EREM 81/2
Journal of Environmental Research, Engineering and Management
Vol. 81 / No. 2 / 2025
pp. 92–111
10.5755/j01.erem.81.2.39461

Comparative Environmental Impact Assessment of Conventional Pavement Layers and Cement-Treated Recycled Base: Equipment Usage Analysis in Tropical Road Construction Projects

Received 2024/11 | Accepted after revisions 2025/04

https://doi.org/10.5755/j01.erem.81.2.39461

Comparative Environmental Impact Assessment of Conventional Pavement Layers and Cement-Treated Recycled Base: Equipment Usage Analysis in Tropical Road Construction Projects

Lendra Lendra[1]*, Jati Utomo Dwi Hatmoko[2], Mochamad Agung Wibowo[2], Apria Brita Pandohop Gawei[1], Lelo Sintani[3], Vivi Friskila Angela[4]

[1] Department of Civil Engineering, Faculty of Engineering, Palangka Raya University, Indonesia

[2] Department of Civil Engineering, Faculty of Engineering, Diponegoro University, Indonesia

[3] Department of Management, Faculty of Economics and Business, Palangka Raya University, Indonesia

[4] Department of Public Administration, Faculty of Social and Political Sciences Palangka Raya University, Indonesia

***Corresponding author:** lendraleman@jts.upr.ac.id

This study investigates the fuel consumption, energy consumption, and carbon dioxide emissions associated with different pavement foundation structures in road construction projects in Palangka Raya, Indonesia. Using field data gathered at two study locations, the study contrasts the environmental impact of Cement-Treated Recycled Base (CTRB) with that of conventional Sub-Base and Base layers. Palangka Raya's tropical climate offers difficulties for construction equipment operations, given its proximity to the equator and constant high temperatures. The study used a quantitative method to gather primary data on heavy equipment fuel consumption and verify it against theoretical calculations using known formulas and emission factors. Results show that CTRB works exhibit significantly higher fuel consumption (12.23 L/m^3), energy consumption (440.13 MJ/m^3), and carbon emissions (32.65 kgCO_2/m^3) compared to conventional Sub-Base (1.47 L/m^3, 52.73 MJ/m^3, 3.91 kgCO_2/m^3) and Base layers (1.53 L/m^3, 54.96 MJ/m^3, 4.08 kgCO_2/m^3). With variations between field data and calculations ranging from–3.22%

to 7.88%, the study revealed that Palangka Raya's tropical climate equipment regularly consumed 0.48–0.49 L/h more fuel than model projections. This result emphasizes the trade-off between the long-term durability of CTRB and its higher environmental impact during construction, especially in hot tropical areas. Emphasizing the need for a thorough assessment of construction techniques, considering both immediate environmental effects and long-term sustainability elements, the study finds that choosing pavement foundation structures significantly affects energy efficiency and carbon emissions in road building. Particularly in tropical areas, the study offers insightful analysis of environmentally responsible building practices and promotes sustainable methods in civil engineering.

Keywords: carbon emissions, energy consumption, road construction, sustainable engineering, tropical climate.

Introduction

Mainly because of the extensive use of heavy equipment and construction materials, the construction sector, especially road construction, plays a key role in fuel consumption and carbon emissions. Studies show that carbon emissions during the construction phase of road projects account for about 76–86% of total emissions, exceeding those from maintenance and demolition phases (Jang et al., 2015). This underlines the road construction sector's pressing need for sustainable practices. Significant sources of greenhouse gas (GHG) emissions are road construction activities, especially manufacturing construction materials like asphalt and cement, and using heavy machinery (Kim et al., 2013). Emissions are most significantly caused by off-road heavy equipment like bulldozers, excavators, and dump trucks; productivity levels influence fuel consumption and carbon dioxide emissions (Hajji, 2015). Known for their high fuel use and NOx emissions, diesel construction vehicles are expected to see these cut under more rigorous policies and advanced emission criteria (Li et al., 2021). Developing a sustainable transportation system depends on knowing and reducing these emissions during the building phase (Giunta et al., 2019).

Usually, conventional pavement design consists of surface, base, subbase, and subgrade layers. While the subbase and base layers offer structural support, the subgrade is the natural soil foundation (Hatmoko & Lendra, 2021b). Usually composed of asphalt or concrete, the surface layer offers the driving surface and shields the underlying layers from environmental and traffic-related (Vaitkus et al., 2021; Hatmoko & Lendra, 2021a). Usually, this traditional approach calls for several kinds of large machinery for every construction layer, such as graders, rollers, and dump trucks, which could increase fuel use and emissions. The Cement-Treated Recycled Base (CTRB) method, on the other hand, creates a stabilized base layer by mixing recycled materials, such as reclaimed asphalt pavement or construction and demolition waste, with cement and compacting them (Wen et al., 2021). In a more streamlined construction process, CTRB technology calls for specialized equipment, including recyclers/stabilizers, water tankers, and compactors, possibly benefiting equipment use efficiency and lowering environmental effects. Evaluating the environmental effects of these two approaches depends on an awareness of their relative equipment use patterns.

Fuel use and carbon emissions are greatly affected by the tools used in pavement building. Different building techniques call for different kinds, amounts, and operating times of heavy machinery. By changing engine operating points and other factors, optimization models for construction equipment can significantly increase fuel economy and lower emissions (Masih-Tehrani et al., 2020). Further studies by Sizirici et al (2021) reveal that choosing suitable building techniques and tools may significantly affect fuel use efficiency and carbon emissions. Recommended policies to lower emissions include using high-strength building materials, maximizing fuel consumption rates, and using green fuel types (Akhila et al., 2023). Good traffic management throughout construction can also cut emissions and fuel use by 9% (Barati and Shen, 2019). The operational efficiency of construction equipment, especially in tropical settings, raises special environmental concerns. Higher ambient temperatures for diesel construction vehicles may lead to more fuel use and emissions due to more cooling needs and lower engine efficiency

(Oliveira-Nascimento et al., 2021). Especially when contrasting various pavement construction techniques, this link between equipment operation, climate conditions, and environmental effects merits more study.

Road construction sustainability includes pavement durability, lifecycle performance, and emissions reduction. The durability of pavement structures is greatly affected by their mechanical performance, which therefore affects their environmental impact over time; improving the mechanical characteristics of pavement layers can lower the need for maintenance and rehabilitation, therefore promoting more sustainable road infrastructure (Coelho and Guimarães, 2024; Coelho et al., 2024a; Coelho et al., 2024b). Evaluating long-term sustainability requires understanding the connection between mechanical performance and energy use. By quantifying environmental impacts over time and providing a more accurate analysis of sustainable construction solutions, mechanistic-empirical methods comprehensively evaluate pavement lifecycle sustainability (Coelho and Guimarães, 2024; Filho et al., 2024).

Life Cycle Assessment (LCA) methodologies allow for a more accurate quantification of long-term environmental impacts (Lendra et al., 2024), offering a robust framework for sustainable decision-making in road construction (Ribeiro et al., 2022). Focusing on their environmental effect compared to conventional materials, recent research has investigated the possibilities of industrial by-products and alternative materials in pavement subgrade construction. Cement-stabilized mine overburden soil, for example, has greater strength and deformation resistance, qualifying it for sustainable road building (Mishra et al., 2024). Likewise, coal combustion ash and cement slurry waste combinations have been assessed for their mechanical, microstructural, and durability qualities, proving their viability as sustainable subgrade materials (Dixit and Das, 2025b). Fly ash-stabilized red mud has also been evaluated as an alkali-activated sustainable subgrade material with good outcomes in strength, lifetime performance, and durability (Dixit and Das, 2025a). These results draw attention to the possibility of waste-derived materials in improving pavement sustainability and lowering environmental effects. Apart from material choice, the mechanical behaviour of pavement layers is a significant factor for long-term sustainability. Studies have indicated that properly designed pavement systems can help minimize environmental effects by lowering deformation, cracking, and surface deterioration over time (Fernández-Sánchez et al., 2015; Maraqa et al., 2021). Sustainable methods like Reclaimed Asphalt Pavement (RAP) and cold recycling technologies not only help to conserve resources but also to enhance mechanical stability (Coelho et al., 2024a; Coelho et al., 2024b). Stabilization methods reduce lifetime emissions and increase pavement resilience using soil improvement and emulsified binder inclusion (Filho et al., 2024). Adopting mechanistic-empirical approaches even more improves pavement sustainability evaluation by combining mechanical performance data with environmental effect assessments (Coelho and Guimarães, 2024).

Studies on energy efficiency and emission reduction in the building sector have gained significance as more focus is paid to the environmental consequences of development initiatives. Road building is a major contributor to GHG emissions since it intensively uses heavy machinery and materials like asphalt and concrete (Maraqa et al., 2021; Hertwich et al., 2019). Construction materials, energy sources for machinery, and transportation distances are the main determinants of road-building energy efficiency. Different approaches have been suggested and studied to increase energy efficiency and lower sector emissions. Reducing emissions and increasing energy efficiency in road construction calls for several approaches. Recent energy efficiency developments include using low-carbon green construction technologies, energy-efficient statistical monitoring, and alternative pavement technologies (Zhao, 2020). Low-emission and recycled materials (Fernández-Sánchez et al., 2015; Maraqa et al., 2021; Hertwich et al., 2019), warm mix asphalt technologies (Zhao, 2020; Xu et al., 2024; Cheng and Wu, 2017), energy-efficient machinery, and material efficiency strategies (Fernández-Sánchez et al., 2015; Maraqa et al., 2021). Furthermore, improving road networks and infrastructure (Cheng and Wu, 2017; Luo and Yuan, 2023; Palander et al., 2021), in conjunction with technological innovation and encouraging policies (Lu et al., 2020) helps considerably lower the environmental effects of road building activities. Combining these approaches could result in significant GHG emission reductions, supporting a more sustainable road transportation system. Adopting energy-efficient and low-emission road construction techniques has environmental and financial advantages, such as notable GHG emission reductions and the possibility of notable cost savings (Maraqa et al., 2021).

