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Life Cycle Assessment of Flexible Pavement Construction

M. R. Ghazy[1], A. M. Abdallah[2], M. A. Basiouny[3] and M. A. S. Saad[1*]

[1]Department of Civil Engineering, Benha Faculty of Engineering, Benha University, Egypt.
[2]Department of Civil Engineering, Faculty of Engineering, Zagazig University, Egypt.
[3]The Dean of Benha Faculty of Engineering, Benha University, Egypt.

Authors' contributions

This work was carried out in collaboration between all authors. All authors read and approved the final manuscript.

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ABSTRACT

Aims: The main objectives of this study are to submit significant contribution to the field of environmental assessment of flexible pavement construction method in Egypt based on a life cycle assessment study. This contribution will be useful in the planning and management of sustainable road construction in Egypt.
Study Design: A comprehensive life cycle assessment (LCA) of asphalt pavements construction methods were conducted including hot mix asphalt (HMA) method through changing the pavement design parameters such as California Bearing Ratio (CBR) and Average Annual Daily Traffic (AADT). A filed study of the construction data of three main roads in Egypt was carried out. Data are used as base for the inventory data and influent parameters in this study.
Place and Duration of Study: Three major high ways in Egypt, Between November 2013 and June 2015.
Methodology: Nine scenarios represent different design parameters of flexible pavement design methods are investigated. The average annual daily traffic are (10,000 – 25,000 – 50,000 – 100,000 – 150,000) vehicles per day with 10% of heavy vehicles, growth factor (Gf) 3% and California bearing ratio CBR (3%, 6%, 10%, 15%).
Results: The results showed that by changing CBR from 3% to 15% for each AADT, noted the

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*Corresponding author: E-mail: eng_mustafa43@yahoo.com;

environmental effect are decreased by (5 and 40) % due to the improvement in the soil. By increasing AADT from (10,000 to 150,000) veh/day at each CBR value, the environmental impacts are increase by (5 and 25) % due to the increase in traffic volume.

Conclusion: The pavement construction had adverse effect on environmental. The transport of materials used in roads construction produce the most significant environmental impacts. The pavement LCA can help to increase the environmental performance of roads construction and guide authorities towards road sustainability management.

Keywords: Life cycle assessment; hot mix asphalt; flexible pavement.

1. INTRODUCTION

The roads construction is constantly looking for solutions to improve pavement performance, increase construction efficiency, conserve resources and advance environmental protection. As a result of the continuous increase in the population, economic and social development worldwide, it has become an urgent need for development and increase of road networks. This also led to the diversity and development in the materials and methods used in the manufacture of road network. Roads construction could cause negative environmental impacts and pollution effects of air, water and soil.

The two primary types of pavements are flexible and rigid pavements. This study is limited to the flexible pavement alone which is most prevalent in Egypt. Flexible pavement consists of a relatively thin wearing surface of asphalt built over a base course. Base layer course is usually consisting of stone with specified gradation. This layer rest upon a compacted subgrade (compacted soil).

Egypt is one of the most populous countries in Africa and the Middle East. As a result of the continuous increasing in population and Urban Development, there is a marked expansion in the construction of road networks. The total length of road networks in Egypt reached to 100472 km in 2009, World Bank [1]. Total road network includes motorways, highways, and main or national roads, secondary or regional roads, and all other roads in a country.

The construction of pavement causes emissions and pollution to surrounding environment. The emissions occur during the raw materials extraction and manufacture, the transportation of raw materials and asphalt mix, manufacturing of asphalt mix, as well as the construction processes. In this study, the environmental impacts associated with energy consumption and road construction processes in Egypt are assessed based on Life Cycle Assessment (LCA).

Life Cycle Assessment (LCA) is a versatile tool to investigate the environmental aspect of a product, a service, a process or an activity by identifying and quantifying related input and output flows utilized by the system and its delivered functional output in a life cycle perspective Baumann and Tillman [2]. Ideally, it covered all the processes associated to a product from its (cradle to its grave). LCA can also purpose different alternatives for different phases of a life cycle of the system if we have different design alternatives.

Several studies of LCA have been recently discussed many aspects of the roads construction however, still many issues need to be more investigated. A comprehensive life cycle assessment of asphalt pavements was conducted by Enrique Moliner, et al. [3], including hot mix asphalt (HMA), warm mix asphalt (WMA) with the addition of synthetic zeolites, and asphalt mixes with reclaimed asphalt pavement (RAP). By comparing asphalt mixes with different RAP contents, it was shown that the impacts of asphalt mixes were significantly reduced when RAP was added. All endpoint impacts as well as climate change, fossil depletion and total cumulative energy demand were decreased by 13–14% by adding 15% RAP. Thus, the decrease in the impacts achieved by adding large amounts of RAP to WMA could turn these asphalt mixes into a good alternative to HMA in environmental terms. But the author did not take into account the effect of construction base layer which has been observed in this study. Nicholas Santero, et al. [4], has studied the Global Warming Potential Impact (GWP) of various classifications of concrete pavement roadways in the United States by using the LCA. Twelve classifications of roads, six rural and six urban, were evaluated based on their cross-sectional geometric and material design. The results showed that, GWP ranges from 440 Mg CO2equ/km on the rural local road to 6670 Mg CO2equ/km on the urban interstate. GHG emissions from cement production are the largest contributor 45% for urban interstates to 72% for rural local roads. For 9 of 12 pavement designs, the second largest contributor to GWP is fuel consumed from roughness. In this study Nicholas Santero was considered only one environmental category to evaluate the environmental impacts of concrete pavement.

A comprehensive Economic Life Cycle Assessment (EIO-LCA) model was conducted to compare three major rigid pavements of Jointed Plain Concrete Pavement (JPCP), Jointed Reinforced Concrete Pavement (JRCP), and Continuously Reinforced Concrete Pavement (CRCP) within the perspective of economic transactions, greenhouse gases, energy use, hazardous waste, toxic releases, water withdrawals, and transportation movements, Zhuting Mao, [5]. The results indicate that CRCP be the most cost-efficient and sustainable choice among the selected rigid pavement alternatives as it requires the lowest life-cycle cost and has the least unfavorable impact on environment when compared to the JPCP and JRCP. The processes of cement manufacturing, power generation and supply, ready-mix concrete manufacturing, and truck transportation are the top sectors contributing to the energy use and greenhouse gases emissions. The results also indicate that some sectors such as storage of materials, landfills, and soil waste management should be taken into account in order to reduce toxic releases. A LCA study was applied for four different pavement types, two concrete pavements and two asphalt pavements, according to ISO 14040 by investigating various case of pavement construction scenarios, Charlotte Milachowski, et al. [6]. Most of input and output values for the individual processes in the production and use of pavement were taken into account such as the production of materials, provision of energy, manufacture of the necessary products, transport services and the employment and disposal of the individual products. The results observed that, the effect on Photochemical Oxidants Creation Potential (POCP) and Eutrophication Potential (EP) is similar in asphalt and concrete. For Global Warming Potential (GWP) the asphalt construction methods cause a potential environmental impact which is 166% more than with concrete. In the case of Ozone Depletion Potential (ODP), the impact is 300% more with asphalt. In contrast, the potential impact of concrete construction methods for category Acidification Potential (AP) is 135% that of the asphalt construction methods.

The main objectives of this study are to study the environmental impacts of the roads construction methods including HMA (Hot Mix Asphalt) in Egypt based on the LCA approach. Environmental impacts associated with energy consumption and air emissions as well as other environmental impacts resulting from the extraction and processing of minerals, binders and chemical additives, asphalt production, transportation of materials asphalt paving, land use, dismantling of the pavement at the end-of-life and its landfill disposal or recycling. The results are intended to be used by decision-makers in industries and authorities as a basic tool to elaborate strategies and policies for the roads construction management as well as to estimate the investments for new roads construction facilities.

2. MATERIALS AND METHODS

The LCA methodology is applied in this study to evaluate and compare the environmental impacts of different flexible pavement during their entire life cycle. The LCA software application Umberto 5.5 was used to tackle the development of the study more effectively.

