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Life Cycle Cost Analysis of Flexible Pavements Reinforced with Geo-Synthetics: A Case Study of New Construction or Repair Overlays in Thailand's Roads

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Abstract

This study investigates the economic viability and cost-effectiveness of the construction or repair of flexible pavements reinforced with geosynthetics in Thailand. The analysis was conducted on the road construction project under Muang District, Uttaradit province authority in Thailand, by adopting the life cycle cost analysis (LCCA) considering the agency, user, and environmental costs for the selected road segment. The study evaluated the economic analysis of the National Primary Road with and without geosynthetic materials by focusing on theoretical analysis and life cycle cost analysis considering the Thailand Highway Department's costs. Two types of geosynthetics were considered in this study, Polyfelt PGM-G 100/100 Geotextile paving fabric with a unit area of 430 g/m^2 and Miragrid GX100/100 geogrid made from high tenacity polyester with a unit area of 335 g/m^2. The results revealed that using geosynthetics can extend the road maintenance cycle as much as the material's life, making the road maintenance cycle cost about 36.67% less than conventional pavement. Geosynthetic materials, particularly nonwoven geotextiles, demonstrated lower embodied carbon values (2.35 CO_2e/ton) than geogrids (2.36 - 2.97 CO_2e/ton). Combining Polyfelt PGM-G 100/100 geotextile with on-site pavement production resulted in lower total CO_2 emissions (70,888 kg CO_2 eq) than traditional flexible pavement. Hence, the utilization of geosynthetic materials can lead to more sustainable and economical approaches in road pavement construction in Southeast Asia where similar approaches can be adopted.

Keywords: Geosynthetics; Flexible pavement; Life cycle cost analysis; Geogrid; Geotextile.
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1. Introduction

In the last twenty years, the volume and weight of traffic have increased significantly in Thailand's road network. Most roads in the network consist of asphalt roads (flexible pavements), which often show premature damage due to rutting. Rutting accounts for more than 65% of the total damage to paved roads and can make pavement layers inoperable. Traditionally, the repairs involve chiselling away the damaged or cracked pavement layer, subsequently constructing a new overlay surface.[1,2] However, the overlay eventually presents issues such as delamination and re-emergence of wheel track impressions, thus requiring repetitive maintenance and increased costs.[3,4] To address these drawbacks, past studies proposed the use of geosynthetics as an environmentally viable and cost-effective solution to issues like surface rutting. Geosynthetics can reinforce and stabilize pavement layers built on weak natural soils, particularly in difficult-to-use cement or lime cases. Geosynthetics in a reinforced material provide benefits through confinement, separation, and reinforcement effects of pavements.[5-7] Asphalt Concrete (AC) pavements deteriorate with time due to traffic loading and

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environmental exposure. In the Thailand road network, rutting is one of the most observed AC pavement distresses and is a major safety concern for transportation agencies, representing the largest component of government investment in public transport (more than $50 billion). To address rutting, partial depth or full-depth patching and overlay techniques are adopted, but these have been found by the Department of Highways (DOH) to last only for 3 to 4 years and to require periodic maintenance.[8] Hence, the study focuses on geosynthetics utilization as a solution to contradict this issue. Past research have proven the benefits of employing geosynthetics (either geotextiles and geogrids) as reinforcement in pavement applications.[9-12] Geosynthetics can reduce rutting by 13% - 70% depending on the type and quality,[13] increase the longevity of the pavement two to three times higher than the conventional pavement,[14] reduce the thickness of the base course layer by 20% - 40%.[15] and enable construction on unstable, soft, natural soils.[16,17] Both geosynthetic products greatly enhanced pavement section performance in terms of minimizing surface permanent deformation and prolonging pavement section service life, The adjusted traffic benefit ratio (TBR) for pavement created with a 457 mm (18 inches) thick base layer on top of unstable subgrade soil can be enhanced to 1.52 with a single layer of geosynthetic which implement at the base to subgrade interface.[18,19]

The use of geotextiles and geogrids underlays provides adhesion between new and old pavements, reduces pavement deformation, and enhances the service life of the pavement by 50% compared to the original. According to Perkins *et al*.[20] (2005), geosynthetic reinforcements have been used in pavement restoration operations to reduce reflective cracking in overlays and to lower initial construction costs by reducing the thickness of the unbound aggregate layers or the bound asphalt concrete layer while maintaining the same service life. Furthermore, the geosynthetic interlayer will increase the life of the overlay by 100% when compared to the same thickness overlay without a geosynthetic interlayer, and the placement of geosynthetic interlayer is equivalent to increasing the asphalt concrete overlay thickness by 25 mm to 45 mm (1 to 1.8 inches). Yang and Al Qadi (2007)[21] present a cost analysis process that takes an account expenses related to initial construction, rehabilitation, moving delays, work-zone queuing delays, accidents, and fuel usage. The study conducted significant research regarding the geotextile effectiveness for improving flexible pavements. The main aim of the study was to quantify the cost effectiveness of using geotextiles in pavements. The study used woven geotextile, which has a ratio of minimum to maximum 2% secant tensile modulus of 0.641, strength at 2% strain in the cross-machine direction of 12.7 kN, and secant tensile modulus at 2% axial strain of 637 kN/m. The study concludes that incorporating geosynthetics in pavements, especially over weak subgrade is beneficial and would increase pavement service life. Additionally, the study design method gives a 20% reduction in the agency cost for the 25 preventive pavement design alternatives in life cycle cost analysis.

Nonetheless, due to stress and environmental deterioration, the asphalt pavement itself may crack or distort under repetitive loading. Rutting and weariness from high traffic volume are two of the most serious difficulties with AC flexible pavements. Hence, geosynthetics are used as a separator for aggregates and subgrade soil, as well as to reinforce the subgrade. The use of geotextiles and geogrids are the frequently used geosynthetic materials incorporated in the pavement base course and improve the overall performance of the pavement and increase service life.[22,23] Fig. 1 depicts the Miragrid GX100/100 geogrid underlayment, which provides adhesion between new and old pavement, decreases pavement deformation, and increases pavement service life by 50% over the original.

Fig. 1 Asphalt Road reinforced using Miragrid GX100/100 geogrid (Photo from the field construction by the authors[8]).

The primary foundations of pavement sustainability are life cycle assessment (LCA) and life cycle cost analysis (LCCA). LCA considers the environmental impact of a pavement structure, whereas LCCA considers the life cycle costs. While both strategies help transportation organisations make decisions, they are normally utilised separately because there are no tools or procedures that examine both within the same framework. To address the environmental impact, Life Cycle Assessment (LCA) has been developed as one proper approach characterizing environmental impact capable of considering all the interactions between pavements and natural systems. Therefore, it is of great interest to develop an optimal Maintenance & Rehabilitation (M & R) strategy considering performance, cost and environmental impacts based on the existing LCA framework. When evaluating M&R strategy, much research and applications have been conducted considering multiple objectives, including pavement performance and maintenance cost. Life-Cycle Cost Analysis (LCCA) is an economic analysis process to evaluate holistic costs, including agency cost, user cost and environmental damage cost (EDC) and has been widely used in M&R strategy for many types of infrastructures.[24] The Life Cycle Cost Analysis (LCCA) is a vital performance parameter for geosynthetic pavement, significantly impacting functionality and riding surface quality. Agency costs are influenced by maintenance and user-related costs, encompassing factors like fuel efficiency.[25,26] Additionally, the life cycle cost also describe the costs of raw materials, machinery, labor, traffic management, and lane closure expenses.[27-29] The application of LCCA is considered in three stages, the primary stage is the Input stage where the data collection of equipment, construction materials, fuel consumption, the geometry of pavement and fuel price will be taken as input. The second stage is the Inventory stage where the input data are functioned in terms of methodology and the final stage is the output stage in which the results are assessed based on the first two stages. Life cycle cost analysis provides a generic framework for determining the requirement for additional costs during the useful life of a project. Previous studies.[30,31] states that, the usage of low temperature asphalt will reduce the environmental impacts in the construction phase of pavements. This encourages the use of cold or warm mix asphalt rather than hot mix asphalt to reduce energy usage in material manufacture and thereby Green House Gas (GHG) emissions. However, care must be taken to minimize unexpected consequences (for instance, excessive GHG emissions from additive use, increased material transport distances, or maintenance frequencies), which should be evaluated using life cycle analysis.