Despite the growing literature on energy efficiency and emissions reduction, few studies have directly compared fuel consumption and carbon emissions across various pavement structures. This study aims to fill the information gap regarding fuel consumption and carbon emissions at two research sites in Palangka Raya, which have different pavement foundation structures. Palangka Raya, the capital city of Central Kalimantan Province, is strategically located in the heart of Kalimantan Island, Indonesia. Situated at coordinates 113°30′ – 114°07′ East Longitude and 1°35′ – 2°24′ South Latitude, the city spans an area of 2,678.51 km^2. Although not directly crossed by the equator, its proximity of about 1.5° to 2.5° south of the equatorial line produces a unique tropical climate marked by consistently high temperatures all year round. This equatorial location significantly influences the city's environmental conditions, leading to higher average temperatures than other regions. These elevated temperatures pose unique challenges, affecting heavy equipment operations by potentially increasing fuel consumption and carbon emissions (Oliveira-Nascimento et al., 2021). Therefore, this study is highly relevant to understanding the impact of a hot tropical climate on the operational efficiency of construction equipment and the resulting carbon emissions during road construction.

This research will comprehensively analyze the effects of various pavement foundation structures on energy efficiency and carbon emissions. Specifically, this research will compare the environmental impact of Sub-Base and Base layers with CTRB. The objectives of this research include: (1) Analyzing the difference in fuel consumption between formula calculations and field data to identify significant variations between theoretical and actual consumption rates. (2) Conducting a comparative analysis of energy consumption and carbon emissions from conventional Sub-Base and Base layers work compared to CTRB, explicitly focusing on equipment usage. (3) Comparing the hourly fuel consumption based on field data with equipment manufacturers' specifications to categorize the fuel consumption of heavy equipment used at both sites as low, medium, or high. The novelty of this research lies in its direct equipment-based comparative analysis of two distinct pavement construction methods (conventional vs. CTRB), specifically in a tropical climate context. Unlike previous studies that focused primarily on material properties or lifecycle assessments, this research emphasizes the operational aspects of construction equipment and their environmental implications. This study bridges an important gap between laboratory-based calculations and real-world applications by examining fuel consumption and emissions in actual field conditions rather than theoretical estimates. Furthermore, the tropical setting of this research provides valuable insights into how climate factors influence equipment efficiency—an aspect often overlooked in existing literature. The results of this research are expected to provide important insights into environmentally responsible construction practices and encourage the adoption of sustainable practices in civil engineering, particularly in tropical regions where infrastructure development continues to accelerate.

Methods

Using a statistical method, this paper evaluated the energy use and carbon dioxide emissions of heavy machinery in road construction projects at two Palangka Raya, Indonesia locations. The study examined CTRB methods against conventional pavement layers (Sub-Base and Base) in tropical settings. Highlighting the various pavement design strategies, *Figs. 1* and *2* show the usual cross-sections used at both research locations. Topped with a somewhat thinner Hot Rolled Sheet–Base (HRS-Base) layer (0.035 m) and Hot Rolled Sheet–Wearing Course (HRS-WC) (0.03 m), the first site uses traditional pavement construction with distinct structural layers made up of a Base (0.20 m) and Sub-Base (0.125 m). Measuring 5.50 m wide with 0.80 m shoulders, this conventional design is smaller.

On the other hand, the second site uses CTRB technology with a denser single structural layer (0.30 m) replacing the usual Base and Sub-Base layers. This CTRB layer is topped with slightly thicker HRS-Base (0.04 m) and identical HRS-WC (0.03 m) wearing courses. The CTRB design accommodates a broader carriageway of 6.00 m with 1.00 m shoulders. It should be noted that the roadside shoulders were excluded from this investigation as the research focuses exclusively on the main pavement structure. Additionally, the shoulder construction was scheduled to be executed after the completion of the leading pavement structure, falling outside the timeframe of this research project. This exclusion allows for a more precise and controlled comparison between conventional construction methods

Fig. 1. *Typical pavement cross section of the first site*

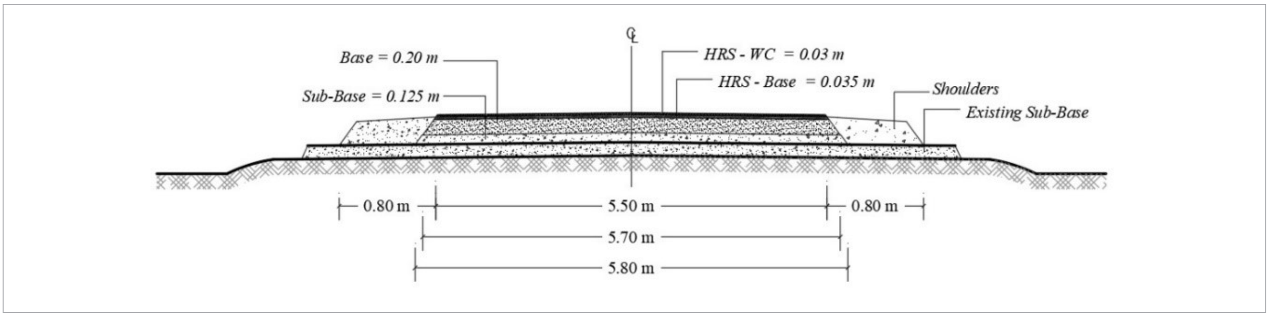
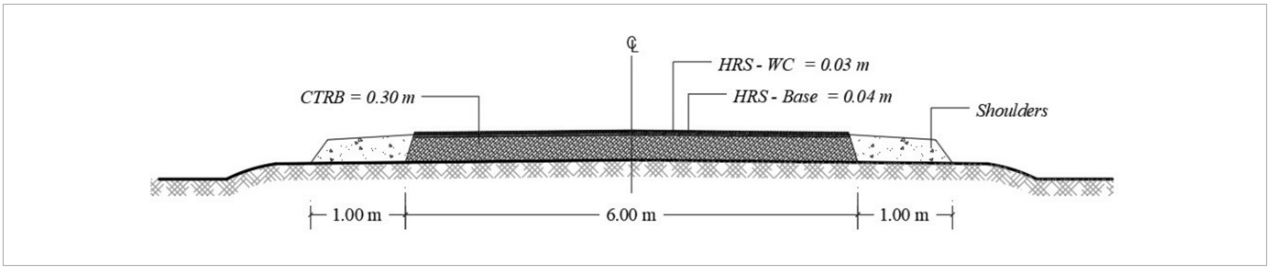


Fig. 2. *Typical pavement cross section of the second site*



and CTRB technology on the primary structural components of the road. These structural variations directly influence construction processes, equipment utilization patterns, and consequently, the energy consumption and emissions generation that form the focus of this comparative environmental assessment.

Data collection was conducted by surveying the work site from June to September 2024, during which research team members conducted daily monitoring on-site, applying a rigorous multi-step process to ensure data reliability. Fuel consumption was documented through direct observation of refueling operations, recording fuel gauge readings at shift change, and verifying equipment operation records. The contractor provided standardized fuel allocation and consumption reports, including detailed dispensing records with equipment identification, time stamps, and volumes supplemented by a digital fuel management system and maintenance records. The research team then conducted random field checks to compare reported values with actual tank measurements, assessed consumption levels against similar regional projects, triangulated data from multiple sources and conducted statistical analyses to detect anomalies to reduce reporting bias. Additional data collection included comprehensive field surveys, equipment specifications documentation, and environmental conditions monitoring during construction.

Fuel consumption is then validated using the fuel consumption per hour formula by multiplying the engine/heavy equipment horsepower (HP) by the machine efficiency factor and 0.04 multiplied by 3.785 conversion factor from gallon/h to L/h (Lewis and Rasdorf, 2017), or written by the formula:

$$\text{Fuel Consumption (L/h)} = 0.04\ (\text{gl/hp-h}) \times 3.785 \times HP \times Fa \quad (1)$$