Main inventory data are collected through a field study from the construction of three major high ways in Egypt. Tanta - Kafer Elshik High way with width 22.5 m and 9 km length, Cairo –Benha high way with width 21 m and 27 km length and N-A High way with width of 18 m and 5 km length.

Nine scenarios represent different design parameters of flexible pavement construction in Egypt are investigated. The average annual daily traffic are (10,000 – 25,000 – 50,000 – 100,000 – 150,000) vehicles per day with 10% of heavy vehicles, growth factor (Gf) 3% and California bearing ratio CBR (3%, 6%, 10%, 15%), which takes into account the type of soil and the volume of traffic expected.

2.1 Goal and Scope Definition

The current study aimed to evaluate the environmental impacts of different road pavements during their entire life cycle as well as submit a significant contribution to the field of environmental assessment of roads construction in Egypt.

2.1.1 Purpose of the study

This study is aimed to evaluate and compare the environmental impacts of different flexible pavement options / scenarios by using LCA according to the Egyptian condition To develop an overall comprehensive approach for sustainable roads construction management in Egypt.

2.1.2 Function unit

The functional unit is a measure of the function of the studied system and it provides a reference to which the inputs and outputs. The functional unit for road pavements is defined here by the section of road concerned is 1 km long with a width of 1 m. All emissions, materials, cost and energy consumption is calculated according to this functional unit.

2.1.3 System description and boundaries

The life cycle of roads construction are consisting of mainly four major subsystems (material production, construction, use, and end-of-life). However, asphalt production is considered as a separate subsystem to highlight the effect of production technology on the overall impact. Transportation of asphalt mixes to the construction site was also treated as separate subsystem. Therefore, the overall system under study was divided into the following subsystems Fig. 1.

2.2 Flexible Pavement Scenarios

Nine main scenarios of flexible pavement design methods represent a wide variety of different parameters to cover all expected cases of design methods according to the Egyptian conditions are studied. These scenarios are developed by changing the values of the mainly road design parameters, the California Bearing Ratio (CBR) and Annual Average Daily Traffic (AADT) as indicated in Table 1.

2.3 Assumptions and Limitations

The current study has been conducted under the following limitations:

(1) The environmental impacts associated with the construction of different pavement layers process operation were considered for the analysis.

(2) The construction and operation of the excavation was not considered since it is shared by all the scenarios, as the pavement layer was selected as the starting point in this study.

(3) The environmental impacts arising from loading of material into truck will neglect.

(4) The environmental impacts arising from landfilling do not include the impacts of generating noise, dust, odors or the change of natural scenery as well as the increase in road traffic.

(5) The environmental impacts of the extraction of raw materials, production processes, pre-chain of diesel fuel and the pre-chain of electrical energy production are estimated according to the Egyptian conditions.

(6) The environmental impacts of the extraction of raw materials, production processes, pre-chain of diesel fuel and the pre-chain of electrical energy for production sand and filler will neglect.

2.4 Life Cycle Inventory (LCI)

The inventory analysis describes the material and energy flows to and from the system. The inventory analysis is depending on the life cycle of sub-components that have emerged from different sub-systems to develop the boundary of the main system. The system consists of different sub-steps such as raw materials extraction, transportation, production, consumption and waste disposal. All of these sub-steps require different types of inflows and generate different types of outflows for different basic activities. All the inventory data to trace all inflows from cradle (extraction of raw materials) and to trace all outflows to the grave (as emissions to the environment) within the studied scenarios and system boundaries are estimated. The result of the inventory analysis is a summary of all inflows and outflows related to the “functional unit”. Field data supplied by the construction companies were used to gather information about all inputs materials for each sub-component.

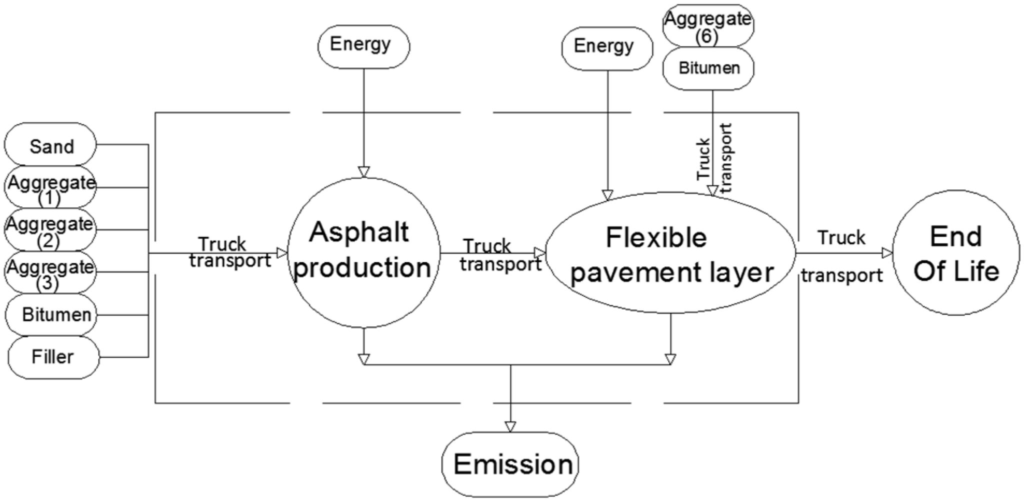

Fig. 1. System boundaries for flexible pavement

Table 1. Flexible pavement scenarios

Scenario	CBR	AADT (Veh / day) x 10^3
1	3%	(10-25-50-100-150)
2	6%	(10-25-50-100-150)
3	9%	(10-25-50-100-150)
4	15%	(10-25-50-100-150)
5	(3%-6%-10%-15%)	10
6	(3%-6%-10%-15%)	25
7	(3%-6%-10%-15%)	50
8	(3%-6%-10%-15%)	100
9	(3%-6%-10%-15%)	150

For those sub-components where no field data were available from the company, data were collected from LCA databases and from the scientific literature. After completing the gathering of data, each sub-component was modeled using the Umberto 5.5 software application.

2.4.1 Materials

Basically, Asphalt mixes consist of natural aggregates and binder constituents, although other materials may also appear to a lesser extent. Stones and sand are used as coarse and fine aggregates, respectively, while bitumen is used as a binder constituent. Filler product from cement and lime products (such as limestone and hydrated lime). The quantities of these materials of each scenario are estimated based on the sizing of the design cross sections. The cross sections of the different scenarios are designed based on AASHTO Interim Guide for design of pavement structures [7]. Fig. 2 shows the dimensions of the studied scenarios cross sections.

Fig. 3 indicates the component of the cross section elements that consist of, wearing surface, which is the top layer of a road that carries the traffic and the thickness of this layer is selected by 5 cm. Binder course is a coarse aggregate bound with bitumen between the wearing course of an asphalt pavement and the base layer and the thickness of this layer between 5 to 6 cm. Bituminous base is layer which serving as a foundation for binder courses and surface courses in asphalt paving operations and it is used in high traffic volume and the thickness of this layer between 5 to 7 cm. Base layer is the layer of aggregate material laid on the subgrade, used as strong foundation to the roads and the thickness of this layer between 15 to 50 cm.

2.4.2 Asphalt mix production

This section deals with the LCI of the asphalt production of Hot Mixes Asphalt (HMA). Besides the production process, the asphalt plant was also inventoried separately. The LCI was based on field data on the production of HMA for three major high ways in Egypt and the asphalt plant of the General Nile Company Mix Plant.

2.4.2.1 Asphalt plant

The inventory data of the asphalt plant are estimated based on the General Nile Company Plant. The life span of the plant was estimated to be about 50 years and the average yearly production about 204,400 tons of asphalt. The machinery used in the asphalt plant includes: 4 cold-feed bins, 4 sieves, 1 rotary dryer, 1 mixer, 1 drum mixer, 1 burners, 1 boiler, 1 filtering units, 2 big filler silos, 3 big bitumen tank, 2 big solar tank, 1 compressor air and a conveyor belt. The service life for all machines was assumed to be 20 years, except for the conveyor belt, which was considered to have a service life of 15 years. Fig. 4 present the general layout of the General Nile Company Mix Plant.