Thailand Highways Department has only considered two main factors; the engineering factor is primary which includes the International Roughness Index (IRI), pavement deflection, and other pavement physical conditions and secondary is the economic social environmental factor, which includes popularity density, traffic volume, and truck volume, among other things. These considerations only apply to the current state of the roads and do not take into account the future advantages and value-added of the road that will result from road repair. Thailand Department of Highways (DOH) has used empirical and mechanistic approaches to flexible pavement research and design. The DOH has conducted a thorough study of the deflection-based design method in preparation for the future adoption of national design standards and practices. the DOH uses the falling weight deflectometer (FWD) as a monitoring aspect to measure the defection and structural capacity evaluation through non-destructive testing. The DOH practically adopts a normal FWD loading stress of 700 - 800 kPa and compare it to a regular 10-wheel 25-ton truck with a tandem axle-dual wheel configuration having a tire pressure of 690 kPa to suggest the approach as simple, conservative and practical.[32]

The effects of climate change on flexible pavements are indirect and are mostly driven by demographic changes caused by climate-related migrations such as temperature, precipitation, groundwater, and wind speed. In Thailand's environment, Climate change-related migration is thought to have an impact on the population of specific locations as well as the shift in local transportation demand. Particularly traffic of large vehicles, is the leading cause of pavement deterioration. As a result, climate change can have a considerable indirect impact on the performance of flexible pavements in the context of Thailand. Pavements are a type of climate-sensitive infrastructure in which climate can affect the rate of deterioration, subsequent maintenance, and life-cycle costs. For example, in places where high temperatures are increasing, upgrading binder grade, or increasing layer thickness in pavement design may be desired.[33,34] Furthermore, as the difference between daily/monthly/seasonal high and low-temperature fluctuations, the choice of binder needs to be able to cover all extremes.[35] However, it may increase economic/environmental costs significantly when applying binder upgrading or increasing layer thickness at network levels.[36] For instance, rutting may not be a concern for asphalt pavements in cold climates, but thermally induced cracking could be an issue.[37-39] Conversely, rutting can be significant in hot climates and thermal cracking critical. Therefore, it is vital to consider local climate changes and material responses when estimating performance and pavement cost through life cycle analysis.[40-43] The results of the geosynthetic materials can extend the service life of pavements by reducing the thickness of the base course layer and enhance the rutting property of the pavements. Geotextiles and geogrids are two types of geosynthetic products usually used in real time applications that provide various characteristics like reinforcement, durability, service life & cost reduction.[44]

This study investigates the economic cost analysis of geosynthetic materials for flexible road construction in Thailand. The theoretical analysis of flexible pavements is divided into two phases which describe the economic value of benefits compared with the investment value or expenses throughout the project life of the pavement. From the previous assessments, the geosynthetic pavement has proved to be slightly more expensive as compared to conventional pavement.[45] This information provides valuable guidance for selecting the most suitable pavement material based on budget considerations and long-term maintenance needs. Subsequently, the quality of pavement performance data is assumed on the cost and the data collection of the applied method which helps the DOH in making informed decisions in pavement construction, considering both costs and materials in the context of Thailand. Further, the outcomes of this research provide benchmark data for future studies and infrastructure consultants who desire to use this economical method. Numerous experimental studies, ranging from laboratory to full-scale field tests, have investigated the reinforcement effects of geosynthetics in pavement structures. However, most of these studies are limited and do not report the life cycle cost analysis of flexible pavement with and without geosynthetic reinforcing material in the context of Thailand.

2. Research methodology

In this study, the Huai Nam Cham - Pa Kluai highway, which is a four-lane road with two lanes in each direction, serves as a vital transportation link connecting provinces in the central region with those in northeastern Thailand. The total length of the Huai Nam Cham - Pa Kluai highway is 102 km. The originally intended lifespan of Highway No. 11 is 20 years, with minor maintenance and rehabilitation (M and R) work done. The Department of Highways (DOH) has unveiled an ambitious 20-year plan to improve Thailand's interprovincial network by building new highways throughout the country. The plan intends to build a modern and efficient transport infrastructure that will promote regional connectivity and economic prosperity. Hence, the significant level of interest in innovative solutions among highway engineers and other organizations, the DOH financed a 5-year project (beginning in 2011) to evaluate the long-term performance of geosynthetic-reinforced materials in traditional flexible pavements. The minimum pavement design life for roadway rehabilitation projects in the context of government projects shall be 20 years except for roadways with existing rigid pavements or with a current Annual Average Daily Traffic (AADT) of at least 12,000 vehicles.[46] Further, according to the flexible pavement design manual (revised for January 2024), the minimum pavement design life for roadway new construction and rehabilitation projects in the context of government projects shall be 20 years.[47]

Therefore, investments of this nature can be measured through capital cost assessment and analysis, which considers the cash flows generated over the calculation period for eternal investment value.

The information on the reliability and accuracy of this data source was found in the International Highway Project Management Office, Department of Highways, Thailand.[48] Department of Highways represents the Thai government's commitment to upgrading and developing the country's infrastructure by improving connectivity and accessibility for inhabitants. To assess such investments, a capital cost analysis examines the cash flows generated throughout the calculation period, aiming to determine the eternal (long-term) value as per the guidelines of the American Association of State Highway and Transportation Officials (AASHTO).[15] The capital cost involves the calculation of material quantities to be provided in each pavement structure and multiply by their unit prices.

As per the AASTHO, the major initial cost and recurring cost that should be considered for the economic evaluation of pavement include the following parameters, primary is the agency cost which includes Initial construction cost, rehabilitation cost (overlays, reconstruction *etc.*), maintenance cost, engineering & administration cost. Secondary is the user cost which includes Vehicle operating cost (Fuel consumption, Tire wear, maintenance, parts replacement *etc.*) and accident cost.

2.1 Theoretical analysis of flexible pavements

In this study, the primary objective is to assess the cost-effectiveness of the currently employed primary pavement. The research project is divided into two phases, outlined in the next subsections. The initial phase involves evaluating the effectiveness of synthetic fiber-reinforced test fields, while the second phase focuses on the economic analysis of the first phase.

2.1.1 Phase1- Efficiency of synthetic fiber reinforced test fields

In phase 1, pavement behavior was investigated on non-reinforced and reinforced paved road construction test plots using two types of synthetic fibre materials, Geotextile (Polypropylene + glass fibers) and synthetic mesh (Geogrid: Polyester). Fig. 2 shows the plan having the location of the test plot from the Department of Highways. The geosynthetic material was laid 200 meters long located on highway No. 11, named Huai Nam Cham - Pa Kluai Section (km. 102 + 700 - km. 102 + 900), Muang District, Uttaradit Province as shown