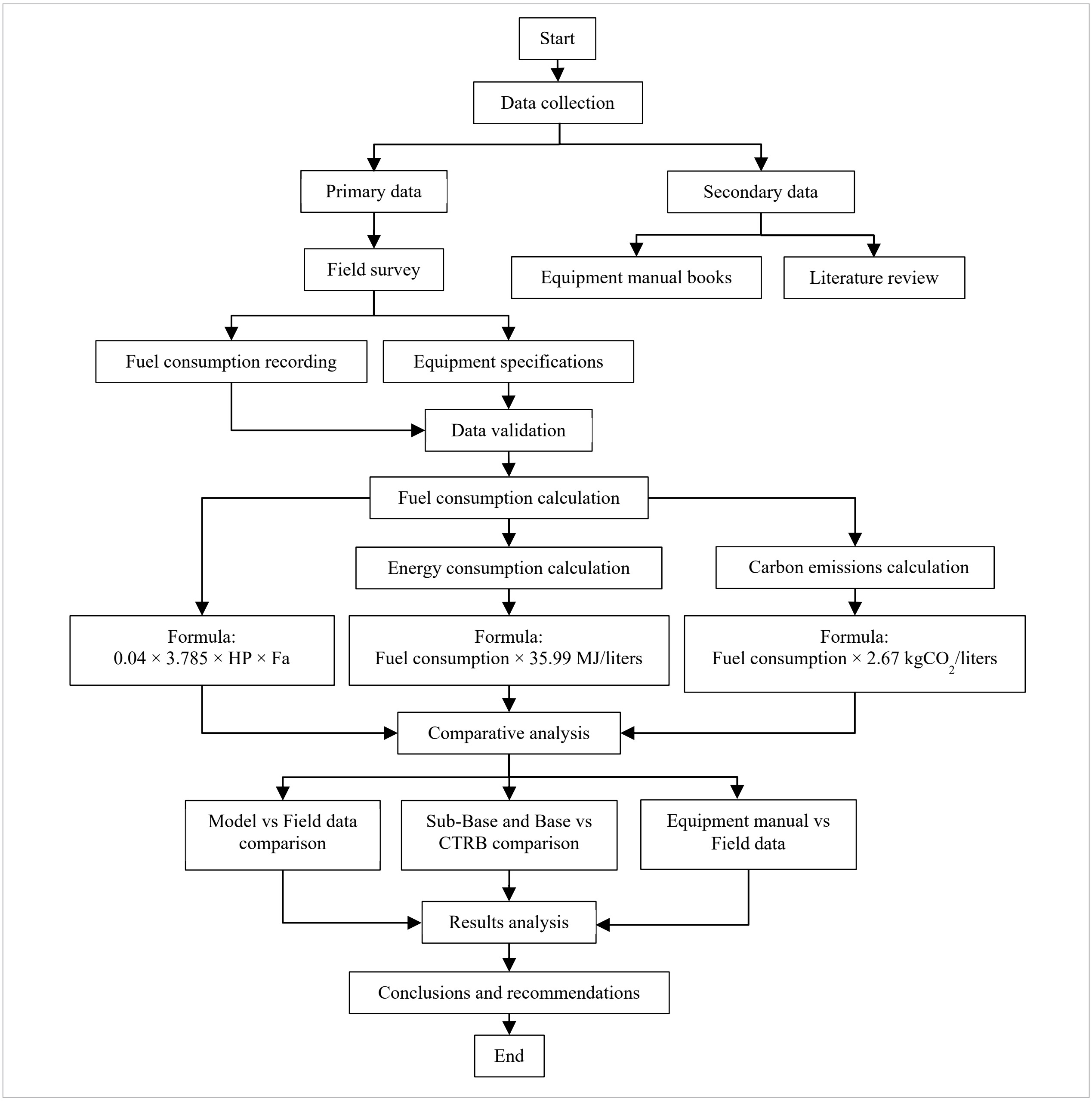
All the heavy equipment has the same efficiency factor (Fa) of 0.83 concerning the standard unit price analysis of road construction work applicable in Indonesia (Bina Marga, 2023), which indicates a standard efficiency applied to all heavy equipments regardless of the specific type and operating conditions. Energy consumption calculations were carried out using a diesel caloric value of 35.99 MJ/L, and carbon dioxide emissions were calculated based on an adjusted emission factor from the Intergovernmental Panel on Climate Change (IPCC), which is 2.67 $kgCO_2$/L of diesel (Garg et al., 2006), using these formulas:

$$\text{Energy Consumption (MJ/L)} = \text{Fuel Consumption} \times \text{Caloric Value} \quad (2)$$

$$\text{Carbon Emissions } (kgCO_2) = \text{Fuel Consumption} \times \text{Emissions Factor} \quad (3)$$

Next, a comparison was made between the results of the theoretical calculation model and field survey data to identify differences in energy consumption and carbon emissions in each road construction work. The analysis focused on comparing energy consumption and emissions between the Sub-Base, Base, and CTRB to evaluate the effect of material selection on energy efficiency and carbon emissions. The next step is to compare fuel consumption per hour based on field data against the heavy equipment manual book (handbook). The data is then compared with the fuel consumption table in the handbook to determine which category of heavy equipment used from the two road construction work sites is in the low, medium, or high category. The results can be used as a benchmark/reference in selecting and operating environmentally friendly heavy equipment by the pavement design; in summary, the flowchart of the research method can be seen in *Fig. 3.*

Fig. 3. *Flowchart of the research methods*



Results and Discussion

Model accuracy at the first site

Table 1 provides valuable insights into the dynamics of heavy equipment fuel consumption in road construction at the first site by comparing model predictions with actual usage, highlighting the need for continuous improvement of predictive models to reflect real-world conditions better. The average difference between the model calculation and the survey data was recorded at 0.49 L/h with an average percentage deviation of 3.59%. Although the calculation method generally showed good accuracy, some equipment, such as asphalt distributors and compressors, showed considerable deviations of up to 8.54%. In contrast, equipment such as wheel loaders, asphalt mixing plants, water tankers, and motor graders had less than 1% deviations.

Table 1. *Fuel consumption per hour of equipment operation at first site*

No.	Work item	Equipment name	Equipment efficiency factor (Fa)	Engine power (HP)	Fuel consumption by calculation model (L/h)	Fuel consumption per hour from survey data (L/h)	Difference (L/h)	Percentage (%)
1	Sub-Base	Wheel Loader	0.83	96.00	12.06	12.15	0.09	0.71
		Dump Truck	0.83	100.00	12.57	13.00	0.43	3.34
		Motor Grader	0.83	135.00	16.96	17.00	0.04	0.21
		Vibratory Roller	0.83	83.00	10.43	10.80	0.50	3.43
2	Base	Wheel Loader	0.83	96.00	12.06	12.15	0.09	0.71
		Dump Truck	0.83	100.00	12.57	13.00	0.43	3.34
		Motor Grader	0.83	135.00	16.96	17.00	0.04	0.21
		Vibratory Roller	0.83	83.00	10.43	10.80	0.50	3.43
		Water Tanker	0.83	135.00	16.96	17.00	0.04	0.21
3	Prime Coat on Base	Asphalt Distributor	0.83	115.00	14.45	15.80	1.35	8.54
		Compressor	0.83	75.00	9.42	10.20	0.78	7.60
4	HRS–Base	Wheel Loader	0.83	96.00	12.06	12.80	0.74	5.75
		Asphalt Mixing Plant	0.83	294.00	36.94	37.00	0.06	0.15
		Generator Set	0.83	180.00	22.62	22.80	0.18	0.79
		Dump Truck	0.83	100.00	12.57	13.00	0.43	3.34
		Asphalt Pavers	0.83	73.80	9.27	9.50	0.23	2.38
		Tandem Roller	0.83	100.00	12.57	13.50	0.93	6.92
		Pneumatic Tyre Roller	0.83	135.00	16.96	17.90	0.94	5.23
5	Tack Coat on HRS–Base	Asphalt Distributor	0.83	115.00	14.45	15.80	1.35	8.54
		Compressor	0.83	75.00	9.42	10.20	0.78	7.60
6	HRS–WC	Wheel Loader	0.83	96.00	12.06	12.80	0.74	5.75
		Asphalt Mixing Plant	0.83	294.00	36.94	37.00	0.06	0.15
		Generator Set	0.83	180.00	22.62	22.80	0.18	0.79
		Dump Truck	0.83	100.00	12.57	13.00	0.43	3.34
		Asphalt Pavers	0.83	73.80	9.27	9.50	0.23	2.38
		Tandem Roller	0.83	100.00	12.57	13.50	0.93	6.92
		Pneumatic Tyre Roller	0.83	135.00	16.96	17.90	0.94	5.23
						Average	**0.49**	**3.59**

Model accuracy at the second site

Table 2 shows similar results for the second site, where CTRB works were the focus. The average difference in fuel consumption between the model calculation and the field survey was 0.48 L/h, with an average percentage deviation of 3.03%. Work with Water Tanker, Tandem Roller, and Pad Foot Roller showed a significant difference, with a deviation reaching 8.22%. Meanwhile,

Table 2. *Fuel consumption per hour of equipment operation at second site*

No.	Work item	Equipment name	Equipment efficiency factor (Fa)	Engine power (HP)	Fuel consumption by calculation model (L/h)	Fuel consumption per hour from survey data (L/h)	Difference (L/h)	Percentage (%)
1	Cement for CTRB	Spreader	0.83	115.00	14.45	14.00	–0.45	–3.22
2	CTRB	Wheel Loader	0.83	96.00	12.06	12.50	0.44	3.49
		Dump Truck	0.83	190.00	23.88	24.00	0.12	0.52
		Motor Grader	0.83	145.00	18.22	18.50	0.28	1.51
		Recycler Machine	0.83	670.00	84.19	85.71	1.52	1.77
		Water Tanker	0.83	130.00	16.34	17.80	1.46	8.22
		Padfoot Roller	0.83	173.00	21.74	22.50	0.76	3.38
		Vibrator Roller	0.83	130.00	16.34	16.25	–0.09	–0.53
		Pneumatic Tire Roller	0.83	135.00	16.96	17.85	0.89	4.96
3	Tack coat on CTRB	Asphalt Distributor	0.83	115.00	14.45	15.50	1.05	6.77
		Compressor	0.83	75.00	9.42	10.00	0.58	5.75
4	HRS–Base	Wheel Loader	0.83	96.00	12.06	12.50	0.44	3.49
		Asphalt Mixing Plant	0.83	294.00	36.94	37.00	0.06	0.15
		Generator Set	0.83	180.00	22.62	22.78	0.16	0.71
		Dump Truck	0.83	190.00	23.88	24.00	0.12	0.52
		Asphalt Pavers	0.83	45.70	5.74	6.00	0.26	4.29
		Tandem Roller	0.83	80.00	10.05	10.50	0.45	4.26
		Pneumatic Tire Roller	0.83	135.00	16.96	17.85	0.89	4.96
5	Tack coat on HRS–Base	Asphalt Distributor	0.83	115.00	14.45	15.50	1.05	6.77
		Compressor	0.83	75.00	9.42	10.00	0.58	5.75
6	HRS–WC	Wheel Loader	0.83	96.00	12.06	12.50	0.44	3.49
		Asphalt Mixing Plant	0.83	294.00	36.94	37.00	0.06	0.15
		Generator Set	0.83	180.00	22.62	22.78	0.16	0.71
		Dump Truck	0.83	190.00	23.88	24.00	0.12	0.52
		Asphalt Pavers	0.83	45.70	5.74	6.00	0.26	4.29
		Tandem Roller	0.83	80.00	10.05	10.50	0.45	4.26
		Pneumatic Tire Roller	0.83	135.00	16.96	17.85	0.89	4.96
						Average	**0.48**	**3.03**

tools such as Asphalt Mixing Plant and Generator Set had minimal differences, with a deviation of less than 1%. Detailed analysis reveals distinct patterns across equipment types and power categories, with high-powered equipment like the Recycler Machine (670 HP, 85.71 L/h) showing relatively low deviation (1.77%) despite its high consumption rate.