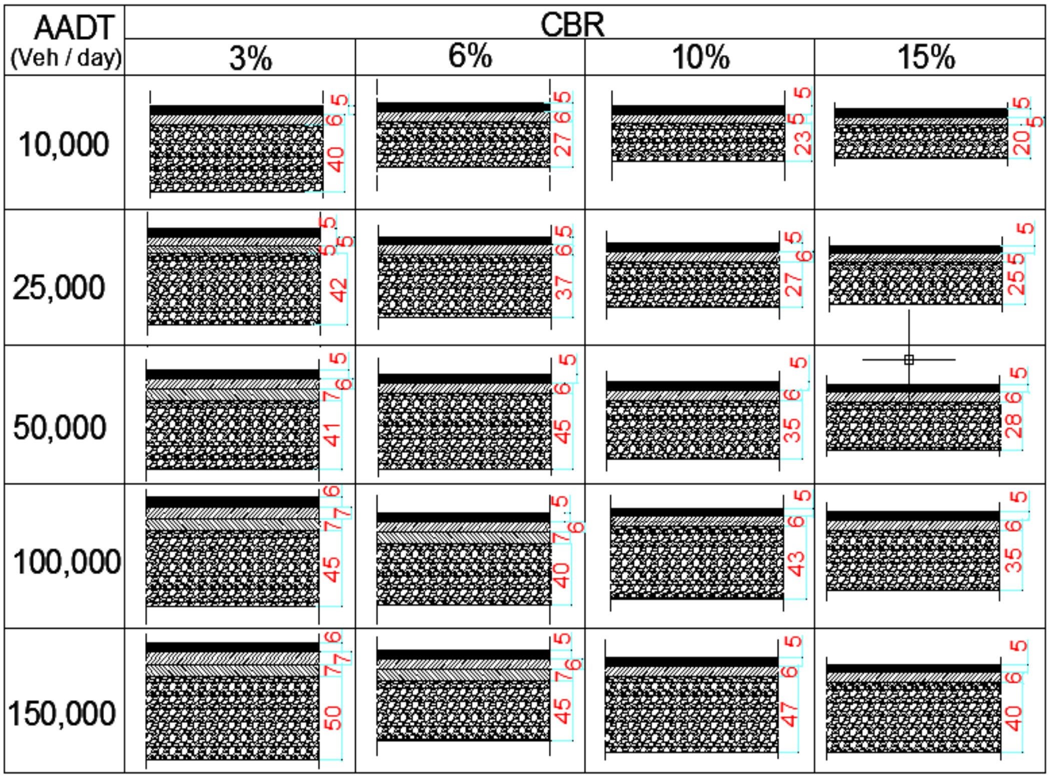

Fig. 2. Dimensions of design cross sections

Notes: All dimension in the figure by centimeter

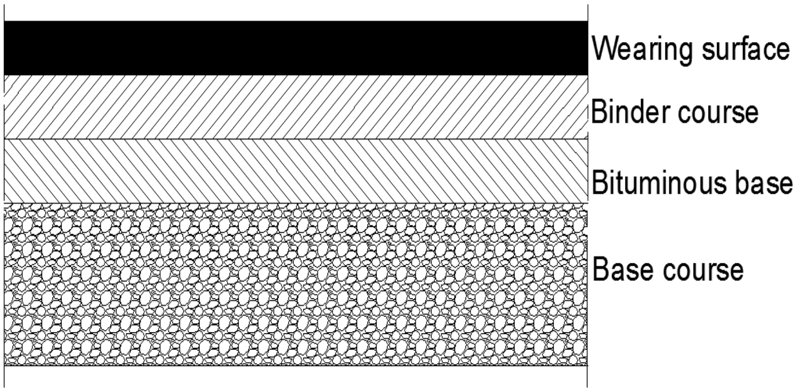

Fig. 3. Typical cross section elements

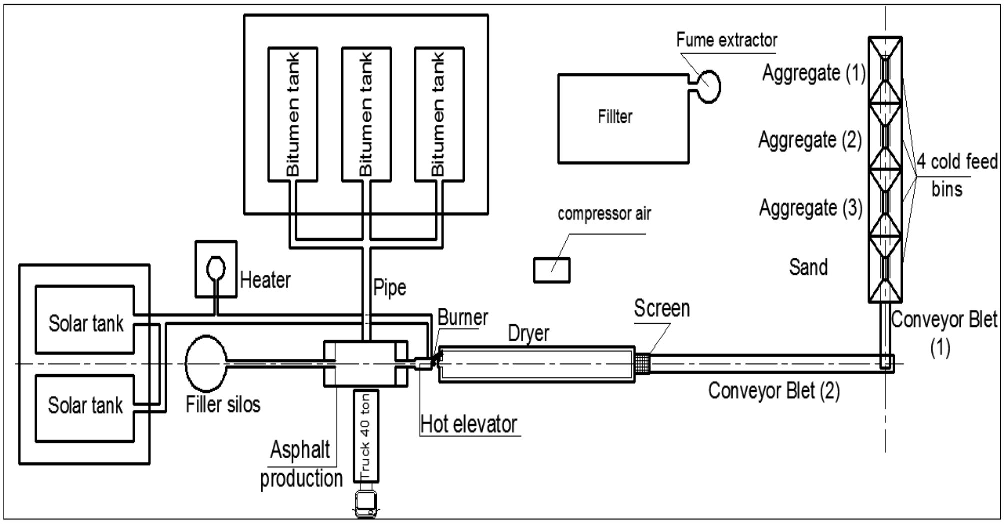

Fig. 4. Dimensions of design cross sections

Source: General Nile Company for roads [8]

2.4.3 Transportation

The LCI data of pavement transporting process is mainly based on vehicle type and travelled distance. The raw materials are delivered from the extraction and processing sites to the asphalt plant by trucks. Likewise, the asphalt mixes are transported to the construction site by road after production. The travel distances are basically depending on the local boundary conditions. The high volume of transported material and long distances may eventually have a strong influence on the energy balance of the system Remy, 2010 [9]. The transportation distances of raw and construction materials have an important and effective role in the environmental impacts of road construction. Theses distances are often different from site to other.

In this study, the transportation process inventory data are described with the respective dataset for truck transport from UMBERTO database, which is based on the comprehensive life cycle inventories of ecoinvent data V2.0 IFU, [10]; Spielmen et al. [11]. The applied distances for all material transport processes which are assumed in this study are indicated in Table 2.

2.4.4 Construction

Roads construction consists of many processes. The current study focused on all layers paving. The environmental burdens depend on the construction phase, which arise from fuel consumption and air emissions from the paving machinery, air emissions and leachate from the asphalt pavement, and transformation of land.

2.4.4.1 Machinery

There are many machines are normally used by the company to spread and compact the asphalt and base layer: an asphalt paver, a heavy vibratory roller, a rubber tire roller, and grader.

Table 2. Materials transportation

Component	From	To	Distance (km)
Sand	Extraction and processing sites	Plant	140
Aggregate (1)	Extraction and processing sites	Plant	150
Aggregate (2)	Extraction and processing sites	Plant	150
Aggregate (3)	Extraction and processing sites	Plant	150
Aggregate (6)	Extraction and processing sites	Site	185
Bitumen	Extraction and processing sites	Plant	150
Filler	Extraction and processing sites	Plant	150
Bitumen to spray	Extraction and processing sites	Road site	185
asphalt mixes	Plant	Road site	35

Source: General Nile Company for roads [8]

Basic data of energy consumption based on the Egyptian operating conditions are shown in Table 3.

Table 3. Machinery energy consumption

Machine	Energy consumption
Grader	80 liter /1000 m2 (Solar)
Heavy vibratory roller	20 liter /1000 m2 (Solar)
Rubber tire roller	20 liter /1000 m2 (Solar)
Asphalt paver	40 liter /1000 m2 (Solar)

Source: Arab Contractors Company [12]

2.4.4.2 Egypt electricity generation mix

Electricity considered a major point in any LCA study. It is important in order to model and evaluate the resources use and pollutant releases for the activities related to its generation and distribution. In Egypt, the total generation capacity of electricity was 22583 MW in 2008 and the electricity generation mix was as follow: 58.3 % natural gas, 28.9 % petroleum products and 12.8 % hydroelectric, Moee, [13].

