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An Evaluation of the Economic Viability and Accessibility of CRCP and JPCP: A Comparative Analysis

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Abstract: Road infrastructure serves as a foundational driver of a nation's economic and cultural growth. Incorporating life cycle cost analysis (LCCA), as well as considerations of availability and environmental impact, enables policymakers to make strategic decisions that not only enhance fiscal efficiency but also support sustainable progress. This paper centers on an in-depth examination of two prevalent pavement technologies: continuously reinforced concrete pavements (CRCP) and jointed plain concrete pavements (JPCP). It specifically delineates the application of these methods to a hypothetical one-kilometer motorway construction in Germany. Employing LCCA for concrete pavements, the paper evaluates long-term fiscal prudence among alternative investment opportunities, factoring in resource utilization—both materials and machinery—and long-term care and upkeep obligations over the pavements' operational lifespans. The analysis extends to appraise agency expenditures associated with the pair of pavement strategies and estimates the concomitant delay durations and costs relevant to the exemplar project. Central to this research is the investigation of road availability and its quantifiable influence on traffic efficacy, parsing through metrics such as the tally of days roads are out of service and the subsequent repercussions on vehicular flow. The investigation also proposes strategies for the reduction of embodied carbon in CRCP and JPCP systems. While accounting for variances in functional performance and vehicular comfort levels, this study contributes scientifically by tackling pragmatic engineering dilemmas involved in pavement selection, with a spotlight on minimizing costs, curtailing traffic interruptions, and mitigating ecological impacts for the duration of the pavement's life cycle.

Keywords: life cycle cost analysis; continuously reinforced concrete pavements; jointed plain concrete pavements; carbon footprint; availability

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1. Introduction

Asphalt and concrete, the principal materials for pavements, exhibit unique characteristics. While asphalt offers benefits like reduced noise and easy maintenance, it comes with drawbacks such as frequent repairs and a shorter service life, which is the duration from the commencement of road usage until the point where the pavement's performance falls below acceptable benchmarks. This timeframe signifies the period during which the pavement structure, be it flexible pavement (from 15 to 30 years) or rigid pavement (from 30 to 60 years), operates efficiently, supporting traffic loads and enduring environmental conditions, without necessitating substantial repairs or reconstruction [1–5]. In contrast, concrete's high stiffness enables it to withstand traffic stresses over an extended period without permanent deformation. Rigid pavement systems, crucial for high-capacity transit areas like motorways, airports, and industrial zones, contribute to structural resilience and load-spreading efficiency, reducing localized stress and extending service life. [6–9]. Among these, concrete pavements are known for their sustainability attributes: enduring structural integrity, minimal upkeep, superior skid resistance, complete recyclability, cost-efficiency, and a reduced environmental footprint, coupled with limited traffic disruption during both construction and operational phases [10–12]. To address fiscal limitations, agencies must employ rigorous decision-making methodologies that provide insights into long-term economic viability, such as LCCA. It evaluates economic burden and durability, making it one of the three vital components in assessing sustainability and providing a practical framework to assess costs throughout the entire lifespan of road projects [13]. The typical purpose of performing LCCA is to compare different pavement designs over a specified analysis period by converting all significant present and future costs into present value. The costs are compared based on the net present value (NPV), which represents the net monetary value of future cash flows, such as maintenance or preservation costs, subtracted from future benefits like residual value, but after being appropriately discounted to reflect their present value [14,15]. To establish a common comparable entity, costs and benefits occurring in various future time periods can be discounted and converted into their respective present values. The deterministic approach is a commonly used method for conducting LCCA, where calculations are performed without accounting for input parameter variability. Input parameters are defined as discrete values, with the estimated costs for initial construction and future work, along with the discount rate as two crucial factors. The discount rate considers the time value of money, converting future cash flows into their respective present values [14]. The discount rate can be either a constant (real) or nominal discount rate. The real discount rate accounts for fluctuations in the nominal discount rate and the rate of inflation, reflecting the actual change in the value of money over time. In contrast, the nominal discount rate incorporates the inflation component within the costs, resulting in a non-constant cost consideration.

Road availability's influence on traffic quality is a paramount consideration within the transportation sector, due to its effects on congestion, accident risks, and the surrounding community. The shifting of traffic often leads to stresses on these settlements and to an overloading of alternative routes [15]. The lost work time, wasted fuel, and the additional costs for a company due to detours in the transport of goods are all included in the costs incurred by society due to congestion [16,17]. Efforts are directed towards maximizing availability to mitigate societal costs associated with traffic impediments and road works.

In the context of global urbanization, the imperative development of sustainable roads has emerged as a critical facet of infrastructure. The transportation sector, which accounts for a substantial 32% of global greenhouse gas (GHG) emissions, notably attributes 74% of this burden to building and road traffic. These global initiatives targeting climate change mitigation have reverberated across all industry sectors. Notably, the cement and concrete sectors have experienced a profound impact due to the significant contribution of cement production to GHG emissions [18,19]. The Paris Agreement sets a target of limiting global warming to 1.5 degrees Celsius, requiring industries to transition towards carbon neutrality [20,21]. Recent scholarly endeavors have pivoted towards exploring decarbonization methodologies to further the pursuit of carbon neutrality within the cement and concrete sector. The implementation of LCCA serves as a tactical framework for strategic decision-making, allowing for the selection of economically viable and effective strategies from among feasible alternatives to foster sustainable transportation infrastructures [22,23]. Examining the sustainability of alternative construction methods, encompassing design methodologies, construction approaches, and infrastructure materials, is crucial for mitigating environmental impact, specifically by reducing Global Warming Potential (GWP). The imperative to embrace sustainable concrete pavement methods within the transportation sector is underscored by the uncertainties associated with climate change and the depletion of natural and non-renewable resources [24]. In the context of burgeoning environmental initiatives, the criteria for selecting concrete pavement options in the transportation realm are increasingly informed by their sustainability profiles. This paradigm shift in decision-making processes not only aims to meet infrastructural requirements but also aligns with broader climate action goals, contributing to a decrease in GHG emissions within the construction industry. The emphasis on sustainable practices in both design and material choices for concrete pavement reflects a proactive response to environmental challenges, addressing the urgent need for eco-friendly solutions in transportation infrastructure.

2. State of the Art

The manual for LCCA in pavement design published by the Federal Highway Administration (FHWA) covers essential principles and provides detailed procedures [25]. It emphasizes the adoption of probabilistic approaches to integrate risk analysis and account for uncertainties that were often overlooked in traditional deterministic approaches. As part of the PAV-ECO Project [26], two main objectives were pursued. The first objective was to develop economic models for assessing the life cycle costs related to pavements. The second objective encompassed the investigation of the impact on road infrastructure maintenance because of introducing new road links into an existing road network. During the life cycle stage of a pavement, user costs can be classified into two categories: normal operating costs and work zone costs [27]. Normal operating costs are incurred throughout the typical lifespan of the pavement and primarily depend on the surface condition, roadway geometry, and topography. On the other hand, work zone costs arise from the presence of work zones during initial construction or maintenance activities [28]. Furthermore, previous research [29–32] has predominantly concentrated on comparing asphalt and concrete pavements, overlooking the crucial aspect of conducting systematic LCCA to investigate the economic implications of motorway rigid pavement alternatives, considering the availability of the construction method. Heidari's research [33] findings, considering LCCA, resulted in the selection of plain cement concrete pavement over asphalt concrete pavement. This decision was based on a 12% reduction in life cycle environmental impacts and a significant 55% reduction in energy consumption. In their research, Muga et al. [34] found that JPCP exhibited 33–62% lower emissions than CRCP when only steel consumption was considered. Additionally, LCCA revealed that CRCP pavements incurred approximately 80% lower maintenance costs compared to JPCP over the studied duration of 35 years. In their comparison study, Choi et al. [11] found that CRCP showed the lowest land use impact, achieving a remarkable 62.8% reduction compared to jointed reinforced concrete pavement (JRCP). The study also emphasized that cement manufacturing accounted for over 40% of the GWP in terms of carbon dioxide equivalent (tCO_2e) and contributed to more than 35% of total transportation movement in terms of million ton-kilometers. In a comparative analysis conducted by Diependaele [14], CRCP with a service life of 50 years was compared to asphalt with a service life of 36 years, considering LCCA. The findings revealed that while the initial cost of the concrete alternative was 50% higher than that of the asphalt alternative, the maintenance costs of CRCP were 91% lower than those of asphalt. Additionally, the total NPV of CRCP was 8% lower than that of asphalt.