In comparison, medium-powered equipment, such as the Water Tanker (130 HP), exhibited higher deviations (8.22%). The CTRB-specific equipment demonstrated unique consumption patterns, with the Recycler Machine consuming significantly more fuel than other equipment but maintaining good prediction accuracy. The negative deviations observed in some equipment, such as the Spreader (–3.22%) and Vibrator Roller (–0.53%), suggest that the model occasionally overestimates consumption, highlighting the complexity of fuel consumption prediction in tropical conditions.

Comparative analysis and impact of tropical climate

Comparative analysis of *Tables 1* and *2* reveals critical insights into equipment specifications and operational conditions across both sites. A notable difference is observed in the Dump Truck specifications, with the first site utilizing 100 HP units while the second site employs 190 HP trucks. This power differential significantly influences fuel consumption patterns and operational efficiency. The analysis of both sites consistently shows that the tropical climate of Palangka Raya City, characterized by consistently high temperatures, leads to increased fuel consumption of approximately 0.48–0.49 L/h above model calculations. This elevated consumption is attributed to three main factors: (1) Reduced engine efficiency due to high ambient temperatures; (2) Increased fuel vaporization rates; (3) Heightened cooling system demands.

Equipment specification variations between sites

The study identified notable variations in equipment specifications between the two construction sites, particularly for specific equipment used in the HRS-WC application, as shown in *Table 1* and *Table 2*. The difference in engine power of HRS-WC equipment between the two research sites is a consequence of varying contractor fleet availability and adjustments to site-specific conditions. It should be noted that the construction works were carried out by different contracting companies at each site, not by a single firm. At the first site, the contractor-operated Dump Trucks with 100 HP power, Asphalt Paver of 73.8 HP, and Tandem Roller of 100 HP, whilst at the second site, they utilized Dump Trucks of 190 HP (90% higher), Asphalt Paver of 45.7 HP (38% lower), and Tandem Roller of 80 HP (20% lower). These engine power variations directly impacted fuel consumption patterns, with higher-powered equipment generally consuming more fuel per operating hour but completing tasks in less time. In contrast, lower-powered equipment demonstrated lower hourly consumption but required more extended operational periods.

Implications for project planning

These findings provide crucial road construction project planning insights, especially in tropical regions. They underline the need for (1) Equipment-specific adjustment factors for fuel consumption estimates, (2) Real-time monitoring systems to optimize fuel efficiency, (3) Consideration of both equipment power ratings and operational conditions, and (4) Climate-adjusted prediction models for tropical environments. The data indicates that equipment specifications and local climate conditions must be closely considered when creating fuel consumption projections and operational strategies for future projects. This understanding enables stakeholders to optimize equipment selection and resource allocation better while considering environmental impact and operational efficiency in tropical conditions.

Analysis of environmental impact at the first site

Table 3 offers comprehensive data on carbon dioxide emissions, energy consumption, and fuel consumption from heavy equipment operations at the first site. The study shows a total fuel use of 9305.22 L of fuel, resulting in 334,894.82 MJ of energy consumption and 24,844.93 kgCO_2 of carbon dioxide emissions spread over six distinct work categories. HRS-Base works consumed the highest proportion of resources, utilizing 3389.54 L (36.4%) of total fuel consumption, followed by HRS-WC at 3046.87 L (32.7%), and Base works at 1740.90 L (18.9%). This distribution pattern indicates that asphalt-related works account for most of the first site's resource consumption and environmental impact.

Detailed examination of equipment utilization reveals significant variations in equipment coefficients and

Table 3. *Fuel consumption, energy consumption, and carbon dioxide emissions at the first site*

No.	Work item	Quantity of work	Equipment name	Equipment coefficient	Fuel consumption per hour (L/h)	Fuel consumption (L)	Energy consumption (MJ)	Carbon dioxide emissions ($kgCO_2$)
1	Sub-Base	725.00 m^3	Wheel Loader	0.0086	12.15	75.76	2726.43	202.27
			Dump Truck	0.0953	13.00	898.20	32,326.31	2398.20
			Motor Grader	0.001	17.00	12.33	443.58	32.91
			Vibratory Roller	0.0097	10.80	75.95	2733.48	202.79
					Total 1	**1062.23**	**38,229.79**	**2836.16**
2	Base	1140.00 m^3	Wheel Loader	0.0087	12.15	120.50	4336.93	321.74
			Dump Truck	0.0784	13.00	1161.89	41,816.35	3102.24
			Motor Grader	0.0013	17.00	25.19	906.73	67.27
			Vibratory Roller	0.013	10.80	160.06	5760.42	427.35
			Water Tanker	0.0141	17.00	273.26	9834.56	729.60
					Total 2	**1740.90**	**62,654.98**	**4648.20**
3	Prime Coat on Base	4908.75 L	Asphalt Distributor	0.0002	15.80	15.51	558.26	41.42
			Compressor	0.00073	10.20	36.55	1315.45	97.59
					Total 3	**52.06**	**1873.72**	**139.01**
4	HRS-Base	503.83 tonne	Wheel Loader	0.013	12.80	83.84	3017.29	223.84
			Asphalt Mixing Plant	0.0201	37.00	374.7	13,485.34	1000.44
			Generator Set	0.0201	22.80	230.89	8309.89	616.49
			Dump Truck	0.3737	13.00	2447.65	88,090.81	6535.22
			Asphalt Pavers	0.0184	9.00	88.07	3169.61	235.14
			Tandem Roller	0.0129	13.50	87.74	3157.82	234.27
			Pneumatic Tyre Roller	0.0085	17.90	76.66	2758.9	204.68
					Total 4	**3389.54**	**121,989.66**	**9050.08**
5	Tack Coat on HRS-Base	866.25 L	Asphalt Distributor	0.0002	15.80	2.74	98.52	7.31
			Compressor	0.0012	10.20	10.87	391.14	29.02
					Total 5	**13.61**	**489.66**	**36.33**
6	HRS-WC	440.58 tonne	Wheel Loader	0.0056	12.80	31.58	1136.59	84.32
			Asphalt Mixing Plant	0.0201	37.00	327.66	11,792.41	874.85
			Generator Set	0.0201	22.80	201.91	7266.67	539.09
			Dump Truck	0.3826	13.00	2191.35	78,866.57	5850.9
			Asphalt Pavers	0.0184	9.00	102.96	3705.64	274.91
			Tandem Roller	0.0129	13.50	102.30	3681.86	273.15
			Pneumatic Tyre Roller	0.0085	17.90	89.12	3207.27	237.94
					Total 6	**3046.87**	**109,657.01**	**8135.15**
				Total (1+2+3+4+5+6)		**9305.22**	**334,894.82**	**24,844.93**

consumption patterns across different work types. Dump Trucks consistently show high equipment coefficients across multiple work categories (0.0953 for Sub-Base, 0.0784 for Base, 0.3737 for HRS-Base, and 0.3826 for HRS-WC), indicating their critical role in material transportation and overall project execution. The highest fuel consumption for a single equipment type was recorded in HRS Base works, where Dump Trucks consumed 2447.65 L, resulting in 88,090.81 MJ of energy consumption and 6535.22 $kgCO_2$ of carbon dioxide emissions. This substantial consumption can be attributed to the high equipment coefficient and the intensive nature of asphalt work.

Comparative analysis of work categories shows that coating operations (Prime Coat and Tack Coat) have a relatively minimal environmental impact, consuming only 52.06 and 13.61 L, respectively. This stark contrast with significant construction activities highlights the varying resource intensity of different construction phases. Base and Sub-Base works demonstrate moderate consumption patterns. Base works show higher resource utilization due to additional equipment requirements, particularly the Water Tanker, which contributed 276.69 L to the total consumption. The data also reveals that equipment with higher coefficients generally contributes more significantly to total emissions, regardless of hourly consumption rates.

Analysis of environmental impact at the second site

Table 4 presents a comprehensive analysis of resource consumption and environmental impact at the second site, revealing the substantial environmental footprint of CTRB operations. The total site consumption reached 26,267.13 L of fuel, resulting in 945,353.99 MJ of energy consumption and 70,133.24 $kgCO_2$ of carbon dioxide emissions. CTRB works dominated these metrics, accounting for 22,012.46 L (83.8%) of total fuel consumption, 792,228.54 MJ of energy consumption, and 58,773.28 $kgCO_2$ of carbon dioxide emissions. This high consumption is primarily driven by specialized equipment such as the Recycler Machine (8886.41 L) and Dump Trucks (8350.56 L), comprising approximately 78% of CTRB-related fuel consumption.

The equipment coefficient analysis reveals critical patterns in resource utilization, with Dump Trucks (0.1933) and Wheel Loaders (0.1302) showing the highest utilization rates in CTRB operations. Notably, while the Recycler Machine has a lower equipment coefficient (0.0576), its high hourly consumption rate (85.71 L/h) is a major contributor to overall resource consumption. In contrast, non-CTRB activities demonstrate significantly lower consumption patterns, with HRS-Base consuming 1799.04 L (6.8% of total), HRS-WC using 1514.83 L (5.8% of total), and Tack Coat operations showing minimal impact at 9.36–159.81 L.