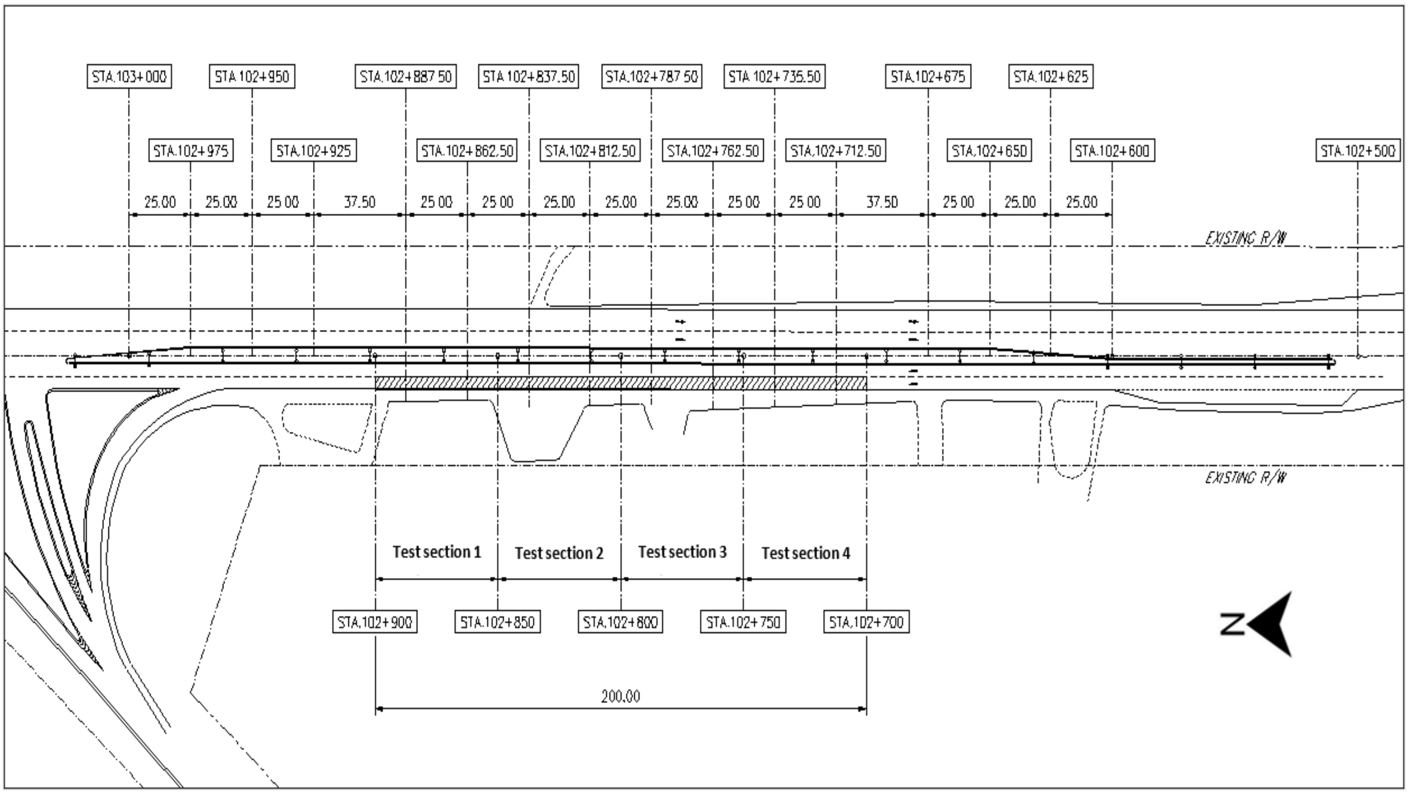

Fig. 2 Testing key Plan from the Department of Highways for Huai Nam Cham - Pa Kluai Section.[8]

in Fig. 3. The research team has established a test area to investigate the effectiveness of reinforcement materials, i.e., geotextile and geogrid, which were subjected to static loading weights of 20, 30 and 40 tons. The highway has a relatively high average daily traffic (ADT) of 8721 vol. per day of which 26.5% are trucks. The test sections are positioned on the approach to a traffic signalized intersection, where all vehicles are compelled to decelerate and stop which creates much distress and rutting of pavements. Hence, the 200-meter-long geosynthetic flexible pavement is selected to unravel the Highway No. 11 test plot in the Thailand road network.

Two different physical and mechanical characteristics of geosynthetic materials were used in the study,

a) Polyfelt PGM-G 100/100 Geotextile paving fabric, a biaxial

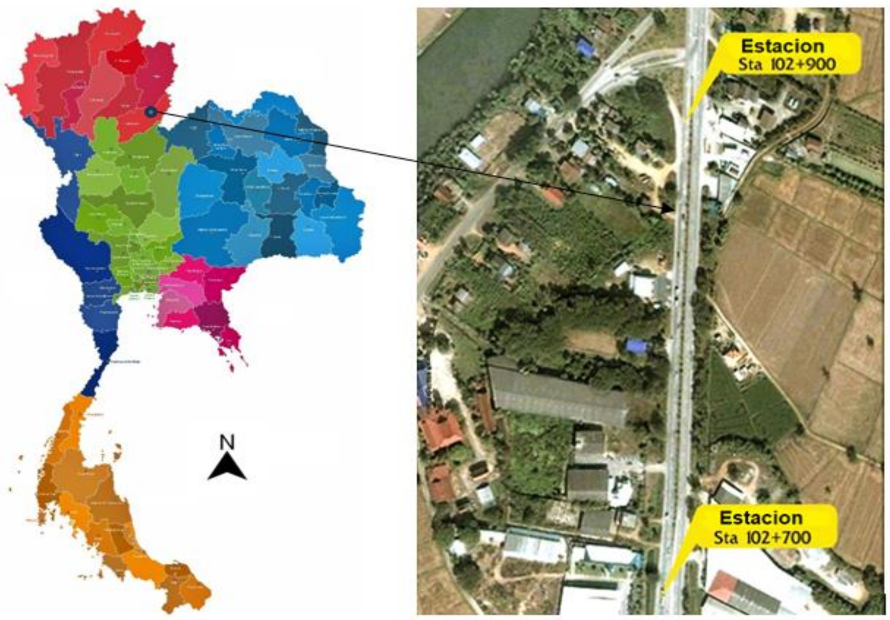

Fig. 3 Testing location of pavement at Muang District, Uttaradit Province.

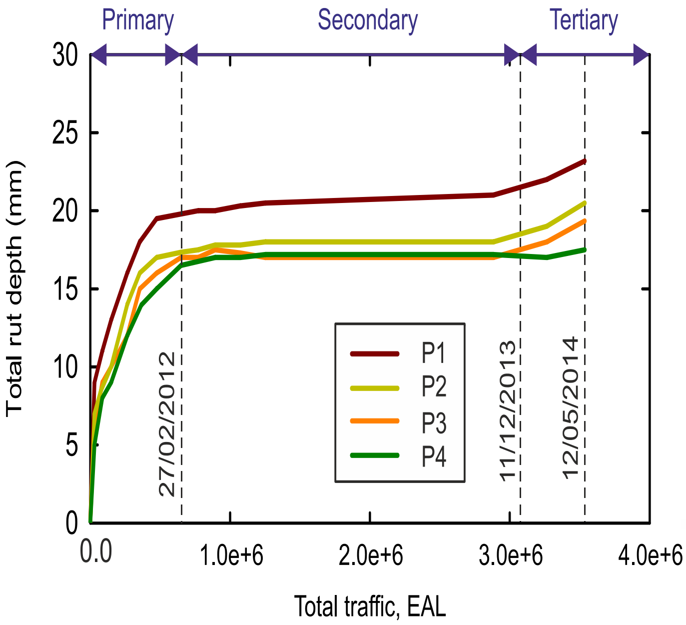

Fig. 4 Comparison results of rutting deformation of the test plot.

polypropylene and glass filament with a break elongation of 3% and 430 g/m^2 unit area.

b) Miragrid GX100/100 geogrid made from high tenacity polyester yarns covered with a black polymeric coating to provide high tensile strength with low creep, break elongation of 11% and 335 g/m^2 unit area.

