Quantifying sustainability for two types of pavement based on life cycle cost and environmental impact

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Abstract
Several types of highway pavement have been adopted by various highway agencies, and each type has both advantages and disadvantages. Estimations of the life cycle cost and environmental impacts of pavement types have thus become major components of roadway planning. The economic and environmental sustainability of pavements depends on both the project characteristics and the maintenance programme applied during the pavement life span. This article focuses on making a comparison of environmental impact in terms of Life Cycle Assessment (LCA) and Life Cycle Cost Analysis (LCCA) of two arterial streets in Al-Diwaniyah city centre. The first street utilises flexible pavement, while the second street is constructed with composite pavement layers, with a Hot Mix Asphalt (HMA) wearing layer implemented over a Portland Concrete Cement (PCC) pavement. The comparison between the streets was conducted using Athena Pavement LCA software, and the resulting analysis clarified the impact of pavement type, construction process and maintenance conditions on the environment in each case, taking into consideration all related parameters such as material, construction processes, and the maintenance and rehabilitation programmes applied to the pavements during their life cycle. The results showed that the environmental impact in terms of gas emissions for the street implemented with flexible pavement was 48% higher than that of street implemented with a composite structure; further, the initial cost for the flexible structure was 17% higher that of pavement constructed with composite PCC and HMA. The LCCA for the street with flexible pavement was also 78% higher than that of composite structure due to the additional maintenance activities required during its service life.

Keywords: Pavement, Highways maintenance, Environmental impact, LCA, LCCA, Athena Pavement LCA software

1. Introduction
The development of most countries depends on growth in different industries to motivate the economy; unfortunately, this also generally depletes natural resources and has a detrimental impact on the environment [1, 2]. Highways and transportation networks are among most important elements in the development of countries, forming an essential part of the infrastructure of every country [3, 4]. In recent decades, the cost of construction, operation, maintenance, and rehabilitation of roads and pavements have increased dramatically, making it necessary for decision makers in highway agencies
to apply powerful tools and to apply restrictive rules before starting any new highway project or maintenance and rehabilitation strategy [5]. These tools significantly affect the type of pavement selected, and the selection of the type of pavement may significantly affect the total cost of construction, maintenance costs, fuel consumption both during construction and by vehicles using the pavement, and overall environmental impact. Consequently, a Life Cycle Cost Analysis (LCCA), as well as assessment of any environmental impact due to construction and operation of roads, should be addressed before the selection of pavement type [6].

The concept of using LCA as an environmental assessment tool was initially suggested in the early 1960s, as developers sought to observe and assess the impact of solid waste and all types of emissions on the surrounding environment [7]. It is now considered a powerful tool for studying the environmental impact of infrastructure development, based on relating input with output in the construction process and quantifying all by-products [8, 9] from all processes linked with construction activity, from the very start of construction until final stage demolition [10].

LCCA is a more specific method to estimate the overall cost of construction, including pavement, during design life, which can be used in the assessment of sustainability aspects. LCCA focuses significantly on the cost, and thus is not directly related to other environmental aspects such as gas emissions or air and water pollution. However, these aspects can be considered where they are converted to costs [11, 12].

The Athena pavement Life Cycle Assessment (LCA) software was developed by Federal Highway Administration (FHWA) to estimate LCCA during the life span of roads and to estimate the environmental impact of constructing roads and performing operation and maintenance activities during the design life of the road. The first version of LCA web app software was released in 2016; several updates have since released, with the current version, V3.2.03, released in September 2019 [13].

Athena pavement LCA software is a powerful tool that can be used to assess both the effect of LCA in terms of environmental impact and the LCCA in terms of cost and economic aspects. Hasan et al. [10] used LCA Software to analyse a case study in Abu Dhabi; the studied section consisted of two carriageways with a length of 3.5 km. The researchers estimated the environmental impact due to all activities of construction associated with the highway as indicated by the greatest effect factor, namely the Global Warming Potential (GWP), and compared the effects of using different virgin and recycled materials during both construction and maintenance. The effect of partial replacement of asphalt binder with specific types of polymer (lignin) on the LCA of according to the assessment of environmental impact of construction of two types of pavement from initial to final stages showed that 25% substitution of binder with lignin reduced the GWP by 5.7% [14]. The study further showed that the production process of pavement had approximately twice environmental impact of the extraction of material.