Table 4. *Fuel consumption, energy consumption, and carbon dioxide emissions at the second site*

No.	Work item	Quantity of work	Equipment name	Equipment coefficient	Fuel consumption per hour (L/h)	Fuel consumption (L)	Energy consumption (MJ)	Carbon dioxide emissions ($kgCO_2$)
1	Cement for CTRB	264.60 tonne	Cement Spreader	0.2083	14.00	771.63	27,770.84	2060.24
					Total 1	**771.63**	**27,770.84**	**2060.24**
2	CTRB	1800.00 tonne	Wheel Loader	0.1302	12.50	2929.50	105,432.71	7821.77
			Dump Truck	0.1933	24.00	8350.56	30,0536.65	22,296.00
			Motor Grader	0.0045	18.50	149.85	5393.10	400.10
			Recyler Machine	0.0576	85.71	8886.41	319,822.00	23,726.72
			Water Tanker	0.0050	17.80	160.20	5765.60	427.73
			Padfoot Roller	0.0219	22.50	886.95	31,921.33	2368.16
			Vibrator Roller	0.0134	16.25	391.95	14,106.28	1046.51
			Pneumatic Tire Roller	0.0080	17.85	257.04	9250.87	686.30
					Total 2	**22012.46**	**792,228.54**	**58,773.28**

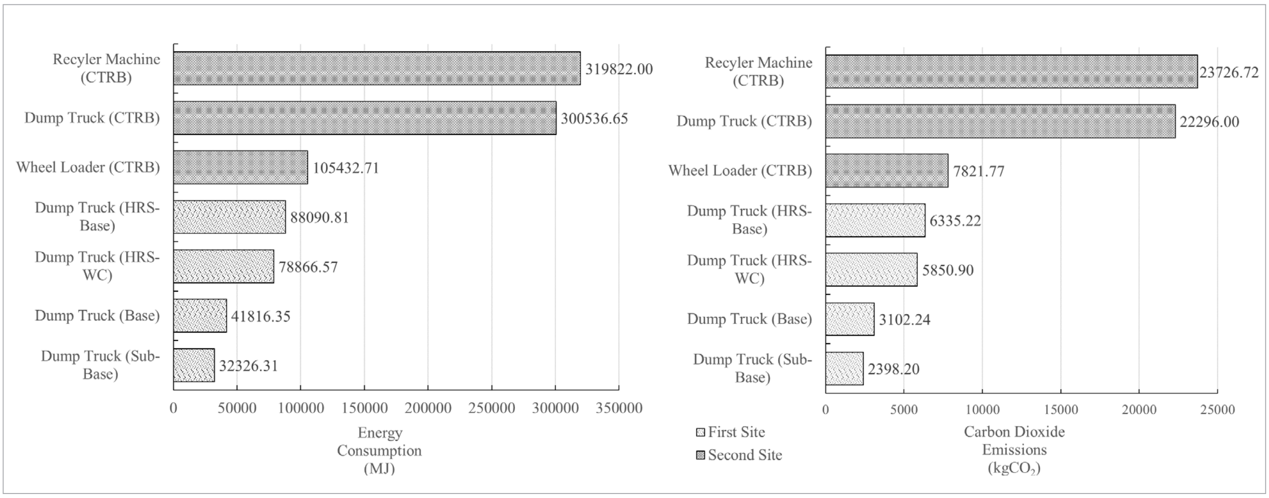
No.	Work item	Quantity of work	Equipment name	Equipment coefficient	Fuel consumption per hour (L/h)	Fuel consumption (L)	Energy consumption (MJ)	Carbon dioxide emissions ($kgCO_2$)
3	Tack Coat on CTRB	2100.00 L	Asphalt Distributor	0.0002	15.50	6.51	234.29	17.38
			Compressor	0.0073	10.00	153.30	5517.27	409.31
					Total 3	**159.81**	**5751.56**	**426.69**
4	HRS-Base	535.20 tonne	Wheel Loader	0.0050	12.50	33.45	1203.87	89.31
			Asphalt Mixing Plant	0.0201	37.00	398.03	14,325.04	1062.74
			Generator Set	0.0201	22.78	245.06	8819.58	654.30
			Dump Truck	0.0444	24.00	570.31	20,525.43	1522.73
			Asphalt Pavers	0.0125	6.00	40.14	1444.64	107.17
			Tandem Roller	0.0340	10.50	191.07	6876.48	510.15
			Pneumatic Tire Roller	0.0336	17.85	320.99	11,552.49	857.05
					Total 4	**1799.04**	**64,747.51**	**4803.44**
5	Tack Coat on HRS-Base	900.00 L	Asphalt Distributor	0.0002	15.50	2.79	100.41	7.45
			Compressor	0.0007	10.00	6.57	236.45	17.54
					Total 5	**9.36**	**336.87**	**24.99**
6	HRS-WC	401.40 tonne	Wheel Loader	0.0050	12.50	25.09	902.90	66.98
			Asphalt Mixing Plant	0.0201	37.00	298.52	10,743.78	797.05
			Generator Set	0.0201	22.78	183.79	6614.68	490.73
			Dump Truck	0.0456	24.00	439.29	15,810.12	11,72.91
			Asphalt Pavers	0.0172	6.00	41.42	1490.87	110.60
			Tandem Roller	0.0466	10.50	196.41	7068.62	524.40
			Pneumatic Tire Roller	0.0461	17.85	330.31	11,887.71	881.92
					Total 6	**1514.83**	**54,518.68**	**4044.59**
				Total (1+2+3+4+5+6)		**26,267.13**	**945,353.99**	**70,133.24**

Comparison of equipment environmental impact between sites

Fig. 4 presents the equipment with the highest energy consumption and carbon dioxide emissions based on the type of work at both research sites. The graph highlights a significant contrast between the two construction methods, where equipment used in the CTRB method consumes significantly more energy and generates substantially higher carbon dioxide emissions per unit than the conventional method. Dump Trucks are the primary contributors to environmental impact at the first site, which employs the conventional method due to their extensive use across various construction activities. The Dump Truck for HRS-Base exhibits the highest energy consumption, amounting to 88,090.81 MJ, with carbon dioxide emissions of 6335.22 $kgCO_2$. This is followed by the Dump Truck for HRS-WC, which consumes 78,866.57 MJ and emits 5850.90 $kgCO_2$. Additionally, the Dump Truck for Base records an energy consumption of 41,816.35 MJ with carbon dioxide emissions of 3102.24 $kgCO_2$, while the Dump Truck for Sub-Base consumes 32,326.31 MJ and emits 2398.20 $kgCO_2$.

Conversely, three primary pieces of equipment dominate the environmental impact at the second site, which utilizes the CTRB method. The Recycler Machine exhibits the highest energy consumption at 319,822.00 MJ, with carbon dioxide emissions reaching 23,726.72 $kgCO_2$. This is followed by the Dump Truck

Fig. 4. *Top equipment by energy consumption and carbon dioxide emissions based on work item*

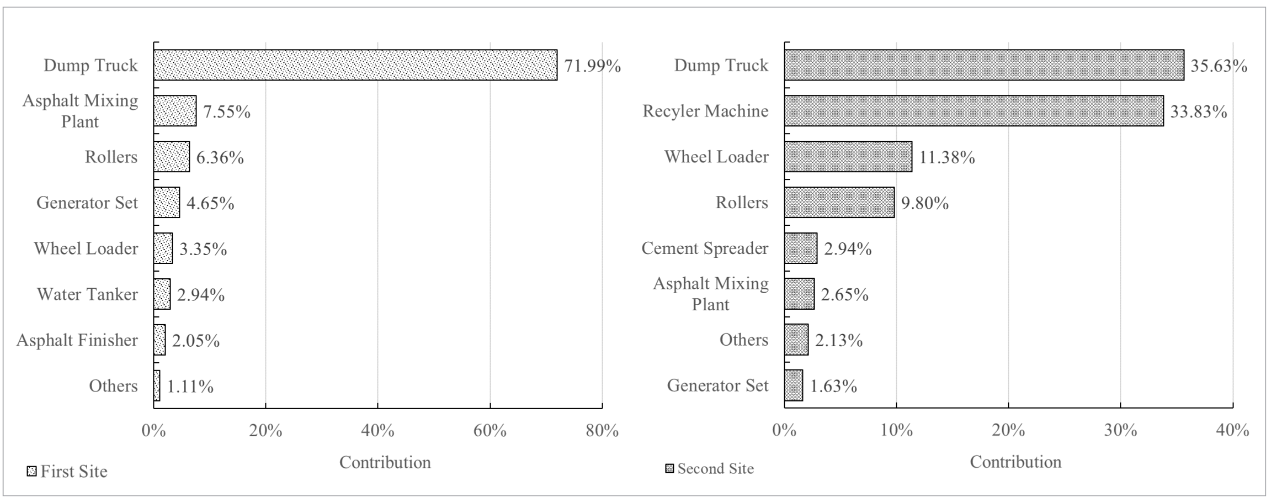


for CTRB, consuming 300,536.65 MJ and emitting 22,296.00 kgCO_2. Lastly, the Wheel Loader for CTRB records an energy consumption of 105,432.71 MJ, with carbon dioxide emissions of 7821.77 kgCO_2.