The high elongation and aperture size of the geogrid make it suitable to provide interlocking with the crushed limestone of the base layer. Geo-textiles and Geo-grids can reduce vertical stresses and also reduce the problem of groove formation. The load weight was approximately 15-20% less in comparison to the control plot (P1), resulting in a stress reduction of about 5-10% when compared to test plots 2 (P2) and 3 (P3). Over 2 years following construction (from 25/02/12 to 12/05/14), the measurement of wheel grooves indicated that the wheels from normal traffic conditions caused around 10-15% less impact on the test plot 1, as depicted in Fig. 4.

2.1.2 Phase 2- Economic analysis of National Primary Road

An economic analysis of the national primary road is used to evaluate the cost-efficiency of alternatives based on the Net Present Value (NPV) concept. The study of the economical pavement is charged in three cases, namely the case of new construction, the case of the overlay with limited damage and the case of the overlay with severe damage. Geogrid and geotextiles are used as reinforcing materials for the overlay. The eternal investment cost of geosynthetic pavements is compared with the new construction to determine its effectiveness for the long-term evaluation.

2.2 Life cycle cost analysis

In this study, the deterministic approach is evaluated where the input variable of design life is fixed as 20 years. The effectiveness of pavement maintenance or rehabilitation is an important component in LCCA. The Department of transports (DOTs) and research institutions have examined LCCA approaches and principles to advance knowledge and research, From the past two decades Various existing tools including Real cost 2.5, SimaPro, APA LCCA, HDM *etc*. were evaluated.[49,50] Based on the methodology of the previous approaches, an Excel spreadsheet was made to merge Life Cycle Cost Analysis (LCCA) parameters which allowed for analyzing diverse construction materials and comparing two geosynthetic material types through cost evaluation. Since, the life cycle analysis of road pavements involves various stages, including extraction, manufacturing, transportation, and road construction activities, a flow chart has been illustrated in Fig. 5.

3. Results and discussions

3.1 Evalution of cost as per Thailand highway department

The study of the test area in the project emphasis on the efficiency of reinforcement to reduce rutting. The cost of construction for a new pavement construction project or a new overlay utilized the existing embankment and the existing foundation and was determined by an analysis of the construction cost of this test area. which consists of asphalt concrete surface work. In line with research conducted by the Department of Highways, the cost-effectiveness of utilizing synthetic fiber materials and the return on investment was assessed on a per-unit basis for projects involving geosynthetic materials reinforcement. According to the Department of Highways data, Table 1 shows the median price for constructing primary roads considered for the year 2014. The National Primary Road features a pavement structure comprising 10 cm of asphalt concrete, 20 cm of paving stone flooring, and a 30 cm foundation layer. In preliminary trials, the test plot cater high average daily traffic (ADT) of 8721 vol per day, 26.5% of which are trucks. The test segment is situated at the entrance to a traffic signal-controlled intersection, compelling all vehicles to deaccelerate to stop, causing significant distress, particularly in the form of ruts. Measurements of rut depth indicated an average depth of 50 mm, categorizing it as a severe rutting failure, according to AASHTO (1993). This substantial rutting significantly influenced the Department of Highways' decision to choose this particular section for the field trials.

However, the relationship between varying traffic volumes and the performance of pavements is reinforced with

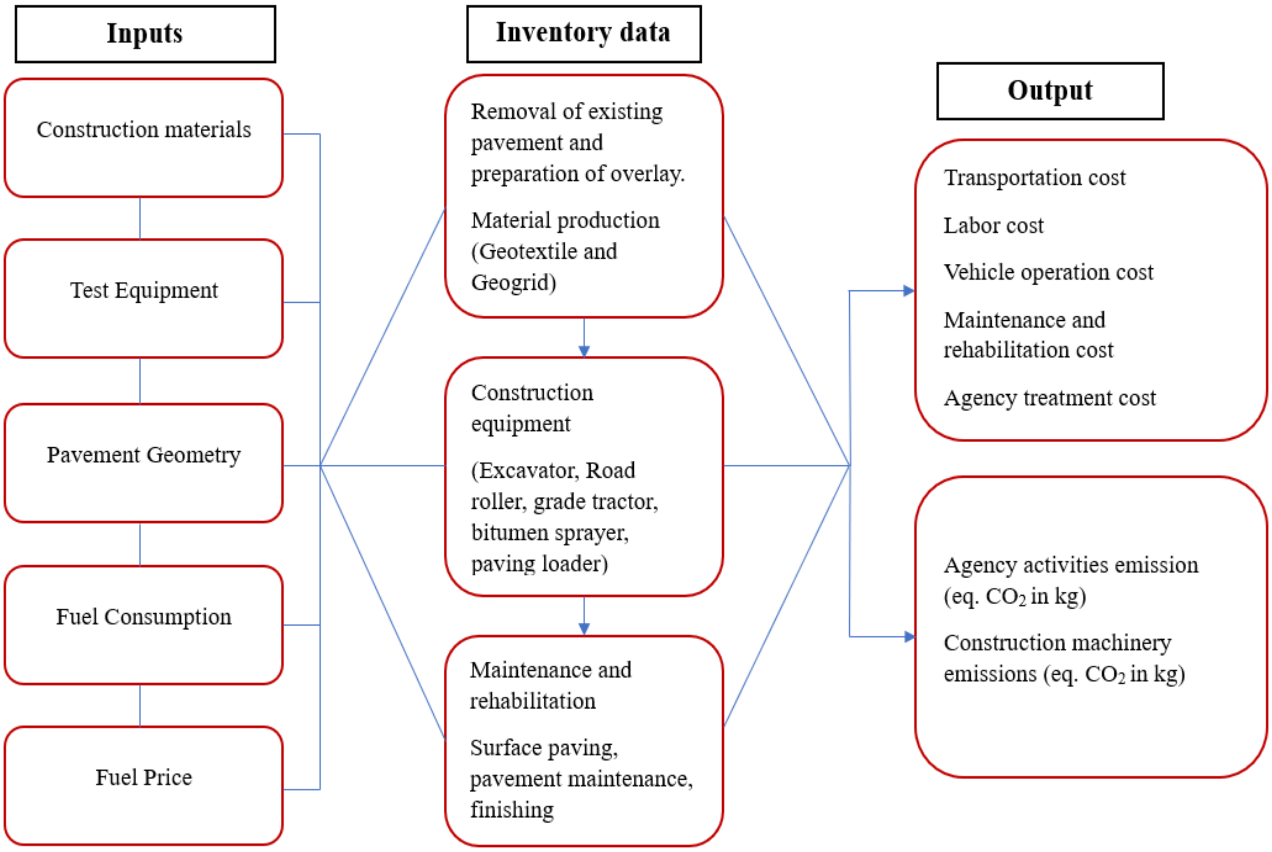

Fig. 5 Life cycle analysis flowchart for flexible pavements.

geosynthetic materials are crucial for understanding longevity and maintenance needs. The traffic benefit ratio (TBR) indicates how well the pavement withstands increased loads, with higher volumes potentially stressing the pavement. TBR is the ratio of cycles required to reach a specific rut depth for the reinforced (N_r) specimen compared to the non-reinforced specimen (N_{ur}). The rutting reduction ratio (RRR) reflects resistance to rutting, and changes in traffic volumes may impact this resistance. It is defined as the ratio between the rut depth of the reinforced section at a certain cycle (N_r) and the rut depth of the unreinforced section at the equivalent cycle (N_{ur}). The effectiveness ratio (EF), comparing TBR for reinforced and unreinforced sections, provides an overall measure of geosynthetic performance, highlighting potential variations in response to different traffic volumes. The EF value is calculated for the reinforced sections (TBR_r) relative to the unreinforced section (TBR_u) (refer to Eq. (1)).

$$EF = \frac{TBR_r}{TRB_u} \quad (1)$$

Managing longevity and maintenance of geosynthetic-reinforced pavements requires careful consideration of these factors, especially in the context of varying traffic demands. A prior investigation conducted by Imjai *et al.* (2019)[8] examined the impact of traffic volume and vehicle types on the durability and performance of the same experimental site. This manuscript focuses on the LCCA of the experimental site.