LCCA and LCA were performed to assess highway pavement sections in Colorado, USA, to help decision makers decide on pavement types [12]. The researchers compared HMA and PCC pavement with results that showed that the LCCA was 7.4% less for HMA, though the LCA in terms of gas emission was 26% less for PCC over the predicted life span of 40 years. Another study conducted in Florida confirmed the results of the previous study [15], with PCC offering lower environmental impact than flexible pavement at a higher initial cost. However, the percentages of gas emissions and total costs differed. A more recent study dealing with the sustainability of pavement confirmed that the use of PCC can increase overall costs by 35% as compared with flexible pavement, yet significantly reduces the carbon emissions and energy consumption of the project over the full lifespan [5].

Little research has been conducted in the Middle East to address the sustainability of different types of pavement in terms of life cycle cost and environmental impact, however, especially in Iraq. The current research thus aims to investigate the effects of pavement type on environmental impacts (gas emissions) and total life cost (from site preparation to final maintenance and rehabilitation) using Athena LCA Software. The life cycle cost assessment requires deep investigation of the design and construction of each pavement type, and the required maintenance and rehabilitation strategies from both technical and
economic perspectives. The types of pavement selected for this in-depth investigation are flexible and composite pavement, with selected streets in Al-Diwaniyah, Iraq, used as case studies.

2. Case Studies

To investigate the environmental impact of pavement types and to perform life cycle cost analysis (LCCA) in terms of site preparation, construction and maintenance conditions using Athena Pavement LCA software, two arterial streets in Al-Diwaniyah city centre were selected as case studies. The first street, Al-Forat Street, is located in the Al-Forat quarter, while the second street, University of Al-Qadisiyah street, is located in the university quarter, in front of the University of Al-Qadisiyah, as shown in Figure 1. These streets have different structural sections requiring different pavement layers, but both streets’ pavements layers were constructed according to the requirement of the Iraqi state commission for roads and bridges (SCRB). The environmental and traffic conditions for both may be assumed to be the same on average, due to their proximity to each other; a brief survey of traffic volume confirmed this assumption, which was required to clarify the effect of pavement type on environmental impact and LCCA. The service life for both streets was identified as 30 years.

![Figure 1. Locations of the selected streets](image)

The pavement structure for the first street is conventional bituminous layers (flexible structure) with asphaltic courses designed according to the Marshall Design procedure. The physical properties of layers met SCRB requirements, with a wearing layer with 50mm thickness being constructed using a dense-graded hot mix asphalt (HMA) with the nominal aggregate size of 12.5 mm (1/2 in) installed above HMA binder layer of 80 mm thickness, and an HMA base layer with 100 mm thickness. The HMAs for the binder and base layers have nominal aggregate sizes of 19 mm (3/4in) and 25 mm (1in) respectively. These layers were constructed on a sub-base layer of type B with 400 mm thickness. The roadway’s initial cost, including both: site preparation ($84,240) and construction ($578,760) costs was $663,000 according to Al-Diwaniyah municipality. Figure 2 shows a typical cross section for the first street (flexible structure).
The second street has a composite structure consisting of an HMA surface layer with properties and thickness similar to those of the HMA surface layer in the flexible structure. The surface layer is implemented above a Portland Cement Concrete (PCC) base with 200 mm thickness, and the sub-base layer of type B is 400 mm thick. The physical properties and thickness of layers meet SCRB requirements. The second roadway had an initial cost including both site preparation ($70,200) and construction ($473,800) costs of $544,000 according to Al-Diwaniyah municipality. Figure 3 shows a typical cross section of the second street (composite structure).

The study considered the materials used and all construction from the ground (subgrade) up to finished road surface level. The subgrade construction and activities for all structures were deemed similar due to the shared properties of subgrade soil. The length of selected sections was 1 km, with two lanes in each direction of 3.5 m width. The shoulders have a width of 3 m and are constructed with interlocked concrete block pavement, with gutters and kerbstones at the interior edge.