The life cycle inventory data for the Egyptian electricity system are not available in commercial LCA databases. The Egyptian electricity generation mix is estimated based on the pre-chains for energy sources, auxiliary materials, processing and transport of primary sources. Transport of electricity to consumer is not taken into account. The cumulative energy demand for electricity production based on the Egyptian conditions is estimated at 9.29 MJ/ kWh.

2.4.4.3 Diesel fuel

Life cycle inventory of the energy required and the associated emissions for extraction, transport and refining of diesel fuel are calculated with Umberto datasets. These datasets are mainly relied on the data from the Global Emission Model for Integrated Systems (GEMIS) databases and ECOINVENT databases Frischknecht et al. [14].

2.5 LIFE CYCLE IMPACT ASSESSMENT (LCIA)

The environmental impact assessments of the studied scenarios will compare using the life cycle assessment methodology, which is largely in accordance with the ISO 14040/14044 standards ISO 14044 2006, ISO 14040 2006 [15]. The life cycle inventories (LCI) of each treatment process include parameters describing energy use, raw materials, emissions to air, emissions to water, and waste generation will be estimated. The life cycle inventories are based on dk, uata gathered from pilot studies, databases and literature. These data will readjust to fit into the specific boundary conditions of current study. Fig. 5 indicates the LCA tool origin and structure based on ISO 14040 where Fig. 6 shows the Life Cycle Impact Assessment (LCIA) Elements of LCIA based on ISO 14042, 2000 [16].

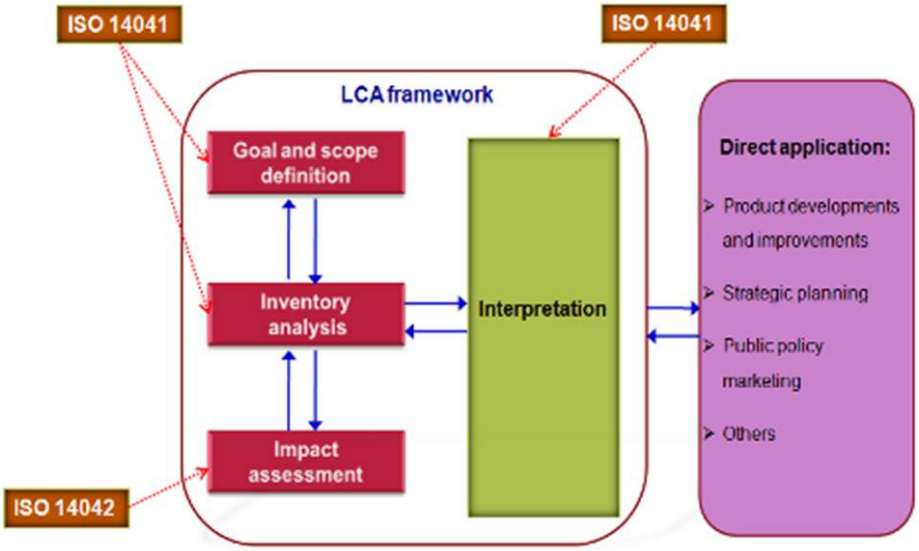

Fig. 5. LCA tool origin and structure based on ISO 14040

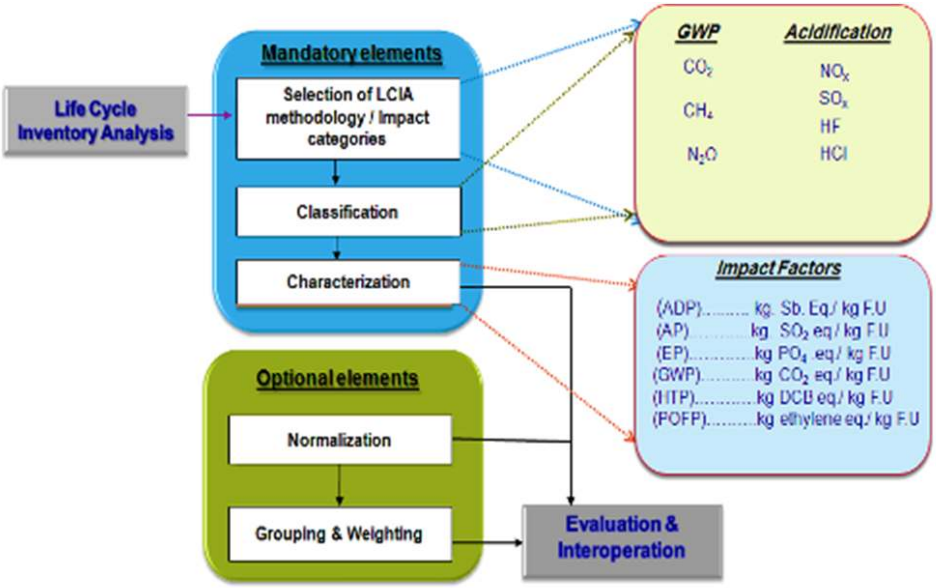

Fig. 6. Life cycle impact assessment element based on ISO 14042

3. RESULTS AND DISCUSSION

The results of environmental assessment for the flexible pavement construction methods using LCA-based tool can be summarized in the following contexts. Six environmental category impacts are evaluated; photochemical oxidation (POFP), Eutrophication (EP), Acidification (AP), Depletion of abiotic resources (ADP), Human toxicity (HTP) and Climate change (GWP).

3.1 Effect of Changing CBR on the Road Design

The following figures indicated the results of the environmental impacts of changing CBR with different AADT (10-25-50-100-150) (Veh / day) x 10^3.

Fig. 7 indicates the environmental impacts of flexible pavement design methods for different AADT (10-25-50-100-150) (Veh / day) x 10^3 with constant value of CBR 3%. The results observed that by increasing the AADT from 10,000-25,000 veh/day the GWP and HTP impacts are increased by 10 % and are increased by 3%, 12% and 5% by increasing the AADT from (25,000 to 50,000), (50,000 to 100,000) and (100,000 to 150,000) respectively. The ADP impacts is increased by 11% when changing AADT from (10,000-25,000) and the emissions are increased by 5%, 9% and 8% by increasing the AADT from (25,000 to 50,000), (50,000 to 100,000) and (100,000 to 150,000) respectively. The results also indicated that the AP impacts is increased by 12% by increasing the AADT from (10,000-25,000), However the emissions are increased by 3%, 11% and 10% by increasing the AADT from (25,000 to 50,000), (50,000 to 100,000) and (100,000 to 150,000) respectively. The EP impacts is also increased by 15% by changing the AADT from (10,000-25,000) and are increased by 2%, 10% and 6% by changing AADT from (25,000 to 50,000), (50,000 to 100,000) and (100,000 to 150,000) respectively. It also observed that POFP impacts are increased by 12%, 3%, 13%, 8% by changing AADT from (10,000-25,000), (25,000 to 50,000), (50,000 to 100,000) and (100,000 to 150,000) respectively.

Fig. 8 shows the environmental impacts of flexible pavement design methods for different AADT (10-25-50-100-150) (Veh / day) x 10^3 with constant value of CBR 6%. The results showed that by increasing the AADT from 10,000-25,000 veh / day the GWP and HTP impacts are increased by 28% and are increased by 14%, 3% and 6% by increasing the AADT from (25,000 to 50,000), (50,000 to 100,000) and (100,000 to 150,000) respectively. The ADP impacts is increased by 29% when changing AADT from (10,000-25,000) and the emissions are increased by 11%, 5% and 4% by increasing the AADT from (25,000 to 50,000), (50,000 to 100,000) and (100,000 to 150,000) respectively. The results also indicated that the AP impacts is increased by 25% by increasing the AADT from

(10,000-25,000), However the emissions are increased by 13%, 6% and 5% by increasing the AADT from (25,000 to 50,000), (50,000 to 100,000) and (100,000 to 150,000) respectively. The EP impacts is also increased by 28% by changing the AADT from (10,000-25,000) and are increased by 16%, 3% and 3% by changing AADT from (25,000 to 50,000), (50,000 to 100,000) and (100,000 to 150,000) respectively. It also observed that POFP impacts are increased by 27%, 17%, 2%, 3% by changing AADT from (10,000-25,000), (25,000 to 50,000), (50,000 to 100,000) and (100,000 to 150,000) respectively.