Equipment contribution to environmental impact

Fig. 5 illustrates the percentage distribution of each equipment type's contribution to total fuel consumption at both research sites. This comparison highlights a fundamental difference in fuel consumption profiles between the two construction methods. The conventional method relies heavily on Dump Trucks, whereas the CTRB method exhibits a more balanced distribution between Dump Trucks and Recycler Machines. At the first site (conventional method), Dump Trucks dominate fuel consumption, accounting for 71.99% of the total. Other significant contributors include the Asphalt Mixing Plant (7.55%), various types of Rollers (6.36%), the Generator Set (4.65%), and the Wheel Loader (3.35%). Equipment such as Water Tankers, Asphalt Finishers, and the "Others" category contribute relatively minor shares, each below 3%. At the second site (CTRB method), fuel consumption is distributed more evenly among several key equipment types. While Dump Trucks remain the most significant contributor at 35.63%, their share is considerably lower than at the first site. The Recycler Machine, a specialized piece of equipment for the CTRB method, plays a significant role, contributing 33.83%, nearly matching the share of Dump Trucks. Other key contributors include the Wheel Loader (11.38%) and various types of Rollers (9.80%).

Fig. 5. *Equipment contribution by based on fuel consumption*



Implications for project planning and environmental management

The distribution of environmental impact across different construction activities highlights the resource-intensive nature of CTRB technology. Despite its potential long-term durability benefits, CTRB demonstrates significantly higher immediate resource demands than conventional methods. This is evidenced by the concentrated impact during the CTRB phase, contrasting with standard paving operations' lower but consistent impact. The data suggests that equipment selection and utilization patterns are crucial in determining overall environmental impact. These findings emphasize the need for strategic planning and resource optimization in road construction projects, particularly when implementing CTRB technology in tropical environments.

The analysis suggests several strategies for environmental impact mitigation. These include emphasizing primary consumption sources for efficiency gains, creating monitoring protocols for high-impact operations, and applying mitigation strategies for peak consumption times. Important factors should also include maximizing CTRB operations to reduce time, effectively planning high-consumption equipment, and assessing equipment combinations that preserve construction quality while minimizing total environmental effect. Project managers who grasp this can more equitably distribute resource use throughout project phases and spot possibilities to lower operational expenses and environmental effects.

Comparison of resource consumption between conventional and CTRB methods

Comparing traditional techniques with CTRB, *Table 5* offers a thorough comparative analysis of resource consumption patterns and environmental effects across both construction sites. From -3.22 % to 7.88%, the

Table 5. *Recapitulation of fuel oil consumption, energy consumption and carbon dioxide emissions*

No.	Work item	Fuel consumption per work quantity	Unit	Energy consumption per work quantity (MJ/unit)	Carbon dioxide emissions per work quantity ($kgCO_2$/unit)	Fuel consumption difference
			First Site			
1	Sub-Base	1.42 (model) / 1.47 (survey)	L/m^3	52.73 (MJ/m^3)	3.91 ($kgCO_2/m^3$)	3.12 (%)
2	Base	1.49 (model) / 1.53 (survey)	L/m^3	54.96 (MJ/m^3)	4.08 ($kgCO_2/m^3$)	2.63 (%)
3	Prime Coat on Base	0.01 (model) / 0.01 (survey)	L/L	0.38 (MJ/L)	0.03 ($kgCO_2$/L)	7.88 (%)
4	HRS-Base	6.53 (model) / 6.73 (survey)	L/tonne	242.13 (MJ/tonne)	17.96 ($kgCO_2$/tonne)	2.98 (%)
5	Tack Coat on HRS-Base	0.01 (model) / 0.02 (survey)	L/L	0.57 (MJ/L)	0.04 ($kgCO_2$/L)	7.79 (%)
6	HRS-WC	6.71 (model) / 6.92 (survey)	L/tonne	248.89 (MJ/tonne)	18.46 ($kgCO_2$/tonne)	2.99 (%)
			Second Site			
7	Cement for CTRB	3.01 (model) / 2.92 (survey)	L/tonne	104.95 (MJ/tonne)	7.79 ($kgCO_2$/tonne)	−3.22 (%)
8	CTRB	12.03 (model) / 12.23 (survey)	L/m^3	440.13 (MJ/m^3)	32.65 ($kgCO_2/m^3$)	1.63 (%)
9	Tack Coat on CTRB	0.07 (model) / 0.08 (survey)	L/L	2.74 (MJ/L)	0.20 ($kgCO_2$/L)	5.79 (%)
10	HRS-Base	3.30 (model) / 3.36 (survey)	L/tonne	120.98 (MJ/tonne)	8.98 ($kgCO_2$/tonne)	1.79 (%)
11	Tack Coat on HRS-Base	0.01 (model) / 0.01 (survey)	L/L	0.37 (MJ/L)	0.03 ($kgCO_2$/L)	6.06 (%)
12	HRS-WC	3.70 (model) / 3.77 (survey)	L/tonne	135.82 (MJ/tonne)	10.08 ($kgCO_2$/tonne)	2.07 (%)

study shows notable differences in fuel use between model calculations and field data, thus stressing the complexity of consumption forecasting in real operations. Fuel use differences between the model and survey at the first site, where traditional techniques were used, ranged from 2.63% to 7.88%, with coating operations exhibiting the most notable differences. The site demonstrated consistent consumption patterns, with Sub-Base works consuming 1.47 L/m^3 (52.73 MJ/m^3, 3.91 kgCO_2/m^3) and Base works slightly higher at 1.53 L/m^3 (54.96 MJ/m^3, 4.08 kgCO_2/m^3). Energy consumption per unit of work ranged from 0.38 MJ/L for Prime Coat on Base to 248.45 MJ/tonne for HRS WC, with corresponding carbon dioxide emissions ranging from 0.03 kgCO_2/L to 18.43 kgCO_2/tonne.

The second site, featuring CTRB works, exhibited significantly higher resource intensity, with CTRB operations consuming 12.23 L/m^3 (440.13 MJ/m^3, 32.65 kgCO_2/m^3), approximately eight times higher than conventional methods. The Cement for CTRB showed moderate consumption at 2.92 L/tonne (104.95 MJ/tonne, 7.79 kgCO_2/tonne) but uniquely demonstrated negative deviation from model predictions (–3.22%). Energy consumption at this site ranged from 0.37 MJ/L for Tack Coat to 440.13 MJ/m^3 for CTRB works, reflecting the complex artistry and additional energy requirements for cement recycling processes.

Efficiency variations in HRS works

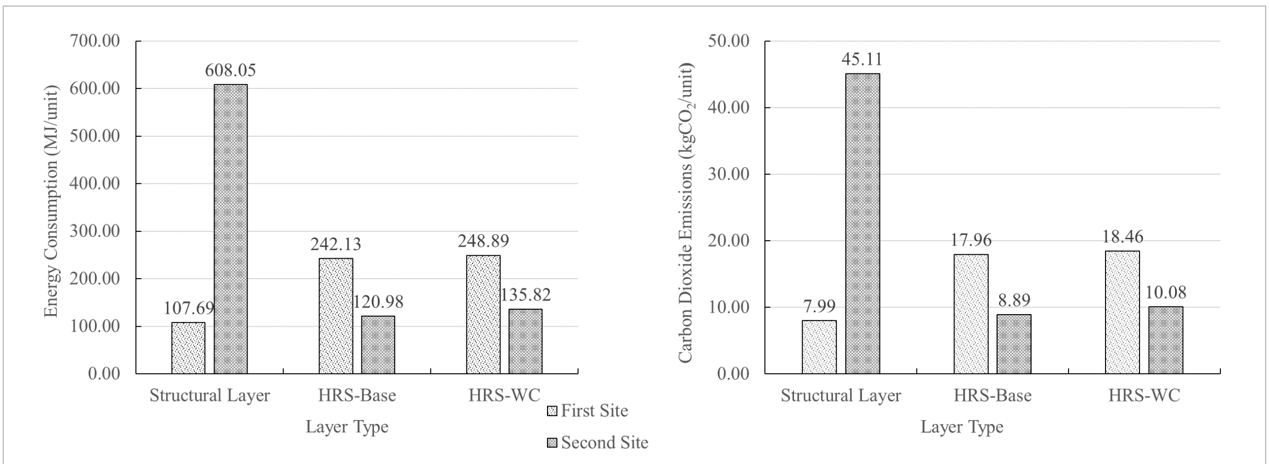
Comparative analysis of HRS works between sites revealed notable efficiency variations, with the first site showing higher consumption for HRS-Base (6.73 L/tonne) and HRS-WC (6.92 L/tonne) compared to the second site is more moderate 3.36 L/tonne and 3.77 L/tonne respectively. These differences suggest the influence of site conditions, equipment efficiency, and operational practices. Model-to-survey deviations remained relatively consistent for HRS works (1.79–2.99%), indicating reliable predictability for these operations.

Trade-offs in environmental efficiency between methods

Fig. 6 presents a comparative analysis of environmental efficiency for three primary pavement layers across both research sites, with values normalized per unit of work (MJ/unit for energy consumption and kgCO_2/unit for carbon dioxide emissions). The graph highlights a critical trade-off in selecting road construction technologies. While the CTRB method exhibits significantly higher energy consumption and emissions in the structural layer, it demonstrates substantial environmental efficiency in the surface layers. For the structural layer, the CTRB method at the second site exhibits substantially higher energy intensity, reaching 608.05 MJ/m^3, compared to 107.69 MJ/m^3 for the conventional method at the first site, representing a nearly fivefold increase. Similarly, carbon dioxide emissions for the structural layer in CTRB construction amount to 45.11 kgCO_2/m^3, approximately five times higher than the 7.99 kgCO_2/m^3 observed in the conventional method. This reflects the energy-intensive nature of CTRB construction, primarily driven by the extensive use of the Recycler Machine and Dump Truck.

However, the trend is reversed for surface layers, namely HRS-Base and HRS-WC. In the HRS-Base

Fig. 6. *Energy consumption and carbon dioxide by pavement layer type*



layer, the CTRB method demonstrates significantly greater energy efficiency, with consumption reduced to 120.98 MJ/tonne, compared to 242.13 MJ/tonne in the conventional method, representing an approximately 50% reduction. Similarly, carbon dioxide emissions for HRS-Base in CTRB construction stand at 8.89 $kgCO_2$/tonne, nearly half that of the conventional method, which records 17.96 $kgCO_2$/tonne. A comparable trend is observed for the HRS-WC layer, where the CTRB method achieves 135.82 MJ/tonne and 10.08 $kgCO_2$/tonne, reflecting an approximately 45% improvement in efficiency over the conventional method, which records 248.89 MJ/tonne and 18.46 $kgCO_2$/tonne.