According to Wiedmann and Minx [35], the carbon footprint (CF) is frequently utilized as an indicator for quantifying carbon dioxide (CO_2) or GHG emissions. Cement production is responsible for generating 5% of global CO_2 emissions [36]. It has been reported that the cement kiln's calculation process results in approximately 0.55 kg of CO_2 emissions for every kilogram of cement clinker [37,38]. The manufacture of concrete emits between 347 and 351 kg of CO_2-equivalent per cubic meter [39]. According to Ma et al. [36] the production of raw materials accounts for 92.7% of total GHG emissions, the concrete manufacturing phase accounts for 7.2%, and the on-site pavement construction phase accounts for 0.1% when constructing one kilometer of Portland cement concrete pavement. This analysis provides insight into the relative environmental impact of each phase during the construction process. This research goes beyond the current state of the art in pavement design and rehabilitation by introducing a comprehensive framework for evaluating CRCP and JPCP. This approach provides a holistic understanding of the economic viability and sustainability of CRCP and JPCP, considering their entire life cycle. This study introduces a fictional one-kilometer test section, ensuring practical relevance for real-world motorway rehabilitation scenarios. By systematically analyzing construction methods, performance variations, and economic factors, this research aims to identify the construction method that minimizes environmental impact and maximizes availability. This work surpasses the current body of literature, informing decision-making processes in pavement design and benefiting researchers, practitioners, and decision-makers involved in motorway rehabilitation projects.

3. Research Objectives

During the decision-making process of pavement selection in new construction, local governmental agencies prioritize the costs related to construction, maintenance, and rehabilitation. While the initial construction cost holds significant influence and is often decisive, conducting a comprehensive economic analysis that considers all associated costs and pavement performance becomes essential for optimal allocation of agency funds [40]. Considering the different influencing factors within the service life is essential to compare different construction methods. Additionally, the policy of motorway administrations focuses on the adoption of long-lasting and low-maintenance pavements. This study specifically focuses on conducting comparisons in terms of LCCA, availability, and environmental impact assessment. The research gap and its need in this study stem from the necessity to comprehensively assess the sustainability and economic viability of CRCP and JPCP, within the context of motorway rehabilitation. By evaluating these aspects, this research aimed to provide a thorough analysis and understanding of the sustainability and viability of CRCP and JPCP. The comparison between CRCP and JPCP was conducted based on their common usage, different construction methods, performance variations, environmental considerations, and economic factors. The primary objective is to determine which of the two construction methods possesses more favorable characteristics in terms of environmental impact and availability. A fictional one-kilometer test section on the A5 motorway in Germany, located between Karlsruhe-Nord and Bruchsal, serves as the reference point for this study. Figure 1 visually depicts the methodology flowchart.

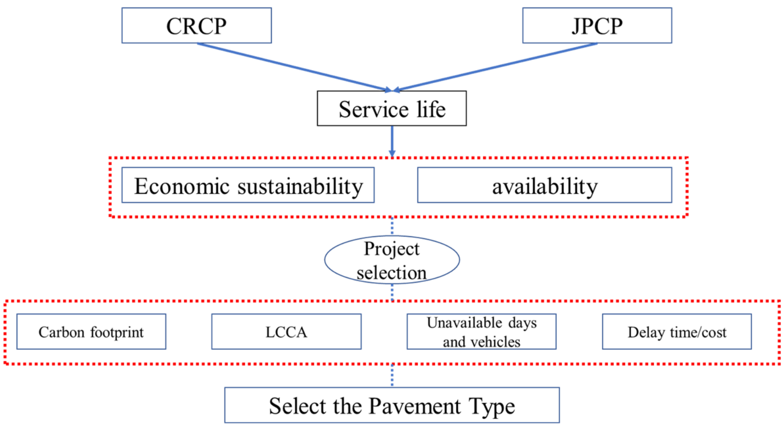

Figure 1. Methodology flowchart.

The subsequent section illustrates the comprehensive analysis process employed in the study:

- The pavement cross-section design was established in accordance with the guidelines outlined by the American Association of State Highway and Transportation Officials (AASHTO) for CRCP and the German "Guidelines for the Standardization of Pavement Structures of Traffic Areas (RStO)" for JPCP.
- Calculation of the service life of each alternative based on an assessment of the slab thickness and the compressive strength of the concrete.

- Conduct a quantity survey for each alternative, considering a one-kilometer section of the motorway.
- Estimate the construction cost and calculate the present value of each alternative, considering a lifespan of 60 years and accounting for the various maintenance activities associated with each alternative.
- Calculation of the unavailable days and heavy traffic based on the due maintenance and repair measures as well as traffic growth on the considered route within the service life period.
- Calculation of delay time during construction and maintenance, as well as estimation of corresponding costs.
- Calculation of the impact indicators of carbon footprint, as well as resource and water use.
- Conduct an analysis of the economic, environmental, and availability impacts for each alternative.

To economically assess CRCP and JPCP construction methods, one possible approach is to conduct a LCCA following the procedure outlined in ISO 15686-5 [41] guidelines. Transaction costs were analyzed to evaluate economic impacts over a comparable period for both alternatives. Another criterion considered is route availability and traffic volume associated with each option [42].

4. Data Acquisition

In this study, a 1 km-long fictitious section on the German motorway A5 with annual average daily traffic (AADT) of 52,900 vehicles (19% trucks) is considered. This section corresponds to a directional carriageway of standard cross-section 31 (RQ 31), which is defined by the German Road and Transportation Research Association (FGSV) in the RStO [43]. Figure 2 illustrates the dimensions of a standard cross-section 31.

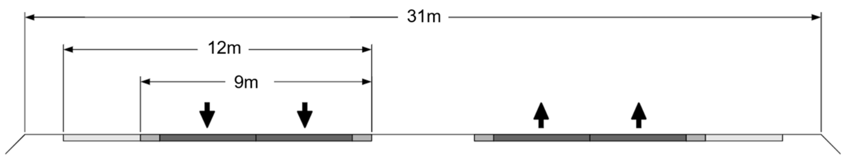

Figure 2. Dimension of a standard cross section 31.

The unreinforced concrete pavement is dimensioned for load class 100 (Bk100) in accordance with Table 2, line 1.1 of the RStO [44]. Since there is no standard in Germany for the dimensioning of a CRCP, AASHTO construction method is considered, and a concrete slab thickness of 24 cm is selected [45]. Figure 3 illustrates the layer structure of CRCP and JPCP in the test section.

JPCP does not incorporate slab reinforcement, with the exception of dowel bars installed at transverse joints and tie bars at longitudinal joints. Dowels facilitate load transfer across transverse joints, enabling movement along the longitudinal axis of the dowel. In contrast, tie bars function to maintain a secure connection between longitudinal joints. The longitudinal reinforcement ratio of the CRCP, with a diameter of 20 mm, is 0.75% and has a spacing of 175 mm. The transverse reinforcement, in turn, has a bar spacing of 650 mm, with a diameter of 16 mm and a reinforcement ratio of 0.13%.