According to data from Al-Diwaniyah municipality, these streets were constructed after the removal of older demolished pavements, a process conducted during the 1980s. As a result, the project site preparation included removing the old, demolished pavements prior to construction of the roadways that were used as case studies in this research. The new roadways were constructed in 2008, and the total costs of site preparation works were equal to $84,240 and $70,200 for the first and second streets, respectively.

3. Material extraction, mix production, and construction processing
Extraction and plant processing of asphalt, aggregates, and cement are required for pavement construction and roadside works. The SCRB recommends HMA as a surface layer in pavement construction. The natural crushed gravel and bitumen (asphalt cement) materials of a surface course have significant environmental impacts due to mining, transport and production operations. This study thus began by assessing the environmental and traffic impacts on the HMA surface layers used for the
different types of pavement structures. The site investigations suggested that pavements constructed with PCC base courses exhibited higher resistance to distress than HMA base courses.

3.1. Material transportation to worksite
The transport of materials from their source (asphalt plant, sub-base material stock pile, etc.) to the construction site is a substantial stage in any road works’ life cycle and thus data from local suppliers was collected to calculate environmental leverage based on the distance to the requisite material fabrication plants and the vehicles used for by-road material transportation to the sites. Heavy goods vehicles’ (HGVs) exhaust fumes are the main source of emissions at this stage.

3.2. Worksite equipment and machinery transportation
The transportation of equipment and machinery used in the construction process to and around the worksite is also a key feature, particularly as HGVs are used to transport excavators, milling machines, and other equipment.

Three types of articulated trucks were assumed: light (<10 tonnes), medium (10 to 20 tonnes), and heavy (>20 tonnes), based on real field data. The load factor was based on the true weight of the individual construction equipment vehicles being transported. Construction environmental impacts due to the operation of on-site equipment such as excavators, asphalt pavers, compactors, and wheel-loaders are also significant, while creating traffic and carriageway concrete barriers, kerbs, concrete foundations for traffic lights, and road markings also contribute to the total environmental impact during road construction. This study considered the environmental impacts from all road construction processes.

Road use environmental impacts are mainly due to emissions from fuel consumption by the vehicles using the road surface, and vehicle-pavement interactions. The surface structure, roughness and other characteristics affect the rolling resistance offered by pavements to vehicles, which affects the fuel consumption of those vehicles.

4. Rehabilitation schedule
The performance of pavement layers in a roadway is affected by environmental conditions and traffic operation, which in turn lead to deterioration of the pavement and initiate distress. Three types of distress tend to occur to pavements: fractures (cracks), permanent deformation (rutting), and disintegration (raveling) [16]. According to Al-Diwaniyah municipality data, the common types of distress that occur on bituminous layer in Iraq are rutting, fatigue cracking, longitudinal cracking, joint reflection cracking, transverse (thermal) cracking, potholes, and stripping.

The Ministry of Construction, Housing, Municipalities and Public Works in Iraq performs scheduled preservation on the pavements of roadways to prolong and preserve their serviceable life. The rehabilitation procedure for the flexible structure and the composite pavement according to Al-Diwaniyah municipality are shown in Tables 1 and 2:

Table 1. Rehabilitation activities for flexible structures

| Activity Timing | Activity Type | Affected Road | % of Element Affected by Activity |
|-----------------|---------------|---------------|----------------------------------|
| Year After Initial Construction | Expect ed Lifespan [Years] | Paved Shoulders | Paved Lanes | % Surface Area | Quantity | Unit |
| 3 | 6 | Crack Cutting, Crack Cleaning & Drying, Asphalt Sealant Material Installation | No | Yes | 6 | 420 | m² |
### Table 2. Rehabilitation activities for composite structures

| Activity Timing | Activity Type | Affected Road | % of Element Affected by Activity |
|-----------------|---------------|---------------|----------------------------------|
|                 |               | Paved Shoulders | Paved Lanes | % Surface Area | Quantity | Unit |
| Year After Initial Construction | Expected Lifespan [Years] | | | | |
| 5 | 10 | Crack Cutting, Crack Cleaning & Drying, Asphalt Sealant Material Installation | No | Yes | 2 | 140 | m² |
| 10 | 15 | Tack Coat Application, Asphalt Paving HMA | No | Yes | 10 | 700 | m² |
| 15 | 20 | Joint Cutting, Joint Cleaning & Drying, Sealant Installation, Backer Rod Installation | No | Yes | 17 | 490 | m² |
| 20 | 25 | Tack Coat Application, Asphalt Paving HMA | No | Yes | 25 | 1,750 | m² |
| 25 | 30 | Crack Cutting, Crack Cleaning & Drying, Asphalt Sealant Material Installation | No | Yes | 30 | 2,100 | m² |
5. Results and discussion