Table 1. Cost of road construction taken from the Department of Highways (Median price).

Construction cost list	Price (Baht / m^2)	Price (USD / m^2)
Price of construction	640	18.0
With Geo-textile	870	24.5
With Geo-grid	780	22.0
Price of overlay	230	6.5
Overlay price with Geo-textile	460	13.0
Overlay price with Geo-grid	370	10.4

3.2. Economic study results

As for the National primary road, in the case of new construction without reinforcement the investment cost was highest in comparison to the construction of overlay with geosynthetic materials (Table 2). The eternal investment costs for National Primary Road (NPR) construction are 99,726 baht/m² without reinforcing material, 24,390 baht/m² with Geotextile, and 75,123 baht/m² with Geogrid. The proportion of vehicles in the case of the overlay with the limited damaged condition shows that the proportion of vehicles with 10% and 20% have the least investment value compared to overlaying without reinforcing materials. The NPV for the new construction without adding reinforcing materials for 10%, 20%, and 30% was 100, 1950, and 4000 baht/m^2. A similar trend was observed in other construction methods for 10, 20, and 30% in Table 2.

Similarly, in the case of overlay with extreme damage conditions, the use of geosynthetic material in overlay results in the lowest investment value in contrast to the overlay without reinforcement, therefore the value of NPV is 2825 and 3809 baht/m^2 (shown in Table 2). In comparison to geotextile material consumption, the use of geogrid shows an economical value of 22.3% for 10% vehicular load, 33.3% for 20% vehicular load and 19.8% for 30% vehicular load. Fig. 6 depicted the net present value per square meter for all cases of National primary road.

In terms of the cost-effectiveness of maintaining the designed road, it is discovered that based on a calculation using a traffic volume of 6,000 cars, the road maintenance cycle will be longer without truck proportions exceeding 20%, making the pavement age equal to the material's age. In the event of overlay with limited damage, It was discovered that the use of geotextile or geogrid would increase the road maintenance cycle where the proportion of trucks should not exceed 10% and the use of reinforcing materials would only slightly increase the road maintenance cycle in the case of overlay in extreme damage.

In the case of a high-traffic road with a traffic volume of 10,000 cars, the road maintenance cycle will be substantially longer in the case of new construction utilizing geotextile. Even though the proportion of vehicles is as high as 30%, the age of the pavement is equal to the age of the material. In the event of overlay, where the damage is minor, it was discovered that the application of geotextile or geogrid will extend the road maintenance cycle by the same amount as the material's life. Reinforcing will increase the road maintenance cycle by around 1.5 times; however, reinforcement is unnecessary if the vehicle share is less than 10%. Table 2 shows an example of the eternal investment cost and NPV for National Primary Roads where a proportion of vehicle is 30%.

Table 2 presents a comparative analysis of eternal investment costs and net present values (NPV) for various National Primary Road construction scenarios. New construction with geotextile displays significant cost efficiency, showcasing the lowest eternal investment cost and NPV over 20 years. Reinforcing materials, particularly geotextile and geogrid, contribute to extended road maintenance cycles in overlay situations, making them economically viable. The choice of reinforcement appears to be sensitive to damage conditions, with geogrid showing significant cost reduction in extremely damaged conditions. These results show that there are important choices to make when building roads, such as deciding on the construction method and materials used. These decisions have economic consequences, and the study provides useful insights for making informed choices in road infrastructure projects.

In Table 2, Net Present Value (NPV) signifies the economic efficiency of different road construction scenarios. It represents the present value of future cash flows over a 20-year period, considering factors like eternal investment cost and annual NPV. In the Table 2, lower NPV values against the type of construction methods indicate cost efficiency. In the "New Construction" category, the option with geotextile has the lowest NPV, suggesting it is the most economically favorable choice among the alternatives presented over the 20 years.

Table 2. Eternal investment costs, and NPV values for National Primary Roads.

Type	National Primary Road (NPR)	Eternal investment cost (baht/m^2)	NPV/20 (baht/m^2/year)	NPV (baht/ m^2)
New Construction	New construction + without reinforcing material	99,726	199	3,989
	New construction + Geotextile	24,390	49	976
	New construction + Geogrid	75,123	150	3,005
Overlay limited damage	Overlay without reinforcing material	95,226	190	3,809
	Overlay + Geo-textile	24,517	49	981
	Overlay + Geo-grid	25,592	51	1,029
Overlay extreme damaged condition	Overlay without reinforcing material	95,226	190	3,809
	Overlay + Geo-textile	88,112	176	3,524
	Overlay + Geo-grid	70,623	141	2,825

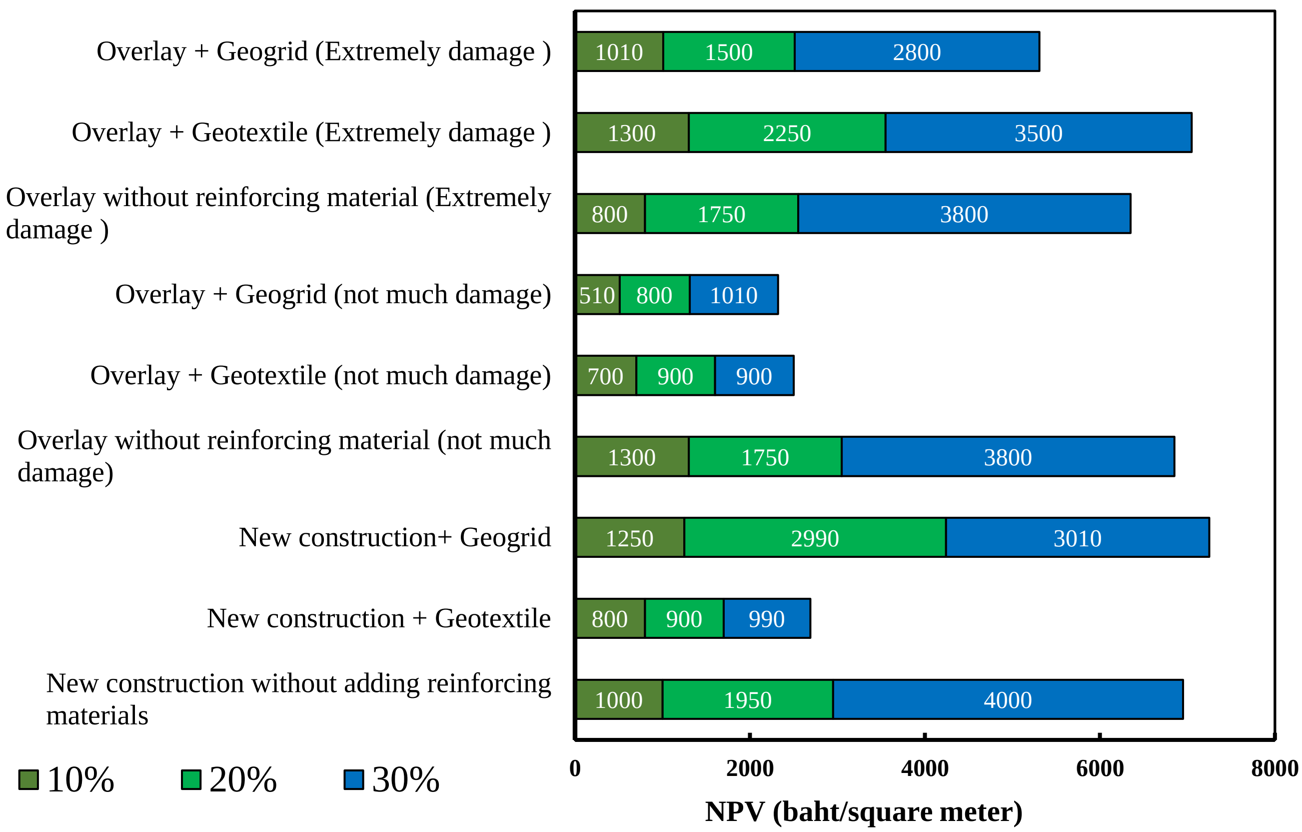

Fig. 6 Comparison of NPV values of national primary roads for three truck proportions.