The evaluation of the structural behavior of the concrete pavements under investigation is performed using VENCON 2.0 [46]. This design tool is utilized to calculate concrete pavement parameters and assess the structural performance of concrete structures. Depending on the concrete compressive strength and the concrete cover thickness, different service lives for JPCP and CRCP were obtained. Considering the real traffic load on the test section, it was assumed that CRCP and JPCP have the characteristic cube compressive strength of 49 MPa and 37 MPa, respectively. A service life of 59 years is calculated for CRCP with a concrete slab thickness of 24 cm, while JPCP with a slab thickness of 27 cm is calculated to have a service life of 27 years. Figure 4 represents the calculation of the service life of the examined construction method in VENCON 2.0.

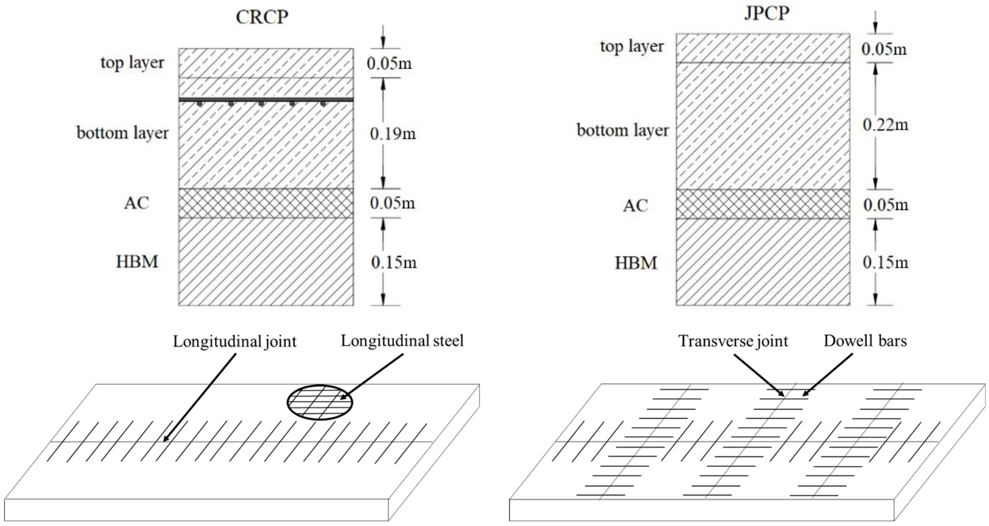

Figure 3. Layer structure and top view of CRCP and JPCP in the test section; AC: asphalt concrete interlayer; HBM: hydraulically bound material.

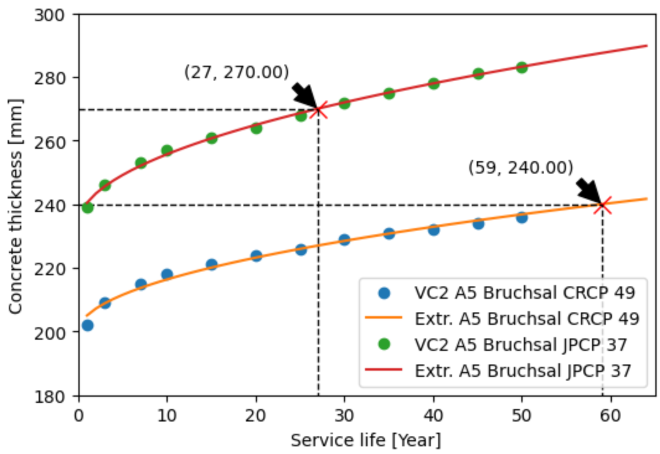

Figure 4. Calculation of the service life of the examined construction methods in VENCON 2.0.

Based on the calculated service life and selected slab thickness, the construction methods CRCP and JPCP can be compared with each other in terms of their life cycle costs (agency cost and delay time/cost), environmental impact (carbon footprint), and availability (unavailable days/vehicles) with an observation period of 60 years.

The system boundary of the LCCA is the manufacturing and construction phase, as well as the utilization and disposal phase. In the analysis of availability, the utilization phase is mainly considered, whereby the installation and demolition of the concrete pavement also play an important role. On the other hand, the boundary for the environmental impact assessment focuses on the production and construction processes.

4.1. Life Cycle Costs Analysis (LCCA)

In LCCA, two primary types of costs are considered: agency costs and user costs [47]. Agency costs are the expenses incurred by the owning agency responsible for constructing and maintaining a pavement section. This includes initial construction and ongoing maintenance costs, such as materials, labor, and equipment. On the other hand, user costs are the expenses borne by the traveling public who use the maintained pavement section. These costs typically include vehicle operating costs, travel delays, crash-related expenses, and emissions. Although there are additional factors like user comfort, local economic impacts, and noise, they are often challenging to quantify and are usually not included in the analysis [13,28,48]. LCCA methodology was carried out in this study according to the International Standard Organization ISO 15686-5 in the following sequences: Goal and scope definition, Inventory and Impact, and interpretation [49]. Figure 5 shows the three phases of LCCA according to the ISO 15686-5.

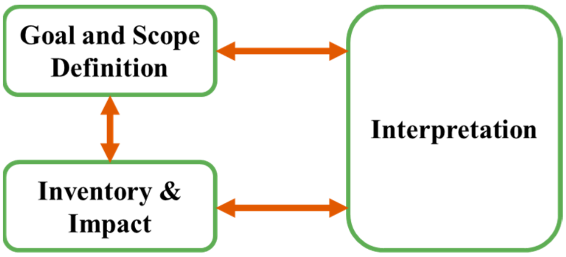

Figure 5. LCCA phases according to the 15686-5 (ISO 2017).

LCCA serves as a tool to assess various life-cycle expenses, encompassing construction, maintenance, rehabilitation, and user costs [50]. To conduct LCCA effectively, it is necessary to meticulously identify all the materials and processes employed throughout each phase [13].

4.1.1. Agency Cost

Goal and Scope

To assess the economic burden of an investment option throughout its entire life cycle, LCCA considers a range of factors such as initial costs, operating costs, maintenance and repair costs, energy consumption, residual value, and other relevant expenses [51]. In addition, LCCA incorporates considerations of inflation and discount rates to accurately evaluate the economic viability and sustainability of the investment option. The discount rate, accounting for inflation's impact over time, plays a critical role in economic analysis and greatly influences the results of LCCA. Through accounting for these factors, LCCA offers a comprehensive analysis of total cost of ownership, facilitating informed decision-making regarding investment options. LCCA proves highly valuable when comparing project alternatives with similar performance requirements that differ in initial and operating costs. Its primary goal is to identify the option that maximizes net savings [52].

Inventory and Impact

Following the general framework, life-cycle analysis is categorized into four information modules, namely A to D. This subdivision also holds true when evaluating the economic performance of a pavement. The life-cycle analysis is divided into modules A0–A5 for the pre-use phase, B1–B7 for the utilization stages, C1–C4 for disposal stages, and an optional module D for potential reuse, recovery, and recycling. This study compares two different concrete pavements, considering all significant present and future costs throughout the pavement's service life and presenting them as present values. Figure 6 illustrates the modules that are considered in the calculation.

To achieve the objective, the initial step involves calculating the necessary quantities of raw materials and assessing the preservation and maintenance activities. Subsequently, the equipment required for paving is identified, and its performance is evaluated. In this study, the real discount rate is applied since future costs are specified as constant cash flows. The cost calculation is thus facilitated by using today's material costs for future periodic repair and maintenance costs. Figure 7 illustrates the steps to calculate the NPV.