Athena Pavement LCA software was used to calculate the environmental impact and LCCA of each pavement structure. In order to determine the differences in environmental performance, the primary characteristics for each pavement layer were entered into the Pavement LCA software; these included the type of materials used, the thickness and width of each layer, and materials as a percentage of total mixture weight. These details were input along with the asphalt type (HMA) and PCC, and data for factors such as hauling distance, where available. In order to accurately compare the different pavement structures, each roadway was assumed to have a 30-year lifespan, with rehabilitation occurring every three and five years for the flexible and composite structures, respectively.

The results were exported and plotted using Excel in Global Warming Potential (GWP) and Acidification Potential (AP) for both roadways. Global warming refers to the current rise in the average temperature of earth’s atmosphere and oceans owing to transmission of incoming short-wave radiation from the sun and absorbance of outgoing long-wave radiation from the earth, while acidification is an environmental problem caused by changes in the pH of rivers, streams, and soil due to anthropogenic air pollutants such as SO2 and NH3 [17]. Acidification increases the mobilisation and leaching behaviours of heavy metals in soil and stimulates adverse effects such as eutrophication, a phenomenon in which inland waters are heavily loaded with excess nutrients due to chemical fertilizers or discharged wastewater, triggering rapid algal growth and red tides that impact on aquatic and terrestrial animals and plants by disturbing food supplies[18]. The GWP and AP Units thus do not represent the chemical composition of the pollution itself, but instead represent a standard normalising factor representative of each pollution type [19].

5.1. LCCA Results

LCCA reports were calculated using Athena Pavement LCA software as shown in Tables 3 and 4. The results include the costs of maintenance activities conducted during the service life of the two streets as estimated based on prevailing prices in Iraq. The total cost of the maintenance activities for the flexible structure is higher than that for the composite structure by 78%, due to the fact that the street with flexible structure is more seriously affected by the environmental conditions of the area the road serves, such as temperature, rainfall, water table, and water drainage, in addition to the impact of traffic operation. An increase in the water table is a common problem in Al-Diwaniyah, which leads to a weakening of the supporting layers (subgrade and subbase layers) of pavement structure due to the increase in the water content of these layers, which damages the surface layer. The differences in the maintenance costs between the flexible structure and the composite structure are thus due to the more frequent maintenance works required by the first street as compared to the second street during the predicted service life.

| Activity Timing | Maintenance Costs |
|-----------------|-------------------|
| Year After Initial Construction | Expected Lifespan [Years] | $ |
| 3 | 6 | 4,191.93 |
| 6 | 9 | 18,827.48 |
| 9 | 12 | 68,379.52 |
| 12 | 15 | 184,947.41 |
| 15 | 18 | 234,856.78 |
| 18 | 21 | 244,093.36 |
| 21 | 24 | 251,912.31 |
| 24 | 27 | 280,896.84 |
| 27 | 30 | 300,309.20 |
Table 4. Maintenance costs for the composite structure

| Activity Timing | Maintenance Costs |
|-----------------|-------------------|
| Year After Initial Construction | Expected Lifespan [Years] | |
| 5 | 10 | $1,397.31 |
| 10 | 15 | $11,505.68 |
| 15 | 20 | $17,782.74 |
| 20 | 25 | $42,798.51 |
| 25 | 30 | $63,313.80 |

Figures 4, 5, and 6 show the consumption of diesel oil during the construction, site preparation, and manufacturing processes for the two streets. The production of a flexible structure requires 53% more diesel oil than the composite structure as diesel oil is a basic material use in preparation, mixing, transportation, and installation of the mixture used for the asphaltic layers. The site preparation of a flexible structure also needs 57% more diesel oil than the equivalent preparation for the composite structure, as the flexible structure contains more paving layers compared to the composite structure, and this leads to more work input being required and higher consumption of diesel. Diesel oil consumption is one of the main reasons for the high cost of construction and maintenance of streets during their service lives.

