Life Cycle Assessment and benchmarking of end of life treatments of flexible pavements in California

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ABSTRACT: Pavement life cycle stages include materials, construction, maintenance and rehabilitation, use, and end-of-life (EOL). The least studied stage in pavement life cycle assessment (LCA) studies has been the EOL stage. Currently the options for EOL are recycling (in-place and in-plant) and landfilling. Recycling has always been closely linked to environmental stewardship and this, added to the scarcity of virgin materials resources in parts of California, has resulted in Caltrans aggressively pursuing recycling in their pavement projects. However, there are limited and unreliable data for quantifying the environmental impacts of EOL treatments. This paper provides benchmarking of alternative EOL treatments in California by developing locally-representative models for material production and simulating state of the practice construction activities in the state through field investigations and communication with contractors and experts.

1 INTRODUCTION

Sustainable transport infrastructure is a major area of focus for Caltrans as stated in its mission and has resulted in Caltrans pursuing innovative materials and construction processes in their projects for many years. As pavements reach their end-of-life (EOL), there are multiple options available amongst which recycling is becoming more popular due to the general perception of recycling as a more sustainable alternative than using new materials. Moreover, virgin aggregate sources have also become scarce in many parts of California. For a better understanding of performance of different alternatives in terms of sustainability, objective quantification of their environmental impacts throughout their life cycle is needed.

Life cycle assessment (LCA) can be considered as a suitable tool for such purposes, and can answer a wide range of questions regarding pavements (Harvey et al., 2015). This paper uses LCA methodology for benchmarking the environmental impacts of the current methods in practice for flexible pavements at their EOL in California. The methods considered for recycling are in place recycling (cold in-place and full depth reclamation, with different additives and asphalt wearing courses on top) versus conventional methods such as asphalt overlay and mill-and-fill.

2 LIFE CYCLE ASSESSMENT FRAMEWORK

2.1 *Goal and Scope Definition*

The goal of this LCA study is to quantify the environmental impacts of the current EOL treatments in use for flexible pavements through a benchmark study. The intended application is to provide an estimate of how different alternatives perform in terms of the environmental impacts during material production, transportation, and construction stages. As this range does not cover the full life cycle of the alternatives, no comparison is made between treatments. Therefore, an attributional LCA, and not a comparative LCA, was conducted on a matrix of alternative treatments for EOL of flexible pavements in California. Table 1 shows the EOL treatments considered in this study.

Table 1. The EOL treatments considered in this study

#	Item
1	CIR (10 cm milled + Mech. Stab.) w. 2.5 cm of HMA OL
2	CIR (10 cm milled + Mech. Stab.) w. Chip Seal
3	FDR (25 cm milled + no stabilization) w. 6 cm RHMA OL
4	FDR (25 cm milled + 4% AE + 1% PC) w. 6 cm RHMA OL
5	FDR (25 cm milled + 3% FA + 1% PC) w. 6 cm RHMA OL
6	FDR (25 cm milled + 2% PC) w. 6 cm RHMA OL
7	FDR (25 cm milled + 4% PC) w. 6 cm RHMA OL
8	FDR (25 cm milled + 6% PC) w. 6 cm RHMA OL
9	HMA Overlay (7.5 cm)
10	HMA Mill & Fill (10 cm)

Mech. Stab.: mechanical stabilization
CIR: cold in-place recycling
FDR: full-depth reclamation
AE: asphalt emulsion
FA: foamed asphalt
OL: overlay
PC: portland cement
RHMA: rubberized hot mix asphalt (gap-graded)
Mill & Fill: milling of a portion of existing asphalt followed by overlay of thickness shown

The intended audience is Caltrans, local government transportation agencies in California, and other agencies for which the results may be applicable. The location of use is limited to the state of California and other environments using similar practices and materials, and the functional unit of the study is one ln-km of pavement. The physical boundary only includes the traveled lanes and not the shoulders. As the system boundary only includes the material production and construction stages, the analysis period is selected to be one year. For the functional unit of one ln-km, the LCI of each of the EOL treatment includes the following life cycle stages:

- Material production
- Transportation of the materials to the site
- Construction activities

The material production inventories are cradle-to-gate for all the materials used in the construction. This means that the LCI includes the energy consumption and emissions of all the processes during: raw material acquisition from the ground, transport to the plant, and further processing of raw materials in the plant until they are ready to be shipped at the gate. The models represent the conditions, technologies, and practices used in local plants and construction processes to the extent possible. For each of the construction materials, models were developed in GaBi^{TM} (2015) and energy sources in the model were calibrated to represent the local conditions in terms of electricity grid mix and fuel type used in plant, which is natural gas in California. The grid mix was taken from the California Energy Almanac website, the table for year 2012 is reproduced here as **Error! Reference source not found.**.