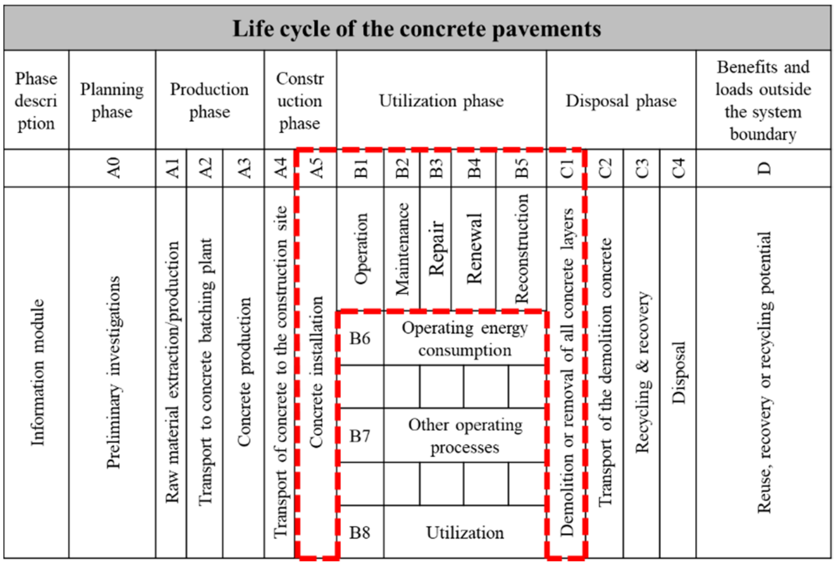

Figure 6. Information modules of the life cycle for the investigation of concrete pavement based on [42,53,54].

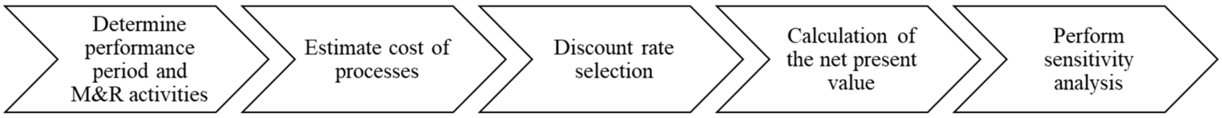

Figure 7. Steps to calculate the NPV.

To calculate the volume of reinforcement for one cubic meter of concrete, consider a length of 0.35 m for a concrete slab 12 m wide and 0.24 m thick. With the reinforcement diameter of 20 mm and the considered pavement length of 0.35 m, the reinforcement length is 24.06 m/m^3. To determine the actual amount of reinforcement per cubic meter of concrete, the reinforcement length is multiplied by the weight for structural steel, which is equivalent to 2.47 kg/m. Thus, the amount of longitudinal reinforcement is 59.44 kg/m^3 of concrete. With a diameter of 16 mm, the weight of transverse reinforcement amounts to 1.58 kg/m. Consequently, the overall quantity of transverse reinforcement in the concrete reaches 8.71 kg/m^3. The dowels are placed in the transverse joints at 0.25 m, but on shoulder at 50 cm [55]. With a lane width of 9 m and a shoulder width of 3 m, this results in a total of 42 dowels per transverse joint. The one-kilometer test section has 200 transverse joints and thus 8400 dowels. The combined weight of the dowels in a section that includes a transverse joint amounts to 82.53 kg/5 m. Five anchors are installed per slab and longitudinal joints. On the one-kilometer-long section there are 200 slabs, so that 1000 anchors per longitudinal joints and 2000 anchors in total are required. If a 5 m long section is considered with a width of 12 m, there are 2 longitudinal joints in this section and thus 10 anchors. The weight of the anchors on the section investigated is 19.36 kg. To fill the two longitudinal joints of the JPCP with the notch width of 0.003 m, the notch depth of 0.45 times the slab thickness (0.27 m), a joint compound of 4.0095 kg/5 m is required. The CRCP has only one longitudinal dummy joint, and due to the 0.24 m high concrete slab, only 1.782 kg/5 m of hot joint sealing compound is needed there. In the case of a transversal dummy joint, the notch depth is 0.3 times the slab thickness of 0.27 m and the length is 12 m. This results in a joint mass of 3.2076 kg/5 m for a transverse dummy joint. To get the components of the concrete to the same functional unit as the other materials, all values for the calculation of the JPCP must be multiplied by 3240 m^3 and for that of the CRCP by 2880 m^3. Table 1 shows the input that was incorporated in the LCCA analysis of CRCP and JPCP.

Table 1. Mass of materials required for concrete.

	In-Situ Weight [t]	
	CRCP	**JPCP**
Sand 0/2	3143.46	3536.4
Gravel 2/8	6501.08	7313.72
Cement	2246.4	2527.2
Air entraining agent	17.21	19.36
Plasticizer	20.91	23.52
Water	1010.88	1137.24

The maintenance of effectively sealed joints plays a pivotal role in safeguarding the structural integrity of the pavement and mitigating the adverse impacts stemming from incompressible materials or water ingress. Engaging in maintenance practices, including the rectification of compromised seals and the mitigation of concerns such as weed growth, serves to enhance the durability and performance of the pavement. These actions contribute to the reduction of potential joint-related distress, thereby fortifying the long-term resilience and operational efficacy of the pavement structure. Table 2 represents unit and final prices for the required quantities of materials for both considered construction methods.

Table 2. Calculation of unit and final prices for the required quantities of materials.

Material	Unit	Quantity	Unit Price (EUR)	Final Costs (EUR)
JPCP				
Concrete	m^2	12,000	71.90	862,800.00
Joint maintenance (longitudinal and transverse)	m	4400	6.50	28,600.00
Single slab renewal (2%)	slab	4	1795.00	7180.00
Single slab renewal (3%)	slab	6	1795.00	10,770.00
Demolition	m^2	12,000	4.00	48,000.00
CRCP				
Concrete	m^2	12,000	71.90	862,800.00
Joint maintenance (longitudinal)	m	1000	6.50	6500.00
Punchouts	slab	1	2243.75	2243.75
Paving of surface course (SMA)	m^2	12,000	10.60	127,200.00

The activities to be performed at different time intervals at the JPCP and the CRCP, as well as the associated costs, are listed in Table 3. The operation time and construction cost data were collected through a meticulous process that involved collaboration with prominent industry experts and organizations specializing in traffic area maintenance and construction.

Table 3. Incidental operations and costs of JPCP and CRCP.

Description of Work	JPCP	CRCP	Cost
Transverse joint renewal	Every 8 years	-	EUR 6.50/m
Longitudinal joint renewal	Every 8 years	Every 12 years	EUR 6.50/m
Single slab renewal	2% after 25 years, 3% after 28 years	-	EUR 1795/slab
Punchouts	-	1 Punchout every 40 years	EUR 2243.75/punchout
Surface layer	-	every 20 years from the 40th year	EUR 10.60/m^2
Demolition of concrete slab	Every 30 years	-	EUR 4.00/m^2

The next step is to determine the real discount rate r. It can be calculated using Equation (1), where i_{int} represents the nominal discount rate and i_{inf} the inflation rate:

$$r = \frac{1 + i_{int}}{1 + i_{inf}} - 1 \quad (1)$$

Since the nominal discount rate varies depending on the project, a constant discount rate of 3% is assumed in this work according to DIN EN 16627 [56] and Eckert et al. [57]. The calculation of the present value (PV) for a specific future amount is achieved by multiplying the future amount with the corresponding PV factor, which is obtained using the following formula [58]:

$$f_{PV} = \left[\frac{1}{(1 + r)^y}\right] \quad (2)$$

The variable y represents the future year in which the payment occurs. Since the JPCP and the CRCP have unequal service lives, the NPV is determined over a so-called "infinite time horizon" and refers to the consideration of all future cash flows without imposing a specific time limit. The factor required for this includes the service life L of the respective alternative in the calculation and is derived from the following formula [14]:

$$\mathrm{F}_{\infty \mathrm{H_L}} = \frac{(1 + \mathrm{r})^{\mathrm{L}}}{(1 + \mathrm{r})^{\mathrm{L}} - 1} \quad (3)$$

This enables the NPV of the two construction methods to be compared, even with different service lives.