**Figure 4.** Diesel oil consumption for both streets during construction and manufacturing processes

**Figure 5.** Diesel oil consumption for both streets during site preparation
Figures 7 and 8 show the consumption of gasoline during the construction process for both streets. Gasoline is a solvent material used in the cutting back process applied to bitumen for the purpose of producing the tack coat asphalt used to promote bonding between old and new pavement lifts. Adequate bonding between constructions lifts, especially between an existing road surface and an overlay, is necessary for a pavement structure to behave as a single unit and provide adequate strength. Gasoline consumption is one of the reasons for the high cost of construction and maintenance of streets during their service lives. The construction of a flexible structure requires more gasoline as compared to the creation of a composite structure, an increase of 67%, as the flexible structure has three HMA pavement layers.

Figure 6. Diesel oil consumption for both streets during operation

Figure 7. Gasoline consumption for both streets during the construction process
5.2. Environmental Impact Results

Figures 9 to 11 show the results for GWP by pavement structure type in units of kilograms of carbon dioxide. GWP acts as a useful parameter to assess the future impact of emissions on the atmosphere [19]. The flexible structure is seen to have a higher environmental impact than the composite structure due in terms of higher GWP, mainly due to the differences in the production processes between the mixtures of the layers for the two streets. The GWP of flexible pavement is about 48% of that of composite pavement based on the manufacturing and preparation (extraction) of materials, yet it is more than 5.27 times of that of composite pavement during the construction process. The GWP emissions during the site preparation process for the flexible structure are higher than those of the composite structure, as the construction of the flexible structure requires more activities that lead to the emission of various gases and vapours, including carbon dioxide, based in part on materials extraction and construction.

Figure 9. GWP for both streets during construction and manufacturing processes
Figures 12 to 14 display the acidification potential of each pavement mix. The results for acidification potential suggest that using flexible pavement produces more CO2 emissions than using composite. During the manufacturing process, the flexible pavement exhibits CO2 emissions about about 14% higher than those of composite, while in the construction stage, the ratio of increase is 5.26 times.

**Figure 10.** GWP for both streets during site preparation

**Figure 11.** GWP for both two streets during roadway operation

**Figure 12.** AP for both streets during construction and manufacturing
Summary and Conclusions
Highway pavement is one of the most important parameters in developing the infrastructure in a country, and the construction of pavements usually requires the consumption of significant quantities of materials and non-renewable energy, which has a significant impact on the environment. Athena Pavement LCA software is a versatile tool used by highway agencies and departments of transportation to select the best alternatives for the development and rehabilitation of road networks.

Extended research was undertaken to investigate the environmental impact and the LCCA, in terms of site preparation, construction and maintenance conditions, for two arterial streets in Al-Diwaniyah city centre, based on official data and site investigations, and using Athena Pavement LCA software modelling.

The results of the analysis offer several significant conclusions:
1. The initial cost of flexible pavement is higher than that of composite structures by 17%.
2. The total cost of maintenance activities for the flexible pavement is higher than that for those required for the composite structure by 78%, due to the more frequent maintenance works required by the flexible structure during its service life.
3. The production of a flexible structure requires more diesel oil than the composite structure by 53%, as diesel oil is a basic material use in the preparation, mixing, transportation and installation of asphaltic layers.

4. The construction of a flexible pavement requires 67% more gasoline than the construction of a composite structure as flexible pavement requires three HMA pavement layers, and gasoline is used in the production the tack coat asphalt required to promote bonding between the surface and binder lifts of the pavement.

5. The GWP of flexible pavement is about 48% that of composite pavement during the manufacturing and preparation (extraction) of materials and more than 5.27 times that of composite pavement during the construction process. This is due the process of material extraction and construction used by each type.

6. During the manufacturing process, flexible pavement creates about 14% more CO2 than composite, while in in the construction stage, the increase ratio exceeds 5.26.

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