While the study provides valuable environmental insights, a deeper understanding of the mechanical behavior and durability of composite FDR treatment is essential for a more precise understanding of its sustainability. This information is crucial for guiding future decision-making in the construction industry, promoting environmentally responsible practices, and achieving a more sustainable approach to pavement rehabilitation.

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