4.1.2. Delay Time/Cost

Work zone costs pertain to the additional expenditures experienced by drivers and the broader community because of work zone activities. This study specifically concentrates on the quantifiable impacts, as assessing other impacts can be challenging. Monetized impacts arising from work zone activities encompass delay costs, vehicle operating costs, crash costs, and emission costs. However, this study solely considers the delay costs resulting from work zones. During scheduled maintenance activities, work zones are established where one lane is closed at a time. To simplify the computation of user delays, a 50/50 directional split was assumed. To calculate traffic delay, various lane closure parameters are considered. These parameters include the number of open and closed lanes, the duration of lane closure, work zone length, work zone capacity, speed limit changes, and the AADT [47]. These factors are considered to accurately estimate the impact of lane closures on traffic delay.

This study focuses on analyzing delay costs, which make up a significant portion of work zone user costs. Calculating the extent of delay involves determining the number of vehicles present in the work zone, utilizing known factors such as the hourly AADT and the capacity of the work zone lanes. Key parameters to consider are the queue length and queue speed, as they govern the rate at which queues form, progress, and dissipate. Delays arise when work zone conditions impede the smooth flow of regular traffic.

4.2. Availability

The work involved during the entire life cycle of a concrete pavement, as well as the duration of this work, varies depending on the construction method. In general, the JPCP requires regular maintenance of transverse and longitudinal joints. According to the OAT company, which is a renowned company specializing in traffic area maintenance that operates in over 10 countries, joint fillings with hot sealing compound must be replaced every 8 years. Transverse and longitudinal joints are treated simultaneously at the JPCP, so the roadway must be closed for this purpose. On the test section, the joint renewal takes 10 h. There are only longitudinal joints in a CRCP. However, since these are not as frequently loaded by vehicles as transverse joints, they only need to be replaced after

12 years and the route is therefore still available 50% of the time. Longitudinal joint replacement requires 5 h per kilometer, as the joint can be renewed in one run and does not have to be reset repeatedly. Punchout repair takes 24 h, during which the affected lane must be closed. According to Ziener [59], 5% of the individual panels of a JPCP must be replaced after 30 years of operation, 2% should be replaced after 25 years, and 3% after 28 years. In addition, most work is carried out at night, so that fewer users are affected by the restrictions. According to OAT, the replacement of a single slab generally takes about 8–10 h with 6 employees. The exact number of hours depends on the setting time until traffic release, which can vary depending on the weather. Individual slab replacement is not necessary for a CRCP. In this case, however, the concrete pavement is to be overlaid with a Stone Mastic Asphalt (SMA) layer after a service life of 40 years. This extends the service life of the pavement by another 20 years. A summary of all the works to be carried out and their duration can be found in Table 4.

Table 4. Required operations and duration for the JPCP and the CRCP.

Description of Work	Duration
Transverse joint renewal	10 h/km
Longitudinal joint renewal	5 h/km
Single slab renewal	9 h/slab
Punchouts	24 h/punchout
Surface layer renewal	72 h/km
Demolition of concrete slab	120 h/km

Due to the increase in goods and passenger car traffic in the coming years, it is important to take the growth factor into account in the calculation of availability. In this study, the average daily traffic of the permanent counting station “Büchenau” is used, which is provided annually by the German Federal Highway Research Institute (BASt). In 2022, the AADT in the direction of Bruchsal was 52,913 vehicles per day, with heavy goods vehicles amounting to 19.9% [60]. Using the data provided by the BASt for the “Büchenau” permanent counting station, it is possible to calculate an average value and thus determine the percentage of vehicles driving at night. Table 5 contains the daytime and nighttime proportions of the Büchenau counting station.

Table 5. Day and night proportions of the Büchenau permanent counting station.

Time	Total Proportion (%)	Vehicle Proportion (%)	Truck Proportion (%)
10 pm–6 am (nights)	13	11	19
6 am–10 pm (by day)	87	89	81

4.3. Environmental Impact

The Functional Unit (FU) in this study is defined as 5 m of rigid slab pavement. In addition to the system boundary “cradle-to-gate”, the transport of the finished concrete to the construction site as well as the paving of the roadway are thus also considered (“gate-to-site”).

The system boundary is inclusive of aggregate extraction, production of concrete, and construction of rigid pavement. Table 6 represents the components of modules A1 to A5 of a concrete pavement.

Table 6. Components of modules A1–A5 of a concrete pavement [61].

Raw Materials Extraction and Processing	Transport of Raw Materials	Production	Transport of the Concrete to the Site	Road Construction
A1	A2	A3	A4	A5
Cement	Transport			
Sand	Transport	Production of concrete in the batching plant		
Gravel	Transport		Transport	
Air entraining agent	Transport			
Concrete liquefier	Transport			Installation
Water				
Reinforced steel			Transport	
Anchor			Transport	
Dowel			Transport	
Joint filler			Transport	

For this purpose, first the required quantities of raw materials as well as the transport routes are calculated, after which the equipment needed for paving and its performance are determined. Finally, the data obtained for the JPCP and CRCP are brought to the same functional unit for clear comparison and are evaluated with the LCA tool "GaBi" life cycle assessment database [62,63]. The distance for transportation of the individual raw materials to the mixing plant, as well as the finished concrete and other construction materials required for the installation of the concrete pavement to the construction site, needs to be determined, to calculate diesel consumption and the resulting GHG emissions. Table 7 presents the distance between production and construction site in terms of material transport.

Table 7. Material transport from production/generation location to project site.

Material	Start Location	End Location	Truck [km]
Basalt	Basalt-Actien-Gesellschaft	Kraichgau Beton	74
Sand-gravel mixture	MinERALiX Sand und Kies	Kraichgau Beton	19
CEM I and III	OPTERRA Wössingen	Kraichgau Beton	8.6
Additive	(Assumption)	Kraichgau Beton	100
Concrete	Kraichgau Beton	Construction site	32.3
Reinforcement	Baier Stahlhandel	Construction site	19.6
Bitumen	BORNIT-Werk Aschenborn	Construction site	440

In this study, the consideration is given to 40-ton trucks equipped with diesel engines, and the calculation of the empty trip is also performed.

5. Results and Discussion

5.1. Life Cycle Costs Analysis (LCCA)

5.1.1. Agency Cost

The costs of the respective construction methods result from the described structure as well as the calculated quantities of the test section. The NPV calculation of the JPCP is summarized in Table 8.

Table 8. Calculation of NPV for JPCP over infinite horizon (r = 3%).

Year	Cost (EUR)	Discount Factor	PV (EUR)	Factor PV over ∞H for 30 Years	PV over ∞H (EUR)
0	862,800.00	1.0000	862,800.00	1.0000	862,800.00
8	28,600.00	0.7894	22,577.10	1.7006	38,395.57
16	28,600.00	0.6232	17,822.57	1.7006	30,309.82

Table 8. *Cont.*

Year	Cost (EUR)	Discount Factor	PV (EUR)	Factor PV over ∞H for 30 Years	PV over ∞H (EUR)
24	28,600.00	0.4919	14,069.30	1.7006	23,926.85
25	7180.00	0.4776	3429.21	1.7006	5831.86
28	10,770.00	0.4371	4707.32	1.7006	8005.46
30	910,800.00	0.4120	375,237.54	1.7006	638,144.71
Σ Net present value:					1,607,414.27

For the CRCP, the corresponding works and costs, as well as the calculated NPV, are shown in Table 9.

Table 9. Calculation of NPV for CRCP over infinite horizon (r = 3%).