3.3 Life cycle cost analysis

The functional unit for cost analysis is the total capital cost, measured in million Thai Baht (THB), for a road with dimensions of 200 m × 14.16 m designed for a 20-year pavement service life. The LCCA focused mostly on the components of the cost involved in pavement construction that were directly payable by stakeholders, such as highway agencies, construction firms, and so on (explained in the next subsection). The analysis incorporated life cycle cash flows and expenses throughout the entire asphalt pavement process. This included the total production cost, including raw materials used in the asphalt mixture, geosynthetic materials (such as geotextile and geogrid), and various types of graded aggregates essential for constructing a 0.321 km road segment. The transportation cost includes fuel used for moving asphalt mixes, aggregates to the construction site, equipment transfers, and material transit to the plant. Construction expenses comprise machinery like various types of rollers and pavers for asphalt material placement. Maintenance costs incorporate the overlay used for road upkeep and the equipment used during maintenance.

3.3.1 Materials Cost

The assessment aimed to identify the cost-effective and environmentally friendly material option. It evaluated two geosynthetic materials for the highway rehabilitation project: geotextile and geogrid. The first set of materials comprised virgin bitumen and the necessary aggregates. The second alternative involved incorporating geotextile with virgin bitumen aggregates, while the third option utilized geogrid with virgin bitumen aggregates. The total pavement cost in Thai Baht (THB) is calculated based on unit costs, with Bitumen at 11,424 THB per ton resulting in a total pavement cost of 40,44,096 THB, aggregate crush size of 10-20 mm at 418 THB per ton totaling 59,189 THB, aggregate crush size of 5-10 mm at 200 THB per ton amounting to 28,320 THB, aggregate crush size of 5 mm at 378 THB per ton yielding 53,525 THB, Geotextile at 230 THB per square meter resulting in 6,51,360 THB, Geogrid at 140 THB per square meter totaling 3,96,480 THB, and Light Diesel Oil (LDO) at 49 THB per liter resulting in 9,912 THB. It has been observed that geogrids are less expensive than geotextiles (Table 3).

However, energy expenditures, such as the fuel used by machines and dump trucks, were considered alongside material transportation and restoration activities. In the real-time application of asphalt concrete pavement construction, the bitumen can cover 8 m^2 of area, aggregates cover 20 m^2 area for gravels of less than 35 mm, and light diesel oil can cover 14 m^2 of area. Table 3 shows the total construction material cost used for the flexible pavement, and Also, the cost

Table 3. Cost of flexible pavement construction materials.

Material Cost			
Material	Unit	Cost (THB/ unit)	Total pavement cost (THB)
Bitumen	ton	11,424	40,44,096
Crush 10-20 mm (38%)	ton	418	59,189
Crush 5-10mm (20%)	ton	200	28,320
Crush 5 mm (42%)	ton	378	53,525
Geotextile	m^2	230	6,51,360
Geogrid	m^2	140	3,96,480
Light Diesel Oil (LDO)	l	49	9,912

of raw materials for conventional pavement is 4,195,042 THB, for pavement with geotextile it is 4,846,402 THB, and for pavement with geogrid, it is 4,591,522 THB.

3.3.2 Production cost

Material production is a stage in which new materials are generated to substitute for the virgin materials that have been depleted through consumption. In the current study, the facility has been used to produce asphalt bituminous concrete. Table 4 shows plant operation and activities, with operation costs identical for conventional and geosynthetic flexible pavements. The ratio of Asphalt Concrete Wearing Course (ACWC) to total work done (WD) stands at 58.35%, slightly below the recommended construction practice threshold of 60%. In terms of total expenditure, the highest costs are associated with utilities (2,327,314 THB), the establishment of a material testing lab, asphalt plant & construction party (468,779 THB), and aluminium frame (336,110 THB). On the contrary, repair & maintenance (19,476 THB), other expenditures (miscellaneous) (13,691 THB), and project stores (111,651 THB) represent comparatively lower expenses. However, ration (145,204 THB) and lub (83,304 THB) fall in the mid-range of the expenditure, with NJ barrier (231,786 THB) and containers (25,647 THB) occupying intermediate positions.

3.3.3 Materials transportation and construction activities

In this stage, material transportation, construction costs, and machinery expenses were considered and detailed in Table 5. Material transportation involved moving asphalt mixture, gravel, sand, and geosynthetic material to the construction site and transporting end-of-life materials from the site to the plant.[51,52] The daily consumption of Petroleum Oil Lubricants (POL) during the 11-hour construction of flexible pavements is also presented in Table 6. The hiring amounts for the equipment varied, with the Paver incurring the highest cost at

Table 4. Plant activities and operation cost of flexible pavement.

Sl.no	Description	Nos	Hiring Amount			Total Amount (THB)
			Per Day (THB)	Total (THB)	No. of Days	
1	Asphalt Plant	1	19,008	19,008	9	1,71,072
	Exp. based on the ratio of Asphalt Concrete Wearing Coarse with total work done (58.35 % ≥ 60 %)					
Sl.no	Description	Per Day	No. of Days	% Age	Total Amount (THB)	
2	Ration	26,890	9	0.6	1,45,204	
3	Lub	15,427	9	0.6	83,304	
4	Utilities	4,30,984	9	0.6	23,27,314	
5	Repair & Maintenance	3,607	9	0.6	19,476	
6	Aluminium Frame	62,243	9	0.6	3,36,110	
7	Containers	4,749	9	0.6	25,647	
8	NJ Barrier	42,923	9	0.6	2,31,786	
9	Project Store	20,676	9	0.6	1,11,651	
10	Establishment of Material Testing Lab, Asphalt Plant & Construction Party	86,811	9	0.6	4,68,779	
11	Other-Expenditure (Miscellaneous)	2,535	9	0.6	13,691	
Total					37,62,963	

Table 5. Material, transportation and construction activity costs.

Sl.no.	Make & Type	Nos	Hiring amount		
			Per Month (26 days) THB	Per Day (THB)	Total (THB)
1	Pneumatic Tire Rollers (PTR)	2	41,519	45	83,038
2	Tendom Roller	1	50,516	54	50,516
3	Paver	1	1,68,326	6,474	1,68,326
4	Loader	1	56,120	2,158	56,120
5	Fuel Bowzer	1	39,270	1,510	39,270
6	Generator (400 KVA)	1	95,390	3,669	95,390
7	Material Transfer Vehicles (MTV)	1	3,16,481	12,172	3,16,481
8	Dumper	8	78,576	3,022	6,28,606
9	Air Compressor	2	35,914	1,381	71,828
10	Tractor (With Boomer)	2	12,352	475	24,704
11	Water Bowzer	1	29,167	1,122	29,167
Total					15,63,446

1,68,326 THB per month, followed by the Dumper with a monthly expense of 78,576 THB for eight units. On the other hand, the Tractor (With Boomer) has the lowest hiring amount at 12,352 THB per month among the listed equipment. The total hiring amount for all equipment collectively is 15,63,446 THB per month. The equipment falling within the range of 12,000 THB to 100,000 THB for monthly hiring amounts includes the Pneumatic Tire Rollers (PTR) at 41,519 THB, the Loader at 56,120 THB, and the Air Compressor at 35,914 THB. Table 6 reveals the consumption and costs of Petroleum Oil Lubricants (POL) for various equipment. The POL rates are constant at 49 THB per unit. Daily POL consumption varies across different equipment, ranging from 15 to 275 units, reflecting distinct operational needs. The total costs for the Petroleum Oil Lubricants (POL) varied, ranging from 735 THB to 17,640 THB. Furthermore, the total amount, which combines deposit/hiring and POL expenses, varies significantly, ranging from 26,860 THB to 6,46,246 THB for different equipment entries. The cumulative total amount for all entries sums up to 16,22,491 THB.