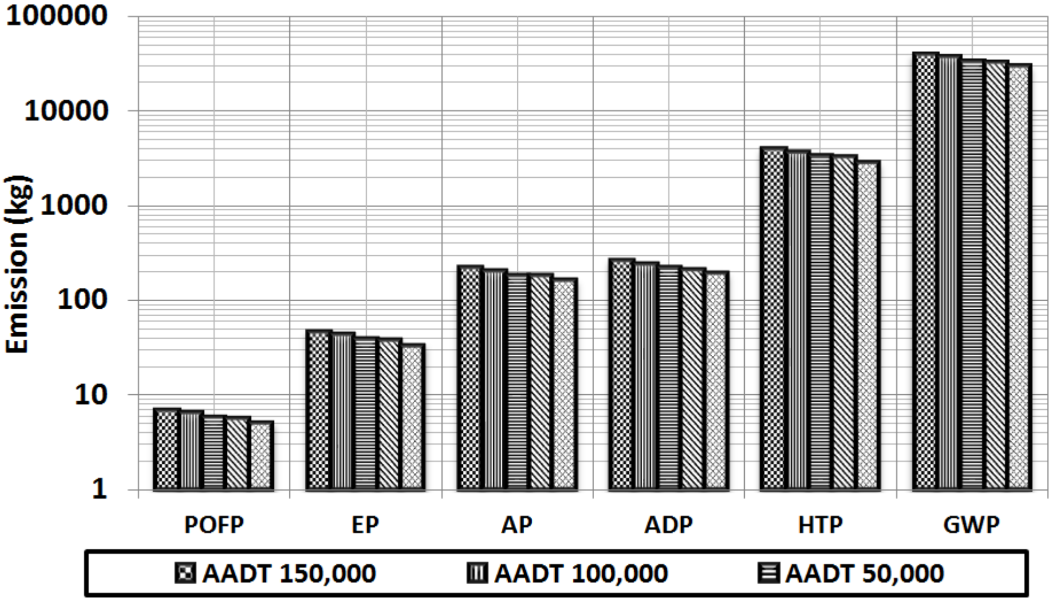

Fig. 7. Environmental impacts of different AADT and CBR 3% on flexible pavement design method

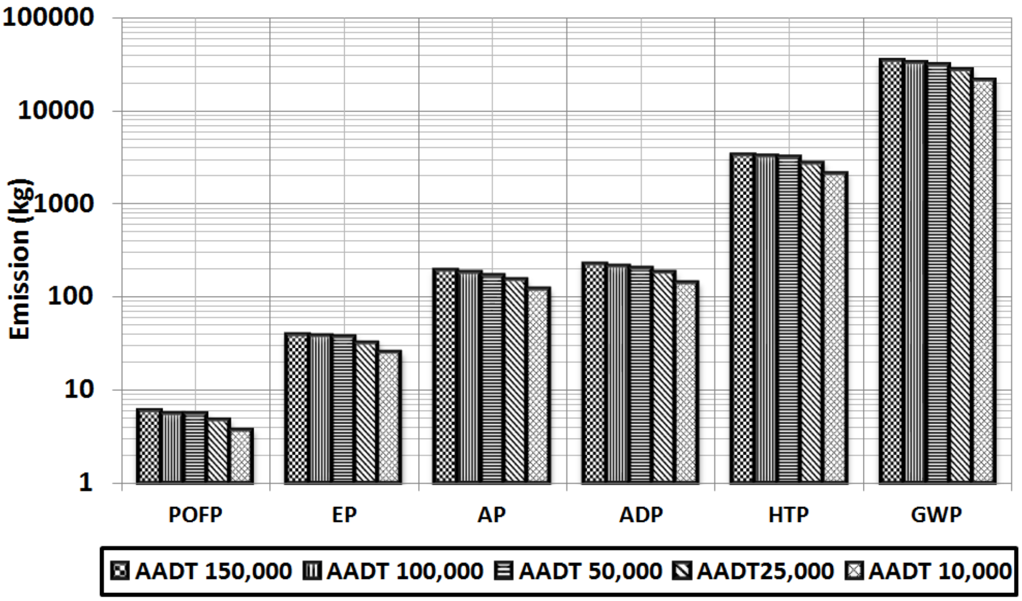

Fig. 8. Environmental impacts of different AADT and CBR 6% on flexible pavement design method

Fig. 9 indicates the environmental impacts of flexible pavement design methods for different AADT (10-25-50-100-150) (Veh / day) x 10^3 with constant value of CBR 10%. The results observed that by increasing the AADT from 10,000-25,000 veh/day the GWP and HTP impacts are increased by 16% and are increased by 23%, 15% and 6% by increasing the AADT from (25,000 to 50,000), (50,000 to 100,000) and (100,000 to 150,000) respectively. The ADP impacts is increased by 17% when changing AADT from (10,000-25,000) and the emissions are increased by 21%, 17% and 5% by increasing the AADT from (25,000 to 50,000), (50,000 to 100,000) and (100,000 to 150,000) respectively. The results also indicated that the AP impacts is increased by 20 % by increasing the AADT from (10,000-25,000), However the emissions are increased by 17%, 21% and 6% by increasing the AADT from (25,000 to 50,000), (50,000 to 100,000) and (100,000 to 150,000) respectively. The EP impacts is also increased by 14% by changing the AADT from (10,000-25,000) and are increased by 20%, 17% and 9% by changing AADT from (25,000 to 50,000), (50,000 to 100,000) and (100,000 to 150,000) respectively. It also observed that POFP impacts are increased by 16 %, 21%, 17%, 8% by changing AADT from (10,000-25,000), (25,000 to 50,000), (50,000 to 100,000) and (100,000 to 150,000) respectively.

Fig. 10 shows the environmental impacts of flexible pavement design methods for different AADT (10-25-50-100-150) (Veh / day) x 10^3 with constant value of CBR 15%. The results observed that by increasing the AADT from 10,000-25,000 veh / day the GWP and HTP impacts are increased by 17% and are increased by 10%, 18% and 11% by increasing the AADT from (25,000 to 50,000), (50,000 to 100,000) and (100,000 to 150,000) respectively. The ADP impacts is increased by 18 % when changing AADT from (10,000-25,000) and the emissions are increased by 8%, 21% and 12% by increasing the AADT from (25,000 to 50,000), (50,000 to 100,000) and (100,000 to 150,000) respectively. The results also indicated that the AP impacts is increased by 17 % by increasing the AADT from (10,000-25,000), However the emissions are increased by 9%, 17% and 14% by increasing the AADT from (25,000 to 50,000), (50,000 to 100,000) and (100,000 to 150,000) respectively. The EP impacts is also increased by 13% by changing the AADT from (10,000-25,000) and are increased by 13%, 15% and 10% by changing AADT from (25,000 to 50,000), (50,000 to 100,000) and (100,000 to 150,000) respectively. It also observed that POFP impacts are increased by 13%, 12%, 18%, 11% by changing AADT from (10,000-25,000), (25,000 to 50,000), (50,000 to 100,000) and (100,000 to 150,000) respectively.