Year	Cost (EUR)	Discount Factor	PV (EUR)	Factor PV over ∞H for 60 Years	PV over ∞H (EUR)
0	1,074,600.00	1.0000	1,074,600.00	1.0000	1,074,600.00
12	6500.00	0.7014	4558.97	1.2044	5490.97
24	6500.00	0.4919	3197.57	1.2044	3851.25
36	6500.00	0.3450	2242.71	1.2044	2701.19
40	129,443.75	0.3066	39,681.87	1.2044	47,794.11
60	127,200.00	0.1697	21,590.05	1.2044	26,003.75
Σ Net present value:					1,160,441.27

A sensitivity analysis is performed after the individual NPVs have been calculated, as shown in Table 10. This is performed because, due to future trends and the consideration of a long-term time horizon, the selected discount rate cannot be specified with absolute accuracy. However, since it has a significant impact on the NPV result, a sensitivity analysis must be performed with different discount rates to evaluate this impact.

Table 10. Sensitivity Analysis—Impact of variability of real discount rate on NPV over ∞H.

Sensitivity Analysis Net Present Value over Infinite Horizon (∞H)			
Discount Rate	**CRCP (EUR)**	**JPCP (EUR)**	**Difference (EUR)**
1%	1,458,070.04	3,818,583.38	2,360,513.34
2%	1,232,457.00	2,149,640.28	917,183.28
3%	1,160,441.27	1,607,414.27	446,973.00
4%	1,126,794.55	1,346,297.97	219,503.42
5%	1,108,361.23	1,197,078.18	88,716.95
6%	1,097,364.35	1,103,298.46	5934.11
7%	1,090,449.46	1,040,738.89	−49,710.57

A critical analysis of the cost comparison between the two construction methods reveals noteworthy insights. Initially, it appears that JPCP has a cost advantage, with EUR 211,800 lower installation costs compared to CRCP. However, a more comprehensive examination, considering the entire life cycle, uncovers a different picture. JPCP exhibits significantly higher utilization costs due to complex joint renewal, increased maintenance, and its shorter service life. Moreover, the necessity of completely replacing the JPCP road surface at the end of its service life incurs additional expenses, including a EUR 48,000 demolition cost. When factoring in these costs, the total expenses for JPCP amount to EUR 910,800, demonstrating that a critical analysis of life cycle costs provides a more nuanced understanding of the economic implications. The CRCP, on the other hand, only requires a punchout repair after the 40th year of service, as well as overlaying the concrete pavement with a SMA [64,65]. The costs for this amount to EUR 129,443.75. By overlaying the concrete pavement with the 4 cm-thick SMA, joint maintenance is no longer required in the following years.

The sensitivity analysis indicates that in comparison with the JPCP, the CRCP alternative becomes more cost-effective as the discount rate decreases, as shown in Figure 8. In principle, high discount rates favor construction projects with low initial costs and high utilization costs.

A critical assessment of the NPVs of the two construction methods over an infinite time horizon reveals intriguing findings. At a discount rate of 3%, the CRCP showcases a substantial cost-saving advantage, amounting to EUR 446,973.00, which may initially suggest its economic superiority. However, it is essential to scrutinize this result within a broader context. As the discount rate varies between 1% and 6%, the NPV comparison indicates a more complex picture. The CRCP exhibits a lower NPV than the JPCP across this range of discount rates, implying a cost-effective edge. This outcome underscores the sensitivity of the analysis to discount rate fluctuations, raising questions about the long-term financial feasibility of CRCP under different economic scenarios.

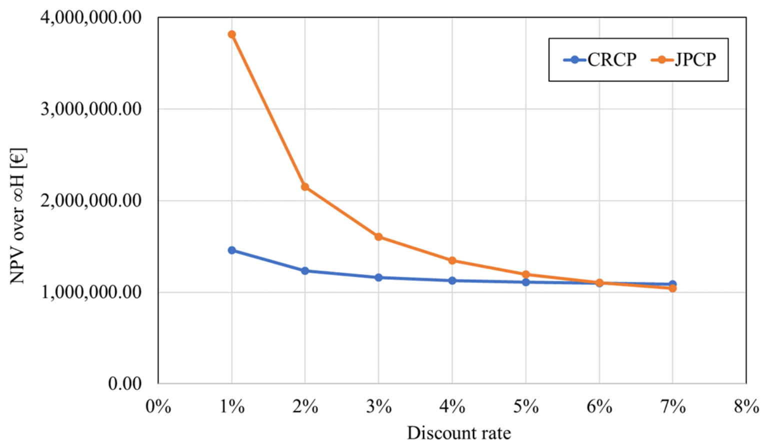

Figure 8. Sensitivity Analysis—Impact of discount rate on NPV over ∞H.

5.1.2. Delay Time/Cost

The total delay can be determined by employing the following calculations [28]:

$$TD = \left(\frac{VMT_{construction}}{FFS_{wz}} + \frac{VMT_{queue}}{\mathrm{v}_D} \right) - \frac{VMT_{construction} + VMT_{queue}}{FFS} \tag{4}$$

where TD: total delay (hours); $VMT_{construction}$: the distance traveled by vehicles within a work zone; VMT_{queue}: the distance covered by vehicles when a queue is present; FFS_{WZ}: the speed at which vehicles can travel without any hindrance in the presence of a work zone; FFS: free-flow speeds under normal operating conditions; and V_D: speed of vehicles in queue. Estimations for free-flow speeds during regular operating conditions were calculated utilizing the following equation [66]:

$$FS = 75.4 - f_{LW} - f_{LC} - 3.22TRD^{0.84} \tag{5}$$

where f_{LW}: the factor to modify the width of a lane; f_{LC}: the factor to consider the lateral clearance; and TRD: the number of exit ramps per mile.

The estimation of free-flow speeds in work zones was conducted using the Equation (6):

$$FFS_{WZ} = 9.95 + f_{sr} + 0.53f_s - 5.60f_{LCSI} - 3.84f_{Br} - 1.71f_{DN} - 1.45f_{Nr} \tag{6}$$

where, f_{sr}: the ratio between the speed limit outside the work zone and the speed limit within the work zone; f_s: the speed limit indicated within the construction zone; f_{LCSI}: lane closure severity index; f_{Br}: barrier type; f_{DN}: day/night indicator; and f_{Nr}: the count of ramps located within a three-mile radius both upstream and downstream of the work zone.

After calculating the total delay, the delay time can be converted to delay cost by using driver wages specific to each vehicle type. This conversion process enables the calculation of the monetary cost associated with the delay [25,28]:

$$Delay\ Cost = TD * Wage_{type} * f_o * \ f_b * A \tag{7}$$

where $W_{agetype}$: hourly wage of a driver; f_o: average number of persons in vehicle type; f_b: business travel factor; and A: percentage of vehicle type in traffic.

Using the provided methodology and considering the specific section, the total delay time was calculated. It was determined that the daily delay amounts to 22,986 h when a partial closure of the motorway is in effect. Furthermore, heavy traffic exceeds 19% of the total traffic on the route. Based on an hourly wage of EUR 30 for a truck driver, the cost of this construction work or partial closure is estimated to be EUR 131,020 per day.

5.2. Availability

The availability considers on the one hand the number of unavailable days and on the other hand the vehicles without availability. As before, the 60-year period under observation is assessed. Figure 9 displays on the left *y*-axis the number of days the roadway is not available due to works and on the right *y*-axis the vehicles without availability.