Implications for sustainable construction practices

These findings emphasize critical implications for sustainable construction practices and resource management. The significant contrast between conventional and CTRB methods' resource consumption highlights the importance of considering environmental impact in method selection. While CTRB offers superior long-term durability, its intensive resource requirements during construction present a crucial trade-off, contributing significantly to the total environmental impact at the second site. This comprehensive analysis confirms the need for more efficient and environmentally friendly construction methods, potentially adopting best practices from conventional methods to optimize CTRB operations.

The findings enable more informed decision-making in balancing construction quality, environmental responsibility, and operational efficiency, particularly in tropical climates where local conditions significantly affect equipment performance and resource consumption patterns. This information is invaluable for decision-making processes that consider the overall environmental impact of road construction.

Comparative analysis of equipment consumption patterns

Table 6 compares heavy equipment fuel consumption between field data and manual specifications, revealing significant patterns across both sites. Due to limited

Table 6. *Comparison of heavy equipment fuel consumption based on field and manual data*

No.	Heavy Equipment and Horsepower	Fuel Consumption by Field Data (L/h)	Fuel Consumption by Handbook/ Manual Book (L/h)	Category by Handbook/ Manual Book	References
		First Site			
1	Wheel Loader: Komatsu WA150-5, 96 HP	12.15	7.90–11.00	High	Komatsu (2019)
2	Motor Grader: Komatsu GD511A-1, 135 HP	17.00	16.50–21.00	High	Komatsu (2019)
3	Vibratory Roller: Caterpillar CS-423E, 83 HP	10.80	9.50–12.90	High	Caterpillar (2018)
4	Pneumatic Tire Roller: Sakai TS200, 135 HP	17.90	12.00–18.00	High	Sakai Heavy Industries Ltd (2012)
5	Tandem Roller: CAT CB44B, 100 HP	13.50	10.20–14.20	High	Caterpillar (2018)
6	Asphalt Pavers: CAT AP355F, 73.80 HP	9.50	9.50–11.40	Medium	Caterpillar (2018)
		Second Site			
7	Wheel Loader: Komatsu WA150-5, 96 HP	12.50	7.90–11.00	High	Komatsu (2019)
8	Motor Grader: Caterpillar 120K2, 145 HP	18.50	15.60–21.90	High	Caterpillar (2018)
9	Vibratory Roller: Caterpillar CS533E, 130 HP	16.25	13.20–17.00	High	Caterpillar (2018)
10	Padfoot Roller: Caterpillar CP74B, 173 HP	22.50	16.60–29.20	High	Caterpillar (2018)
11	Recycler Machine: Wirtgen WR2500S, 670 HP	85.71	71.00–94.00	Medium	Wirtgen America Inc. (2019)
12	Pneumatic Tire Roller: Sakai TS200, 135 HP	17.85	12.00–18.00	High	Sakai Heavy Industries Ltd (2012)
13	Tandem Roller: CAT CB434, 80 HP	10.50	7.60–11.40	Medium	Caterpillar (2018)
14	Asphalt Pavers: CAT AP255E, 45.70 HP	6.00	5.60–9.50	Low	Caterpillar (2018)

information and handbooks, not all machines were included in this comparison. At the first site, 83.3% of the equipment (5 out of 6) operated in the "High" consumption category, with only the Asphalt Pavers showing medium consumption levels. Notable deviations from manual specifications were observed in the Wheel Loader (12.15 vs. 7.90–11.00 L/h) and Pneumatic Tire Roller (17.90 vs. 12.00–15.00 L/h), consistently exceeding the recommended ranges.

This pattern persisted at the second site, where equipment showed a more diverse distribution of consumption categories: six units in "High," two in "Medium," and one in "Low" categories. The highest consumption was recorded by the Recycler Machine (85.71 L/h, 670 HP), while the Asphalt Pavers demonstrated the lowest consumption (6.00 L/h, 45.70 HP), indicating a strong correlation between engine power and fuel consumption.

Geographic and climatic influence on equipment performance

The geographic location of both sites, situated between 1.5° to 2.5° south of the equator, significantly influenced equipment performance and fuel consumption patterns. The consistent tropical climate and high temperatures increased cooling system demands and affected overall equipment efficiency. This environmental element in high-powered machines caused consumption levels to surpass manual specifications by 10–20% for specific equipment.

While lower-powered equipment (<100 HP) mostly kept consumption within advised ranges, the data indicates that higher horsepower (>150 HP) equipment exhibited more significant departures from manual specifications. These results underline the importance of location-specific operational plans, including improved maintenance schedules, operator training courses, and real-time monitoring systems to maximize fuel economy in tropical areas. The study also emphasizes the need to consider environmental conditions while choosing equipment and scheduling operations, since they greatly influence operational expenses and environmental sustainability.

Study limitations and future research directions

When reading the findings, one should consider several shortcomings of this study. First, the study was done in a particular tropical climate area, Palangka Raya which could restrict the generalizability of results to places with other climatic circumstances. The second study concentrated only on fuel use and emissions during construction; it did not consider the long-term environmental effects throughout the pavement's lifetime. Third, various construction techniques' economic factors and cost-benefit studies were not thoroughly investigated. Fourth, the study applied a constant efficiency factor 0.83 to all equipment, which might not precisely represent the differences in equipment efficiency under various operating conditions. Fifth, the study ignored operator skill levels, equipment maintenance history, and thorough soil conditions, which could significantly affect fuel consumption patterns. The study period was also short, and seasonal changes in weather conditions that could impact equipment performance were not recorded. Future studies should include lifecycle analysis, economic considerations, variable efficiency factors, and a broader spectrum of geographical and climatic conditions to offer more thorough insights into sustainable road building practices, addressing these constraints.

Conclusions

This study offers important new perspectives on the environmental effects of several pavement foundation structures in tropical climate settings, especially contrasting conventional techniques with CTRB. Examining fuel use data from two Palangka Raya construction sites showed that actual field consumption regularly surpassed theoretical estimates by 0.48–0.49 L/h, with differences between -3.22% and 7.88%. This difference is especially notable in equipment running under the high-temperature equatorial conditions of the area, therefore highlighting the need for climate factors in construction planning. The comparative analysis showed that CTRB works, while offering superior pavement quality, resulted in substantially higher environmental impacts, consuming 12.23 L/m^3 of fuel compared to conventional Sub-Base (1.47 L/m^3) and Base (1.53 L/m^3) methods. This translated to significantly higher energy consumption (440.13 MJ/m^3 for CTRB versus 52.73 MJ/m^3 for Sub-Base and 54.96 MJ/m^3 for Base) and carbon emissions (32.65 kgCO_2/m^3 for CTRB versus 3.91 kgCO_2/m^3 for Sub-Base and 4.08 kgCO_2/m^3 for Base). Field data analysis further revealed that most heavy equipment operated in the "high" fuel consumption category according to manufacturer specifications, with tropical conditions exacerbating consumption rates.

These results draw attention to the complex trade-offs in road building between long-term pavement durability and short-term environmental effects. Particularly in tropical areas, where environmental conditions greatly affect equipment performance, the study emphasizes the importance of a thorough approach to construction method selection. Sustainable road construction techniques should consider the technical requirements of tools and materials and their environmental performance under climate conditions. Emphasizing climate-adapted practices in civil engineering, this paper provides important insights for decision-makers in tropical areas to balance environmental responsibility and construction quality. Future studies should create predictive fuel consumption models considering temperature, humidity, and tropical terrains. Examining green technologies in heavy equipment would also help improve energy efficiency and lower emissions, promoting sustainable road building in the tropics.

Acknowledgements

The authors would like to thank the Palangka Raya University for the funding this research.

References

Akhila B. R. S., Ahmed S., Arocho I. (2023) Simulation of real-time operational level emissions from nonroad equipment: case study of a construction site. Practice Periodical on Structural Design and Construction 28(2): 1–10. Available at: https://doi.org/10.1061/ppscfx.sceng-1142

Barati K., Shen X. (2019) Modelling traffic conditions on fuel use and emissions of on-road construction equipment. Proceedings of the 36th International Symposium on Automation and Robotics in Construction, ISARC 2019, Isarc 945–952. Available at: https://doi.org/10.22260/isarc2019/0126

Bina Marga (2023) Lampiran III Surat Edaran Direktur Jenderal Bina Konstruksi Nomor 73/SE/Dk/2023 Tentang Tata Cara Penyusunan Perkiraan Biaya Pekerjaan Konstruksi Bidang Pekerjaan Umum dan Perumahan Rakyat [Annex III Circular Letter of the Director General of Bina Konstruksi Number 73/SE/Dk/2023 Regarding the Procedure for Preparing Construction Cost Estimates in the Field of Public Works and Public Housing] Kementerian Pekerjaan Umum Dan Perumahan Rakyat. Available at: https://binakonstruksi.pu.go.id/produk/produk-hukum/surat-edaran-direktur-jenderal-bina-konstruksi-nomor-73-se-dk-2023/ (accessed 5 July 2024) *(in Indonesian).*

Caterpillar (2018) Caterpillar Performance Handbook (48th ed.). Caterpillar.