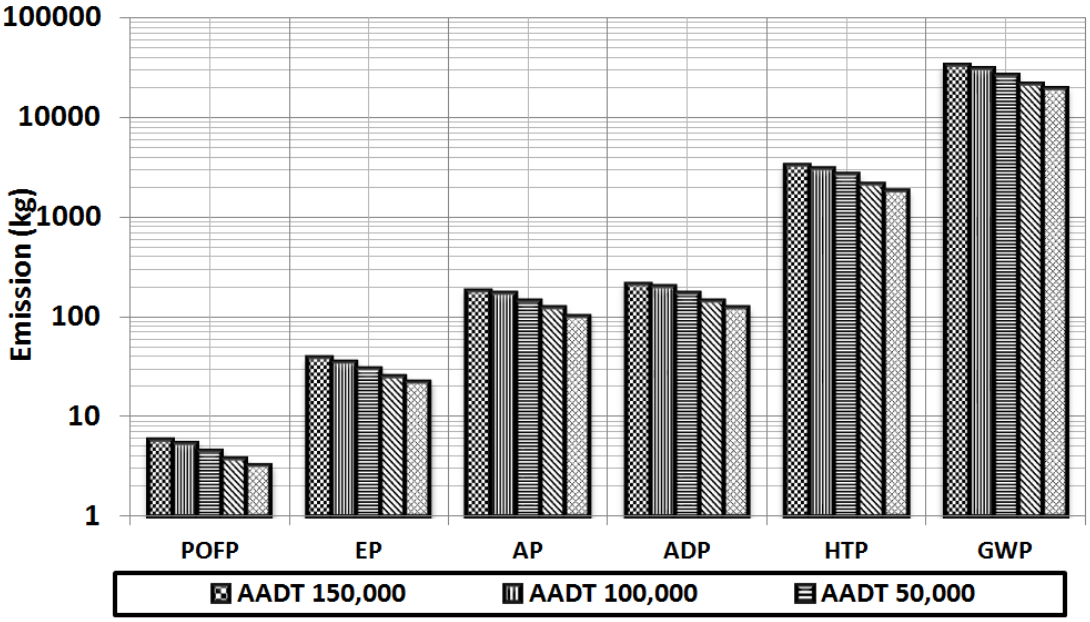

Fig. 9. Environmental impacts of different AADT and CBR 10% on flexible pavement design method

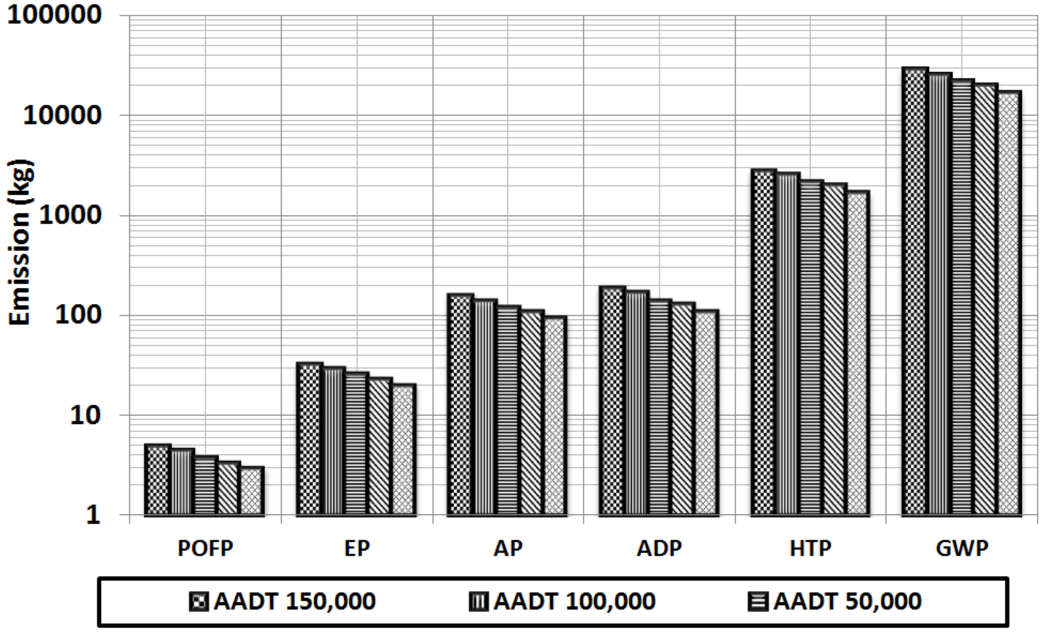

Fig. 10. Environmental impacts of different AADT and CBR 15% on flexible pavement design method

The results observed that the overall impacts of flexible pavement by increasing AADT from (10,000 to 25,000) veh/day at CBR 3% are increased by 10%, However these impacts are increased by 4%, 10% and 5% by increasing the AADT from (25,000 to 50,000), (50,000 to 100,000) and (100,000 to 150,000) veh/day respectively. The overall impacts at CBR 6% and by increasing AADT from (10,000 to 25,000) veh/day are increased by 22% and also increased by 10%, 3% and 6% by increasing AADT from (25,000 to 50,000), (50,000 to 100,000) and (100,000 to 150,000) veh/day respectively. The overall impacts at CBR 10% and by changing AADT from (10,000 to 25,000) veh/day are increased by 10% and increased by 20%, 14% and 7% by increasing AADT from (25,000 to 50,000), (50,000 to 100,000) and (100,000 to 150,000) veh/day respectively. Where the overall impacts of at CBR 15% and by increasing AADT from (10,000 to 25,000) veh/day are increased by 15% and increased by 10%, 16% and 10% by increasing AADT from (25,000 to 50,000), (50,000 to 100,000) and (100,000 to 150,000) veh/day respectively.

3.2 Effect of Changing AADT on the Road Design

The following figures indicated the results of the environmental impacts of changing AADT with different CBR (3-5-10-15%) of flexible pavement design methods.

Fig. 11 indicates the environmental impacts of flexible pavement design methods for different CBR from (3-15)%, with constant value of AADT of 10,000 veh / day. The results indicate that by changing CBR from (3% to 6%), the emissions of GWP and HTP impacts of HMA are decreased by 28% and by increasing CBR from (6% to 10%) the emissions decreased by 14 %, while by increasing the CBR from (10% to 15%) the emissions of GWP and HTP impacts are decreased by 11%. By changing the CBR from (3% to 6%), the ADP impacts is decreased by 26%, where the ADP impacts is decreased by 14% and 8% for increasing CBR from (6% to 10%) and (10% to 15%) respectively. The AP impacts is decreased by 25% by increasing the CBR from (3% to 6%) and decreased by 17% and 6% by increasing the CBR from (6% to 10%) and (10% to 15%) respectively .However, By changing the CBR from (3% to 6%), the EP impacts is decreased by 24 % and is decreased by 12% and 9% for increasing CBR from (6% to 10%) and (10% to 15)% respectively. The POFP impacts is decreased by 26% by increasing the CBR from (3% to 6%) and decreased by 14% and 6% by increasing the CBR from (6% to 10%) and (10% to 15%) respectively.

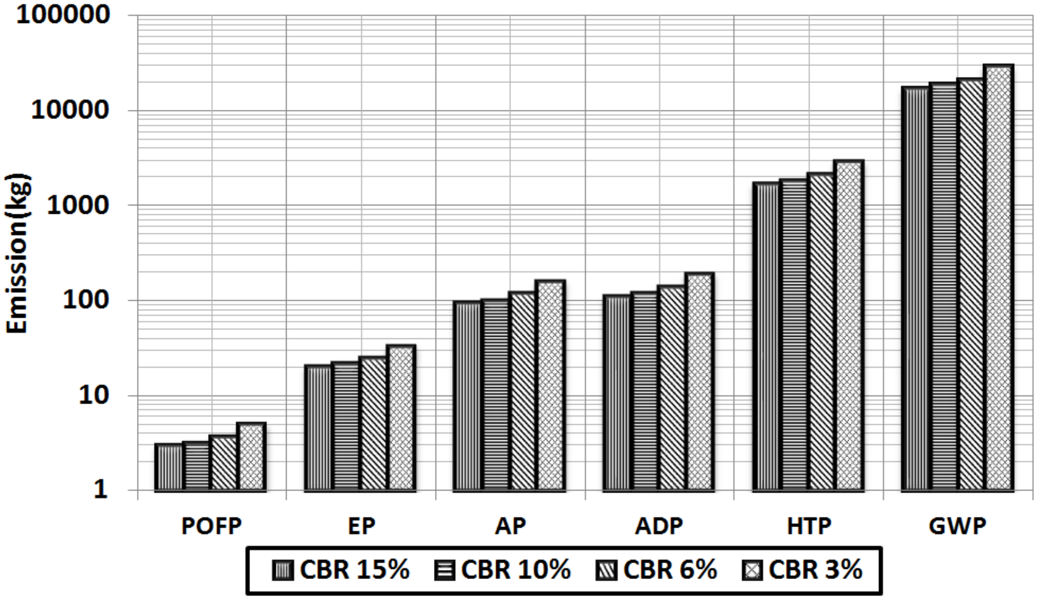

Fig. 11. Environmental impacts of different CBR and AADT 10,000 veh/day on flexible pavement design method