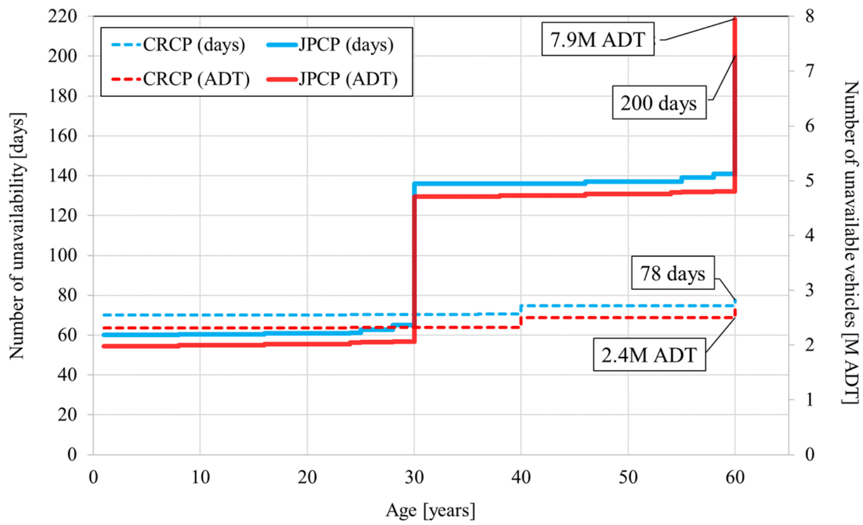

Figure 9. Number of days and vehicles without availability.

At 60 days for installation, the JPCP takes 10 days less than the CRCP. However, even if the installation of the JPCP takes less time, maintenance and repair works are still necessary earlier and more often. Since this work takes less time compared to installation, the JPCP has a higher overall availability than the CRCP up to the 30th year of service. However, because the JPCP has reached its service life after 30 years, it must be demolished and completely replaced. This work is very time-consuming, which is why there are very large gaps in the number of unavailable days and vehicles without availability between the JPCP and the CRCP. At the end of the 60-year analysis period, the roadway is unavailable 200 days for JPCP and 78 days for CRCP. This means that the CRCP can be utilized 61% more than the roadway of JPCP in this period. Considering the times of single slab renewal after 25, 28, 55, and 58 years, a significant increase can be seen in the number of unavailable days. At the same time, for the unavailable vehicles, this increase is barely noticeable. This shows that traffic is much less affected by work performed at night than by shorter work performed during the day. In total, the JPCP has 7,951,269 vehicles without availability, whereas the CRCP has only 2,644,360. Due to the increase in goods traffic in the coming years, it can be observed how the availability of heavy traffic differs between the JPCP and the CRCP. The higher proportion of heavy traffic in the JPCP can be explained by the higher number of works to be constructed, as well as by the nighttime renewal of the individual slabs. This is the case because at night, as can be seen in Figure 10, the proportion of heavy traffic is higher than the share of vehicles.

In total, 1,776,672 more heavy traffic vehicles are affected by the upcoming works at the JPCP than at the CRCP. Furthermore, at the JPCP, after 60 years, the proportion of heavy traffic in vehicles without availability is 29.3%. For the CRCP, the proportion is only 21%.

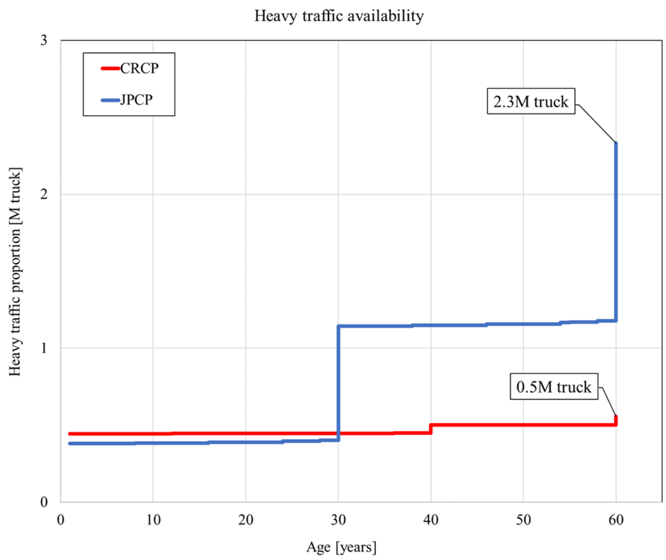

Figure 10. Amount of heavy traffic without availability.

5.3. Environmental Impact Assessment (EIA)

In total, five different scenarios are developed for the calculation of the carbon footprint, resource utilization, and water consumption in JPCP and CRCP, which are shown in Figure 11.

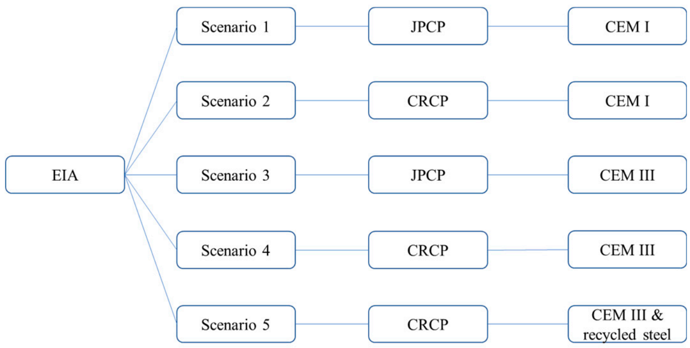

Figure 11. Developed scenarios for calculating the EIA for CRCP and JPCP.

To assess environmental factors, various installation scenarios were examined for CRCP and JPCP, incorporating different types of cement (CEM I and CEM III) and recycled reinforcement. In the sixth scenario, the environmental impact of CRCP with 61.2% recycled steel reinforcement is compared, considering the 100% recyclability of the reinforcement. Utilizing 61.2% steel scrap, as stated by [67], leads to a 33% reduction in primary energy consumption during steel production. The objective was to identify the most suitable alternative among these scenarios. Figure 12 illustrates the impact of the two construction methods on carbon footprint.

The diagram illustrates the impact of different cement types and recycled steel on the carbon footprint. JPCP with CEM III exhibits a 57% lower carbon footprint compared to JPCP with CEM I. Similarly, CRCP with CEM III demonstrates a significantly reduced carbon footprint of 78% compared to CRCP with CEM I. However, the utilization of recycled reinforcement has a minimal effect on carbon footprint compared to cement. When using recycled reinforcement with CEM III, there is only a 25% reduction in CO_2 production, as the recycling process of reinforcement itself contributes to CO_2 emissions. The resource utilization of the examined scenarios is depicted in Figure 13.

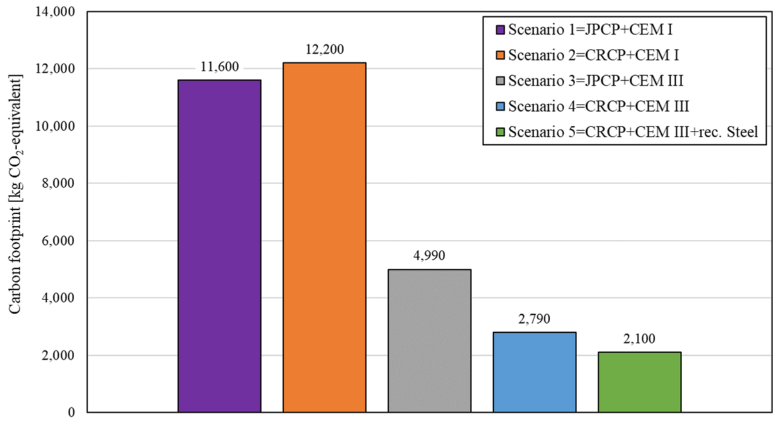

Figure 12. Carbon footprint of the CRCP and JPCP.

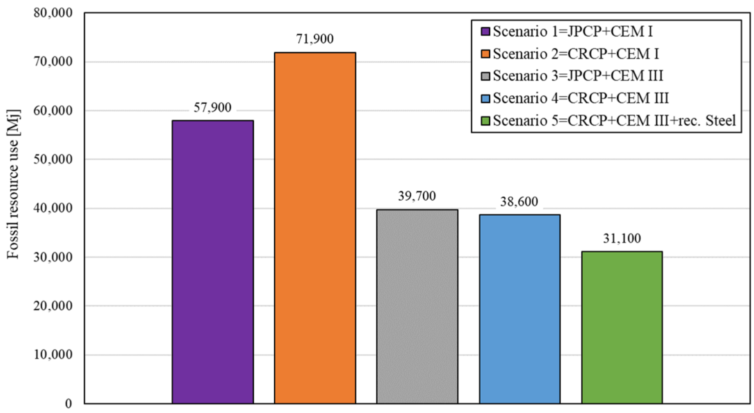

Figure 13. Fossil resource use of the CRCP and JPCP.