Cheng D., Wu L. (2017) A summary of research on energy saving and emission reduction of transportation. IOP Conference Series: Earth and Environmental Science 100(1): 1–6. Available at: https://doi.org/10.1088/1755-1315/100/1/012212

Coelho L. M., Guimarães A. C. R. (2024) Effect of compaction temperature on the mechanical behavior of granular base containing RAP. In C. Rujikiatkamjorn, J. Xue, B. Indraratna (Eds.), Proceedings of the 5th International Conference on Transportation Geotechnics (ICTG) 2024 Volume 5 (Vol. 5, pp. 129–137). Springer. Available at: https://doi.org/10.1016/s0026-0657(99)80218-5

Coelho L. M., Guimarães A. C. R., Azevedo A. R. G. d., Monteiro S. N. (2024a) Sustainable reclaimed asphalt emulsified granular mixture for pavement base stabilization: prediction of mechanical behavior based on repeated load triaxial tests. Sustainability (Switzerland) 16(13): 1–14. Available at: https://doi.org/10.3390/su16135335

Coelho L. M., Kox R. P., Guimarães A. C. R., Travincas R., Monteiro S. N. (2024b) Influence of curing time on the mechanical behavior of cold recycled bituminous mix in flexible pavement base layer. Applied Sciences (Switzerland) 14(17): Available at: https://doi.org/10.3390/app14177612

Dixit A., Das S. K. (2025a) Fly ash stabilised red mud as a one-part alkali-activated sustainable material for pavement subgrade: Strength, durability and life cycle assessment analysis. Road Materials and Pavement Design 1–27: Available at: https://doi.org/10.1080/14680629.2025.2454027

Dixit A., Das S. K. (2025b) Mechanical, microstructural, and durability assessment of cement slurry waste and coal combustion ash mixture as a sustainable subgrade construction material: Experimental and mechanistic modeling approach. Construction and Building Materials 458(December 2024): 139550. Available at: https://doi.org/10.1016/j.conbuildmat.2024.139550

Fernández-Sánchez G., Berzosa Á., Barandica J. M., Cornejo E., Serrano J. M. (2015) Opportunities for GHG emissions reduction in road projects: A comparative evaluation of emissions scenarios using CO2NSTRUCT. Journal of Cleaner Production 104: 156–167. Available at: https://doi.org/10.1016/j.jclepro.2015.05.032

Filho L. H. A., Casagrande M. D. T., Almeida M. S. de S., Costa W. G. S., Santana P. R. L. de (2024) Mechanical performance and life cycle assessment of soil stabilization solutions for unpaved roads from northeast Brazil. Sustainability (Switzerland) 16(22): Available at: https://doi.org/10.3390/su16229850

Garg A., Kazunari K., Pulles T. (2006) Volume 2: Energy. In: Eggleston S., Buendia L., Miwa K., Ngara T., Tanabe K. (Eds.) 2006

IPCC Guidelines for National Greenhouse Gas Inventories Vol. 2: 1–29. Institute for Global Environmental Strategies (IGES)

Giunta M., Lo Bosco D., Leonardi G., Scopelliti F. (2019) Estimation of gas and dust emissions in construction sites of a motorway project. Sustainability (Switzerland) 11(24): Available at: https://doi.org/10.3390/SU11247218

Hajji A. (2015) The use of construction equipment productivity rate model for estimating fuel use and carbon dioxide (CO2) emissions. Case study: bulldozer, excavator and dump truck. International Journal of Sustainable Engineering 8(2): 111–121. Available at: https://doi.org/10.1080/19397038.2014.962645

Hatmoko J. U. D., Lendra L. (2021a) How sustainable are flexible and rigid pavement? A life cycle impact assessment (LCIA) approach. IOP Conference Series: Materials Science and Engineering: 2–12. Available at: https://doi.org/10.1088/1757-899X/1072/1/012071

Hatmoko J. U. D., Lendra L. (2021b) Quantifying energy consumption and greenhouse gas emissions of construction projects: A case study of Semarang - Bawen road project. IOP Conference Series: Materials Science and Engineering 1072(1): 012070. Available at: https://doi.org/10.1088/1757-899x/1072/1/012070

Hertwich E. G., Ali S., Ciacci L., Fishman T., Heeren N., Masanet E., Asghari F. N., Olivetti E., Pauliuk S., Tu Q., Wolfram P. (2019) Material efficiency strategies to reducing greenhouse gas emissions associated with buildings, vehicles, and electronics – A review. Environmental Research Letters 14(4): Available at: https://doi.org/10.1088/1748-9326/ab0fe3

Jang W., You H. W., Han S. H. (2015) Quantitative decision making model for carbon reduction in road construction projects using green technologies. Sustainability (Switzerland) 7(8): 11240–11259. Available at: https://doi.org/10.3390/su70811240

Kim B., Lee H., Park H., Kim H. (2013) Estimation of greenhouse gas emissions from land-use changes due to road construction in the Republic of Korea. Journal of Construction Engineering and Management 139(3): 339–346. Available at: https://doi.org/10.1061/(asce)co.1943-7862.0000620

Komatsu (2019) Specifications & Application Handbook Komatsu (32nd ed., Issue October). Komatsu Ltd.

Lendra L., Hatmoko J. U. D., Wibowo M. A. (2024) Towards sustainable road construction: literature review on addressing environmental impacts and promoting green technologies. Journal of Physics: Conference Series 2916(1): 1–10. Available at: https://doi.org/10.1088/1742-6596/2916/1/012012

Lewis P., Rasdorf W. (2017) Fuel use and pollutant emissions taxonomy for heavy duty diesel construction equipment. Journal of Management in Engineering 33(2): 1–8. Available at: https://doi.org/10.1061/(asce)me.1943-5479.0000484

Li C., Cui M., Zheng J., Chen Y., Liu J., Ou J., Tang M., Sha Q., Yu F., Liao S., Zhu M., Wang J., Yao N., Li C. (2021) Variability in real-world emissions and fuel consumption by diesel construction vehicles and policy implications. Science of the Total Environment 786: 147256. Available at: https://doi.org/10.1016/j.scitotenv.2021.147256

Lu Q., Chai J., Wang S., Zhang Z. G., Sun X. C. (2020) Potential energy conservation and CO2 emissions reduction related to China's road transportation. Journal of Cleaner Production 245(80): 118892. Available at: https://doi.org/10.1016/j.jclepro.2019.118892

Luo S., Yuan Y. (2023) The path to low carbon: The impact of network infrastructure construction on energy conservation and emission reduction. Sustainability (Switzerland) 15(4). Available at: https://doi.org/10.3390/su15043683

Maraqa M. A., Albuquerque F. D. B., Alzard M. H., Chowdhury R., Kamareddine L. A., Zarif J. El. (2021) GHG emission reduction opportunities for road projects in the emirate of Abu Dhabi: A scenario approach. Sustainability (Switzerland) 13(13): 1–22. Available at: https://doi.org/10.3390/su13137367

Masih-Tehrani M., Ebrahimi-Nejad S., Dahmardeh M. (2020) Combined fuel consumption and emission optimization model for heavy construction equipment. Automation in Construction 110(October 2019): 103007. Available at: https://doi.org/10.1016/j.autcon.2019.103007

Mishra A., Dixit A., Singh A. K., Das S. K. (2024) Strength, deformation, and environmental impact assessment of cement stabilized mine overburden soil. Journal of Cleaner Production 447(February): 141475. Available at: https://doi.org/10.1016/j.jclepro.2024.141475

Oliveira-Nascimento K. A., Higuchi N., Dearmond D., Robert R. C. G., Arce J. E., Carvalho J. P. F. (2021) Environmental thermal conditions related to performance, dynamics and safety of logging in the Brazilian Amazon. Croatian Journal of Forest Engineering 42(3): 419–435. Available at: https://doi.org/10.5552/crojfe.2021.865

Palander T., Borz S. A., Kärhä K. (2021) Impacts of road infrastructure on the environmental efficiency of high capacity transportation in harvesting of renewable wood energy. Energies 14(2): 1–20. Available at: https://doi.org/10.3390/en14020453

Ribeiro F. B., Nascimento F. A. C. do, Silva M. A. V. da. (2022) Environmental performance analysis of railway infrastructure using life cycle assessment: Selecting pavement projects based on global warming potential impacts. Journal of Cleaner Production 365(June): Available at: https://doi.org/10.1016/j.jclepro.2022.132558

Sakai Heavy Industries Ltd. (2012) TS200 - Sakai Heavy Industries – PDF Catalog – Technical Documentation. Sakai Heavy Industries, Ltd.

Sizirici B., Fseha Y., Cho C. S., Yildiz I., Byon Y. J. (2021) A review of carbon footprint reduction in construction industry, from design to operation. Materials 14(20): 1–18. Available at: https://doi.org/10.3390/ma14206094

Vaitkus A., Gražulytė J., Kravcovas I., Mickevič R. (2021) Comparison of the bearing capacity of pavement structures with unbound and cold central-plant recycled base courses based on FWD data. Sustainability (Switzerland) 13(11): Available at: https://doi.org/10.3390/su13116310

Wen P., Wang C., Song L., Niu L., Chen H. (2021) Durability and sustainability of cement-stabilized materials based on utilization of waste materials: A literature review. Sustainability (Switzerland) 13(21): 1–27. Available at: https://doi.org/10.3390/su132111610

Wirtgen America Inc. (2019) Recycler WR 2500 Technical Specification. Wirtgen GmbH.

Xu X., Kong L., Li X., Lei B., Sun B., Li X., Qu F., Pang B., Dong W. (2024) Energy conservation and carbon emission reduction of cold recycled petroleum asphalt concrete pavement with cement-stabilized phosphogypsum. Construction and Building Materials 433(March): 136696. Available at: https://doi.org/10.1016/j.conbuildmat.2024.136696

Zhao D. (2020) Quantitative evaluation method for greenhouse gas emissions in asphalt pavement construction stage. IOP Conference Series: Earth and Environmental Science 587(1): Available at: https://doi.org/10.1088/1755-1315/587/1/012019