3.3.4 Pavement maintenance and rehabilitation

Geosynthetic materials improve the rutting resistance of asphalt pavements. Routine maintenance, periodic maintenance, and rehabilitation are all part of the maintenance and rehabilitation process. By accounting for the overall area of the route, the cost summary was applied to both conventional pavement and geosynthetic pavements. The highway repair was planned to last up to 20 years; accordingly, routine maintenance every five years was scheduled, as indicated in Table 7, to extend pavement life and improve pavement performance. Geosynthetics reduced reflective cracking in asphalt overlays and improved base aggregate layers' performance. Table 7 outlines the Maintenance and Repair (M&R) costs for 20 years for Conventional Pavement and Geosynthetic Pavement. The expense of maintaining the

Table 6. POL consumption of material transportation and construction activities.

Sl. no	POL Consumed Per Day (11Hrs)	POL Rate (THB)	Total POL amount in (THB)	Total Amount (Dep /Hiring + POL) (THB)
1	18	49	1,764	84,802
2	22	49	1,078	51,594
3	110	49	5,390	1,73,716
4	105	49	5,145	61,265
5	15	49	735	40,005
6	275	49	13,475	1,08,865
7	44	49	2,156	3,18,637
8	45	49	17,640	6,46,246
9	77	49	7,546	79,374
10	22	49	2,156	26,860
11	40	49	1,960	31,127
Total			59,045	16,22,491

conventional pavement was constant at 1,07,100 THB for every M&R activity for each year. Similarly, the cost for Geosynthetic pavement remained the same at 67,830 THB for each maintenance and repair task over the given years. This indicates a consistent financial dedication to the maintenance activities linked with both types of pavements. For Conventional pavement, the total M&R cost was 3,21,300 THB, and for Geosynthetic Pavement, it was 2,03,490 THB. Uniform M&R cost distribution over the years highlights a systematic financial plan, offering a comprehensive view of sustaining both pavement types.

Table 7. Maintenance and rehabilitation (M & R) activities of flexible pavements.

Sl.no	Component Activity	Year	Cost (THB) Conventional pavement	Geosynthetic pavement
1	M & R - 1	5	1,07,100	67,830
2	M & R – 2	10	1,07,100	67,830
3	M & R – 3	15	1,07,100	67,830
4	M & R – 4	20	1,07,100	67,830
Total M & R Cost			4,28,400	2,71,320

3.3.5 Environmental Impact and Costing

This phase's objective was to assess environmental consequences, including CO_2 emissions, and determine the environmental costs. A life cycle inventory was created to assess the total impact, as illustrated in Tables 8 and 9. A comparison was made between conventional pavement (flexible), pavement with Geogrid, and pavement with geotextile. The objective is to process greenhouse gas (GHG) emissions, to quantify them in terms of carbon dioxide equivalents (CO_2e). The main environmental impacts were observed for machinery, responsible for gaseous emissions in road building and maintenance.[53-57] Manufacturing plants and machinery both rely on fossil fuels. Information on Petroleum Oil Lubricants (POL) was obtained from the plant operator and the highway department overseeing the project to compute CO_2 emissions. The total POL readings were then rendered into CO_2 emissions, with one liter of gasoline equalling 2.19 Equivalent (Eq.) CO_2 in Kg. Furthermore, to account for the environmental impact, the Eq. CO_2 in Kg was translated into tones, and a carbon price, such as THB 1250 per ton of emission, was allocated. The Paver and Generator (400 KVA) gave the highest CO_2 with high fuel consumption, leading to substantial CO_2 costs. In contrast, the fuel bowser despite a lower operational impact, incurs a noticeable CO_2 cost. The material transfer vehicles (MTV) and air compressors exhibited medium environmental impacts and associated costs. For the flexible pavements the emission factors for pavement materials involved emissions from materials like coarse aggregate, fine aggregate, and filler, which have an emission factor of 1.067 kg CO_2 per ton each. Asphalt production, a key component, has a higher emission factor of 11.91 kg CO_2 per gallon. The construction of flexible pavement without any geosynthetic material would emit 70,888 kg CO_2 eq. Where, combining Polyfelt PGM-G 100/100 geotextile (2.35 tCO_2 e/t) with on-site flexible pavement production (70.888 tonnes CO_2 eq) yields total CO_2 emissions will produce more carbon emission as compared to geotextile. Therefore, combining Polyfelt PGM-G 100/100 geotextile and flexible pavement production results in lower CO_2 emissions. The study conducted by Raja *et al.*[58] calculated lower embodied carbon values for geosynthetics, specifically nonwoven geotextiles (2.35 tCO_2e/t), compared to geogrid (2.36 - 2.97 tCO_2e/t) when used in flexible pavements.

Table 8. Embodied carbon values for cradle to gate LCA boundaries.

Sl. no	Material type	Calculated EC values (Eq. CO_2 in Kg)
1	Polyfelt PGM-G 100/100 geotextile paving fabric, a biaxial polypropylene and glass filament	2350 kg CO_2/t[59]
2	Miragrid GX100/100 geogrid	2360−2970 kg CO_2/t[59]
3	Flexible pavement (production and laying) on site	70,888 kg CO_2 eq[58]

3.3.6 Total life cycle costing

In this section, a comparison was conducted among the phases of the chosen pavement materials, as shown in Fig. 7. Moreover, the two materials were manufactured using the same manufacturing plant, geotextile pavement had the highest materials cost, indicating potential differences in the construction materials used. Geotextile pavement incurred a higher materials cost, amounting to 4,846,401.6 THB, compared to the 4,195,041.6 THB incurred by conventional pavement due to differences in the construction materials employed, contributing to the overall expenditure. In comparing the M&R activities, conventional pavement surpassed geotextile pavement, amounting to 321,300 THB compared to 203,490 THB in geotextile. This indicated that maintaining conventional pavement required more attention and resources. Assessing the total financial outlay, geotextile pavement recorded a slightly higher cost at 121,889,08 THB, while conventional pavement amounted to 116,553,58 THB. The equivalent CO_2 emissions remained consistent at 19,045 for geotextile, conventional, and geogrid pavements. Moreover, there were no cost disparities since identical

Table 9. Inventory and assessment of the life cycle.

Sl.no.	Make & Type	Daily hours	No. of Days	POL consumed per day (L)	Total POL consumed (L)	Eq. CO_2 in Kg	Tons	CO_2 Cost (THB)
1	Pneumatic Tire Rollers (PTR)	11	9	18	162	354.78	0.35	443.47
2	Tendom Roller	11	9	22	198	433.62	0.43	542.01
3	Paver	11	9	110	990	2168.10	2.16	2710.12
4	Loader	11	9	105	945	2069.55	2.079	2586.93
5	Fuel Bowzer	-	9	15	135	295.65	0.29	369.56
6	Generator (400 KVA)	11	9	275	2475	5420.25	5.42	6775.31
7	Material Transfer Vehicles (MTV)	11	9	44	396	867.24	0.87	1084.05
8	Dumper	-	9	45	405	886.95	0.88	1108.68
9	Air compressor	11	9	77	693	1517.67	1.52	1897.08
10	Tractor (With Broomer)	11	9	22	198	433.62	0.43	542.02
11	Water Bowzer	-	9	40	360	788.40	0.79	985.50
	Total				6957	15235	15.24	19044.78