Fig. 12 indicates the environmental impacts of flexible pavement design methods for different CBR from (3-15)%, with constant value of AADT of 25,000 veh/day. The results indicate that by changing CBR from (3% to 6%), the emissions of GWP and HTP impacts of HMA are decreased by 16% and by increasing CBR from (6% to 10%) the emissions decreased by 22%, while by increasing the CBR from (10% to 15%) the emissions of GWP and HTP impacts are decreased by 7%. By changing the CBR from (3% to 6%), the ADP impacts is decreased by 14%, where the ADP impacts is decreased by 22% and 7% for increasing CBR from (6% to 10%) and (10% to 15%) respectively. The AP impacts is decreased by 16% by increasing the CBR from (3% to 6%) and decreased by 20% and 8% by increasing the CBR from (6% to 10%) and (10% to 15%) respectively. However, By changing the CBR from (3% to 6%), the EP impacts is decreased by 15 % and is decreased by 21% and 8% for increasing CBR from (6% to 10%) and (10% to 15%) respectively. The POFP impacts is decreased by 16% by increasing the CBR from (3% to 6%) and decreased by 21% and 8% by increasing the CBR from (6% to 10%) and (10% to 15%) respectively.

Fig. 13 indicates the environmental impacts of flexible pavement design methods for different CBR from (3-15)%, with constant value of AADT of 50,000 veh/day. The results indicate that by changing CBR from (3% to 6%), the emissions of GWP and HTP impacts of HMA are decreased by 6% and by increasing CBR from (6% to 10%) the emissions decreased by 16%, while by increasing the CBR from (10% to 15%) the emissions of GWP and HTP impacts are decreased by 15%. By changing the CBR from (3% to 6%), the ADP impacts is decreased by 9 %, where the ADP impacts is decreased by 15 % and 17 % for increasing CBR from (6% to 10%) and (10% to 15%) respectively. The AP impacts is decreased by 6% by increasing the CBR from (3% to 6%) and decreased by 18% and 14% by increasing the CBR from (6% to 10%) and (10% to 15%) respectively .However, By changing the CBR from (3% to 6%), the EP impacts is decreased by 5 % and is decreased by 19 % and 13 % for increasing CBR from (6% to 10%) and (10% to 15%) respectively. The POFP impacts is decreased by 5% by increasing the CBR from (3% to 6%) and decreased by 18% and 14% by increasing the CBR from (6% to 10%) and (10% to 15%) respectively.

Fig. 14 indicates the environmental impacts of flexible pavement design methods for different CBR from (3-15)%, with constant value of AADT of 100,000 veh/day. The results indicate that by changing CBR from (3% to 6%), the emissions of GWP and HTP impacts of HMA are decreased by 13% and by increasing CBR from (6% to 10%) the emissions decreased by 6%, while by increasing the CBR from (10% to 15&) the emissions of GWP and HTP impacts are decreased by 13%. By changing the CBR from (3% to 6%), the ADP impacts is decreased by 13%, where the ADP impacts is decreased by 5% and 15% for increasing CBR from (6% to 10%) and (10% to 15)% respectively. The AP impacts is decreased by 10% by increasing the CBR from (3% to 6%) and decreased by 6% and 17% by increasing the CBR from (6% to 10%) and (10% to 15%) respectively. However, By changing the CBR from (3% to 6%), the EP impacts is decreased by 11% and is decreased by 8 % and 14 % for increasing CBR from (6% to 10%) and (10% to 15) % respectively. The POFP impacts is decreased by 13% by increasing the CBR from (3% to 6%) and decreased by 5% and 15% by increasing the CBR from (6% to 10%) and (10% to 15%) respectively.

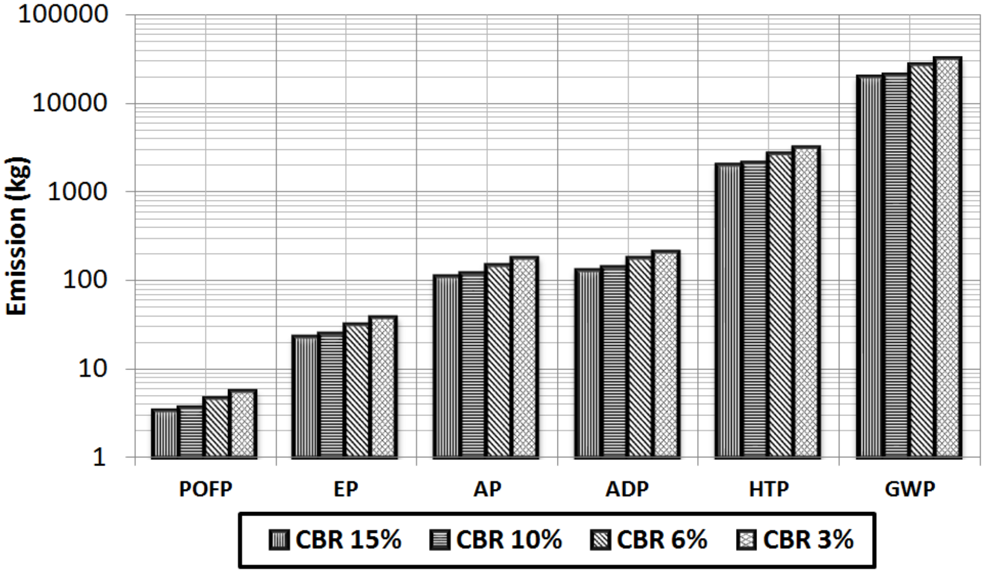

Fig. 12. Environmental impacts of different CBR and AADT 25,000 veh/day on flexible pavement design method

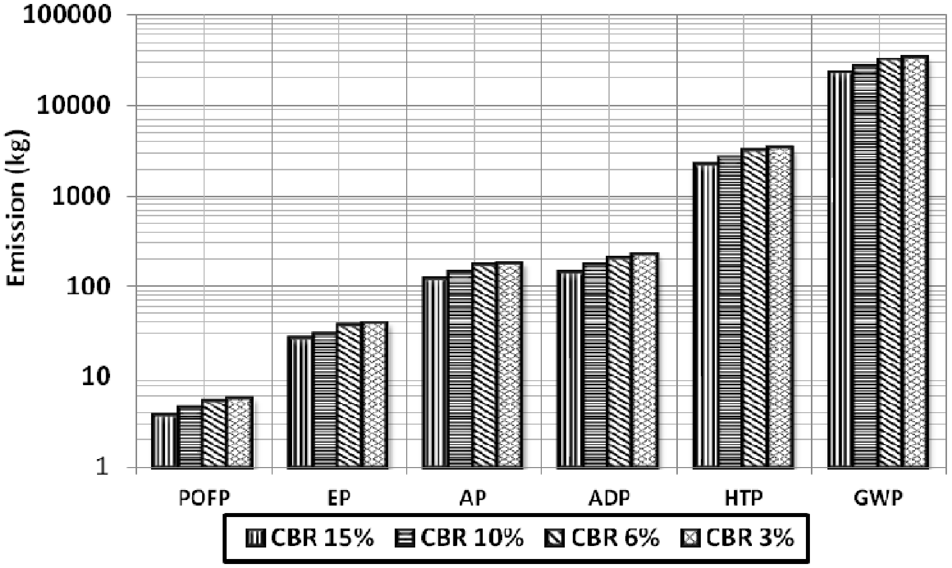

Fig. 13. Environmental impacts of different CBR and AADT 50,000 veh/day on flexible pavement design method

Fig. 15 indicates the environmental impacts of flexible pavement design methods for different CBR from (3-15)%, with constant value of AADT of 150,000 veh/day. The results indicate that by changing CBR from (3% to 6%), the emissions of GWP and HTP impacts of HMA are decreased by 13% and by increasing CBR from (6% to 10%) the emissions decreased by 6%, while by increasing the CBR from (10% to 15) the emissions of GWP and HTP impacts are decreased by 10%. By changing the CBR from (3% to 6%), the ADP impacts is decreased by 15%, where the ADP impacts is decreased by 5% and 11% for increasing CBR from (6% to 10%) and (10% to 15%) respectively.