While evaluating resource utilization, only modules A1–A5 were considered. However, it is important to note that the service life of CRCP is twice that of JPCP. Additionally, CRCP requires significant reinforcement. Therefore, when interpreting the results, the 20% lower resource utilization of JPCP with CEM I compared to CRCP with CEM I can be justified. In contrast, the resource utilization of both construction methods using CEM III will be nearly identical. Figure 14 demonstrates the water consumption of the analyzed scenarios.

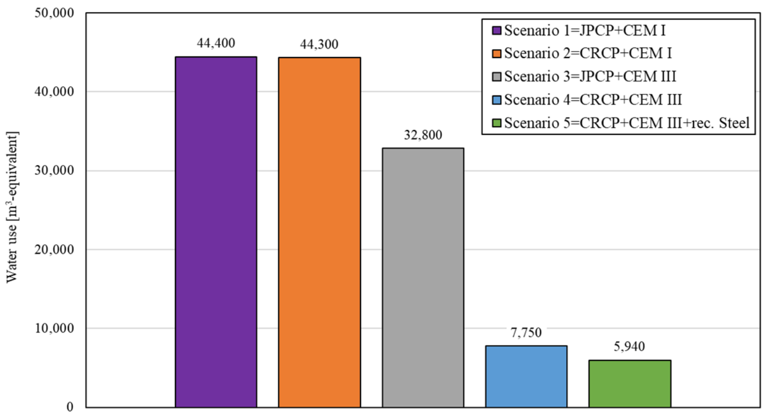

Figure 14. Water use of the CRCP and JPCP.

When CEM III is employed, CRCP exhibits a substantial reduction of 76% in water consumption compared to JPCP. Notably, the fourth and fifth alternatives utilizing CEM III demonstrate significantly lower water usage. CRCP with CEM III showcases an impressive 83% reduction in water consumption compared to CRCP with CEM I. Furthermore, if approximately 61% of the reinforcement is replaced with recycled reinforcement, water usage decreases by 24%.

6. Conclusions and Interpretation

In response to the growing need for sustainable pavement solutions in motorway rehabilitation projects, this research study suggests employing LCCA, availability, and EIA considerations to examine the environmental, economic, and availability implications of two prominent rigid pavement options: CRCP and JPCP. To maintain an equitable comparison, equivalent pavement designs were created for each alternative, following the guidelines set by AASHTO and RStO. In addition to the standard scenario, three alternative scenarios were established to analyze the EIA. The scenarios involved determining quantities, machinery utilization, and energy consumption. Consequently, a 60-year life cycle was chosen as the analysis boundary, and the anticipated number of rehabilitation needs for each alternative was estimated accordingly. The analysis presented in this study enables the quantification of the environmental impact associated with two specific concrete pavement options for constructing a one-kilometer motorway. This comprehensive approach considers the environmental impact throughout the entire life cycle, from initial material extraction to the final placement of the concrete on-site. From a methodological perspective, comparing different construction methods posed challenges due to varying assumptions regarding the functional unit and system boundaries. Concerning the functional unit, the calculations were performed for 5 m-long slabs covering the entire width of the roadway, and these results were then extrapolated to represent a one-kilometer stretch of motorway.

In the LCCA, all significant costs over the service life are considered. Despite a 24.5% higher initial cost, the CRCP option exhibits a NPV that is only 72.2% of JPCP alternative's NPV over an infinite time horizon, mainly due to substantial rehabilitation costs associated with JPCP. Interestingly, maintenance costs, despite their frequent occurrence, have a relatively minor impact on the overall analysis. The sensitivity analysis demonstrates the impact of the discount rate on the NPV, revealing that as the discount rate decreases while keeping other factors constant, the CRCP alternative becomes increasingly cost-effective.

This study also examined the user costs associated with work zone delays, finding a daily delay of 22.986 h on motorway A5 and it estimates the resulting construction cost or partial closure at around EUR 130,000 per day with heavy traffic. Calculating the number of unavailable days for CRCP and JPCP throughout their service life was therefore essential to determine the more economically viable construction method. Availability is a crucial social factor in road infrastructure, as construction and maintenance activities can impact traffic quality. By considering installation duration, necessary maintenance, night operations, and traffic volume, the study estimated availability. CRCP showed significantly higher availability, allowing for 61% more days and 69% more average daily traffic (ADT) compared to JPCP in the same period. Based on the collected data and the defined system boundary, a total of three mid-point impact indicators, namely carbon footprint, fossil resource use, and water use were found to be significantly higher for JPCP when evaluated using the selected impact assessment method (CML).

Furthermore, this research measured the potential for reducing the environmental impact of road development. The study reveals that it is technically feasible to achieve a reduction of over 75% in CO_2 emissions. Specifically, utilizing CRCP with CEM III leads to a significant 44% decrease in CO_2 production compared to JPCP with CEM III. Additionally, CRCP with CEM III exhibited significantly lower water usage, with a remarkable 76% reduction compared to JPCP with CEM III. The environmental analysis conducted over a 60-year service life consistently showed that the CRCP scenario outperformed JPCP as indicated by the outcomes of the EIA approach. Among the various factors considered, CRCP emerged as the primary driver for reducing environmental impacts, particularly in terms of carbon footprint, when compared to standard JPCP.

In conclusion, despite JPCP being the more commonly employed alternative, this study strongly advocates for CRCP as a considerably more favorable choice in terms of minimizing negative environmental, economic, and social impacts. The incorporation of recycled and waste materials aligns with the objectives of the United Nations' Sustainable Development Goals, showcasing CRCP as a practical approach to improve resource and energy efficiency. CRCP exhibits superior durability and performance, requiring fewer resources compared to JPCP, resulting in reduced rehabilitation needs and lower maintenance costs throughout its life cycle. Despite the higher initial construction cost, the long-term benefits of CRCP make it a cost-effective option, as supported by the results of LCCA. Furthermore, the practical consideration of maintenance operations, often constrained by budgetary limitations and leading to delayed joint repairs, provides an additional advantage to CRCP. The ability of CRCP to effectively accommodate delayed repairs underscores the importance of not only technical aspects but also the practical implications of maintenance timing and budget constraints. In summary, this study concludes that CRCP surpasses JPCP alternatives as the most sustainable choice, characterized by a significantly lower carbon footprint, as well as reduced resource and water use.

7. Future Directions

In charting the path forward, several promising avenues for future research emerge. Firstly, the refinement and expansion of our environmental impact assessment (EIA) methodologies, including the incorporation of additional environmental indicators and life cycle assessment (LCA) techniques, are warranted to provide a more nuanced understanding of sustainability. Secondly, we advocate for further exploration into the integration of advanced and sustainable materials into pavement construction, such as eco-friendly binders and recycled aggregates, to continually reduce the environmental footprint. Thirdly, staying at the forefront of emerging pavement construction technologies, including smart materials and self-healing concrete, will be essential to assess their applicability in enhancing sustainability. Additionally, as climate change impacts become increasingly relevant, investigations into adapting pavement designs for climate resilience are crucial. Long-term performance monitoring programs should be established to validate and refine our findings by tracking the real-world performance of CRCP and JPCP over their service lives. Lastly, our research encourages an exploration of the policy implications, public perceptions, and stakeholder engagement aspects, as well as the extension of comparative analyses to other pavement types and regions. These multifaceted future directions aim to contribute to the holistic understanding of sustainability in pavement construction and inform policy decisions and practices in the field.

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