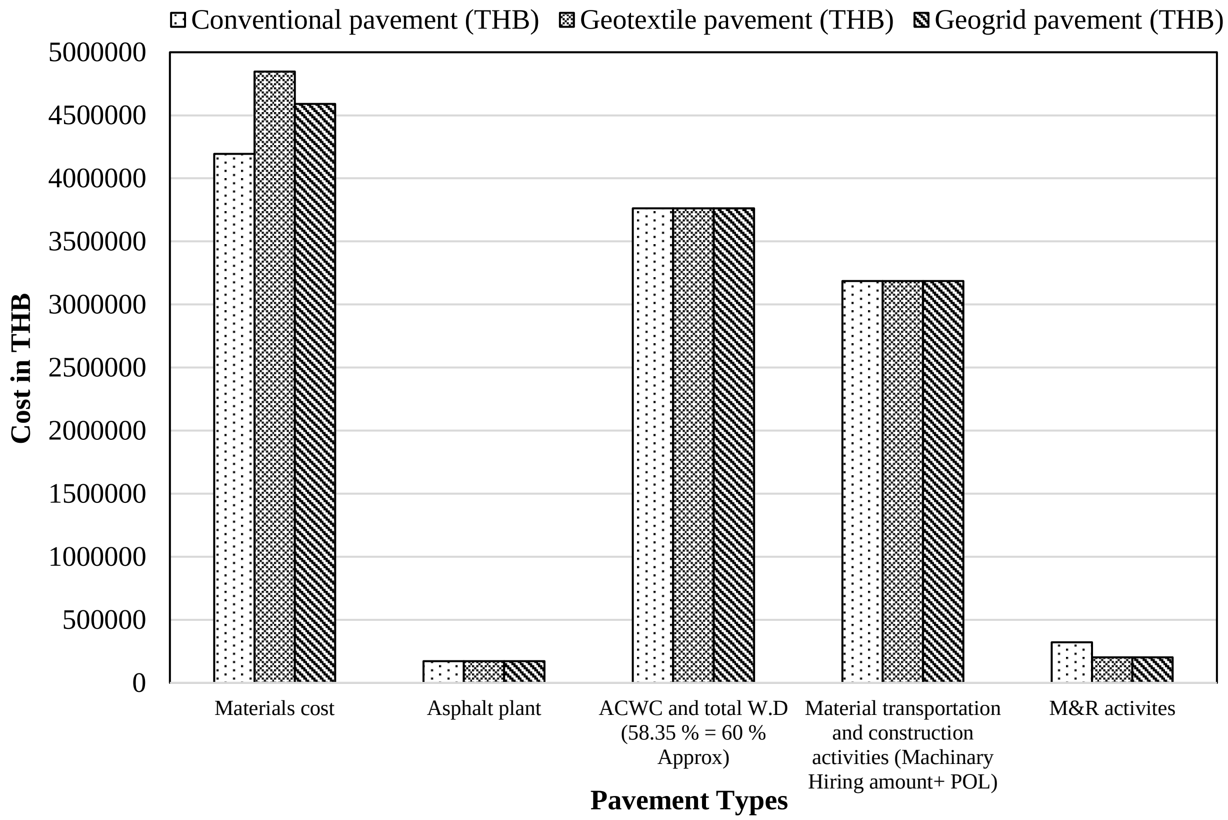

Fig. 7 Total life cycle costing of flexible pavements.

techniques and machinery types were utilized in the subsequent phases of material transportation and construction activities. The CO_2 impacts and costs calculation included emissions from transportation and machinery, amounting to 19045 THB for each case.

4. Conclusions

The study examined the national primary road with the cost of reinforcing materials in three ways, the case of new construction, the case of overlay with minimum damage, and the case of overlay with severe damage. The economic evaluation of the Thailand highways department data highlighted the cost-effectiveness of incorporating geosynthetic material in pavement construction.

- New construction without reinforcement attained the highest eternal investment cost and NPV for the National Primary Road compared to overlay with geosynthetic materials. However, for the overlays with limited damage, geotextile and geogrid also showed lower investment costs and longer road maintenance cycles, especially in limited damage conditions. In the evaluation of geosynthetic materials (geotextile and geogrid) for highway rehabilitation, geogrid was less expensive than geotextile. Geotextile proves economically efficient in new construction, with the lowest eternal investment cost of 24,390 baht/m² and an NPV of 976 baht/m²/year over 20 years. Geogrid offers cost-effectiveness, especially in extreme damage conditions (Eternal Investment Cost: 75,123 baht/m², NPV: 3,005 baht/m²/year). Overlays benefit from geosynthetic materials, with significant cost reduction using geogrid (Overlay + Geo-grid: 25,592 baht/m², NPV: 1,029 baht/m²/year).
- The Life Cycle Cost Analysis (LCCA) focused on the total capital cost for a 20-year pavement service life, emphasizing components directly payable by stakeholders. Bitumen is a significant contributor, accounting for a substantial portion at 40,44,096 THB. Evaluating geosynthetic materials, geogrid emerges as a cost-effective choice, contributing to a total pavement cost of 3,96,480 THB. In comparison, geotextile incurs a higher cost of 6,51,360 THB.
- In plant activities and operation costs for conventional and geosynthetic pavements, utilities, lab, and construction parties constitute significant expenses. Among the various components, the utility category has the highest expenditure, totalling 23,27,314 THB. Equipment costs vary; Paver has the highest monthly hiring expense.
- The materials cost of the geotextile pavement was 4,846,401.6 THB, which was more than the 4,195,041.6 THB which accounts for 13.44% higher than the conventional pavement and the material cost for geogrid pavement was 4591521.6 THB which is 8.63% higher than conventional pavement due to differences in the construction materials employed in flexible pavement.
- In Maintenance and Rehabilitation (M&R), the uniform distribution of M&R costs highlights a systematic financial plan, demonstrating a dedicated approach to sustaining both pavement types. The comparable M&R costs over 20 years suggest that geosynthetic pavement maintenance remains consistently lower than conventional pavement. This underscores the cost-effectiveness and financial sustainability of geosynthetic materials in pavement maintenance, supporting their continued use for long-term performance. The total M&R cost for conventional pavement is 4,28,400 THB, while for geosynthetic pavement, it is 2,71,320 THB.
- The comparison between geotextile pavement and conventional pavement revealed that geotextile pavement had higher material costs, while traditional pavement incurred greater maintenance expenses. This important insight would help the Department of Highway make informed decisions in pavement construction, considering both costs and materials. In the overall assessment, geotextile pavement proved slightly more expensive, followed by conventional pavement, while geogrid pavement emerged as the least costly option. This information provided valuable guidance for selecting the most suitable pavement material based on budget considerations and long-term maintenance needs.
- The Generator (400 KVA) closely follows, with a significant consumption of 275 liters per day and a noteworthy emission of 5420.25 kilograms. Other equipment falls within a comparable range of 18-105 liters daily consumption, emitting 354.78-2069.55 kilograms of CO_2. The daily POL consumption for all equipment is 15.24 liters, resulting in a total equivalent CO_2 emission of 19044.78 kilograms. Strategic equipment selection and optimized usage are crucial for minimizing environmental impact and associated costs during pavement construction.
- The study assessed environmental impacts and CO_2 emissions in flexible pavement construction. Geosynthetic materials, particularly nonwoven geotextiles, demonstrated lower embodied carbon values (2.35 CO_2e/t) than geogrids (2.36 - 2.97 CO_2e/t). Combining Polyfelt PGM-G 100/100 geotextile with on-site pavement production resulted in lower total CO_2 emissions (70,888 kg CO_2 eq) than traditional flexible pavement, emphasizing the environmental benefits of geosynthetics. This research

underscores the significance of having specific embodied carbon values for geosynthetics. Further incorporating the detailed values in CO_2 calculations for construction projects will enhance accuracy, bolstering the credibility of project carbon footprint results for a better selection of methods to choose from economically or ecologically viable.

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Conflict of Interest

There is no conflict of interest.

Supporting Information

Not applicable.

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