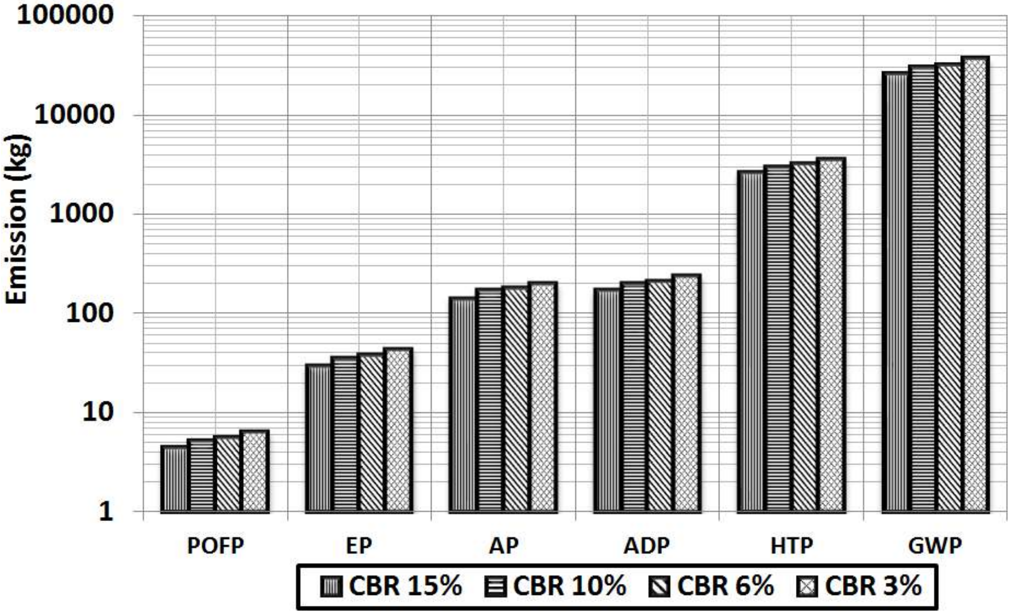

Fig. 14. Environmental impacts of different CBR and AADT 100,000 veh/day on flexible pavement design method

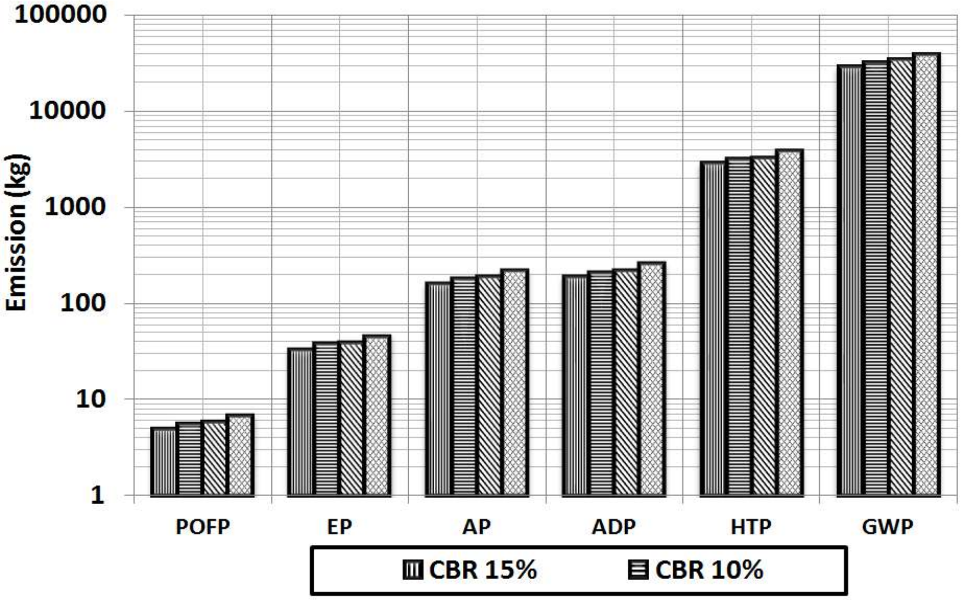

Fig. 15. Environmental impacts of different CBR and AADT 150,000 veh/day on flexible pavement design method

The AP impacts is decreased by 13% by increasing the CBR from (3% to 6%) and decreased by 5% and 11% by increasing the CBR from (6% to 10%) and (10% to 15) respectively. However, by changing the CBR from (3% to 6%), the EP impacts is decreased by 15% and is decreased by 3% and 13% for increasing CBR from (6% to 10%) and (10% to 15%) respectively. The POFP impacts is decreased by 14% by increasing the CBR from (3% to 6%) and decreased by 4% and 13% by increasing the CBR from (6% to 10%) and (10% to 15%) respectively.

The results indicated that, by increasing the CBR from (3-15)% of flexible pavement design methods at AADT 10,000 veh / day, that the overall environmental emissions are decreased by 25%. While the emissions are decreased by 10% by changing CBR from (6% to 10%) and - (10% to 15%). The overall impacts at AADT 25,000 veh / day and by changing CBR from (3% to 6%) are decreased by 16% and by 22% and 5% for changing CBR from (6% to 10%) and (10% to 15%) respectively. At AADT 50,000 veh/day, the overall impacts of pavement by changing CBR from (3% to 6%) are decreased by 6%. The impacts are also decreased by 16% by changing CBR from (6% to 10%) and (10% to 15%). Where at AADT 100,000 veh/day, the overall impacts are decreased by 37% by changing CBR from (3% to 6%) and decreased by 6% and 13% by changing CBR from (6% to 10%) and (10% to 15%) respectively. The overall impacts at AADT 150,000 veh / day and by increasing CBR from (3% to 6%) are decreased by 23% and decreased by 6% and 10% by increasing CBR from (6% to 10%) and (10% to 15%) respectively.

4. CONCLUSION

The application of pavement LCA can quantify the total of environmental impacts occurred from all phases in the pavement life cycle. The pavement life cycle start from acquire raw materials from the nature to produce a product and finish by sending back the product to the nature. LCA-based tool was developed and implemented in a spreadsheet software application to estimate the environmental impacts of flexible asphalt pavement design methods with different CBR and Traffic volume values.

The study proposes to incorporate LCA for the impacts of flexible pavement construction methods without the pavement maintenance and recycle. The life cycle of flexible road pavements construction of the following major stages are investigated:

- Materials, including extraction and processing of bitumen, filler, aggregates and also transportation of materials to the asphalt plant.
- Asphalt production, including land use, infrastructure and machinery, fuel and electricity consumption and air emissions from the asphalt plant.
- Transportation of asphalt mixes to the construction site.
- Construction, including fuel consumption and air emissions from asphalt paving machinery, air emissions.

Six environmental impacts categories of nine scenarios of flexible pavement methods are investigated by using the LCA-based tool. The scenarios are formed by changing of CBR and Traffic volume values. The main results can be concluded as following:

- Flexible pavement had adverse effect on environmental while impact categories that produce high emission is GWP.
- Transportation stage of material is the element which caused most of the impacts, with a contribution to the overall impact ranging between 85% and 90%.
- LCA is a fantastic tool which will be useful to the decision makers in Egypt to improvement performance of flexible pavement construction.

By using the existing results and information of flexible pavement LCA study can help to create more feasible and comprehensive methods that focus more in decreasing the environmental impact extensively. The results will certainly help to increase the environmental performance of roads construction and guide transportation department and authorities towards road sustainability management.

COMPETING INTERESTS

Authors have declared that no competing interests exist.

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