Table 2. Electricity grid mix in California in year 2012 (Energy Almanac website)

Fuel Type	Percent in California Power Mix
Coal	7.50%
Large Hydro	8.30%
Natural Gas	43.40%

Nuclear	9.00%
Oil	0.00%
Other	0.00%
Renewables	15.40%
Biomass	2.30%
Geothermal	4.40%
Small Hydro	1.50%
Solar	0.90%
Wind	6.30%
Unspecified	16.40%

For all the treatments, an 80 km transport distance was assumed for transportation of the materials to the site, which is typical in the state. It was assumed that heavy trucks (24 tonnes gross vehicle weight) are used.

The combustion of fuel in construction equipment plus the electricity and other energy sources used on site contribute to the impacts in the construction stage. To capture the energy consumption and emissions of the construction activities, the construction process was closely simulated for each of the in-place recycling techniques and the conventional rehabilitation methods. Figure 1 shows the flowchart for developing the LCI models for construction activities.

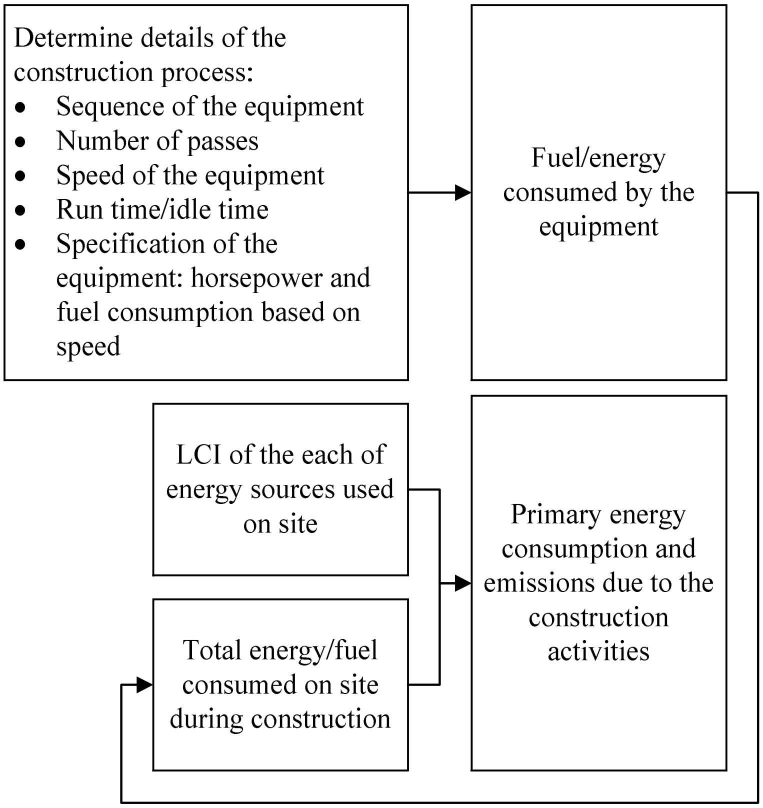

Figure 1. Flowchart used for developing LCI and LCIA of the construction activities

Mix design and construction processes for each of the treatments were taken from Caltrans' Maintenance Technical Advisory Guide (MTAG) (Caltrans 2007) and through field investigations and inquiries from personal observation of the authors and local contractors and experts.

The mix designs for the wearing surface were taken from Wang et al. (2012) and are typical of California practice.

The whole database developed under this study and previous LCA studies performed at the University of California Pavement Research Center (UCPRC) went through critical review, and was recently verified by a 3rd party committee. The details of all the assumptions and final results are available in the documentation of the UCPRC LCI database (Saboori et al., in prep.).

This study follows the US EPA TRACI 2.1 methodology (Bare 2012) for impact assessment. Main areas of concern are primary energy demand (PED), global warming potential (GWP), and air quality (ground-level ozone creation and particulate matter: PM2.5). Table 3 shows the LCI and LCIA items that are reported in this study.

Table 3. Impact categories and inventories reported in this study

Impact Category/Inventory	Abbreviation	Unit
Global Warming Potential	GWP	kg of $CO_{2\text{-e}}$
Photochemical Ozone Creation (Smog) Potential	POCP	kg of $O_{3\text{-e}}$
Particulate Matter less than 2.5 μm	PM2.5	kg
Primary Energy Demand from Renewable & Non-Renewable Resources, fuel (net calorific value)	PED (total)	MJ
Primary Energy Demand from Non-Renewable Resources, fuel (net calorific value)	PED	MJ
Primary Energy Demand from Non-Renewable Resources, non-fuel (feedstock) (net calorific value)	FE	MJ

3 RESULTS AND DISCUSSION

In this section the total impacts for each of the treatments are shown and discussed. Total impacts are the summation of the impacts for each indicator across the three stages discussed in the previous section: material production, transport to the site, and construction. Table 4 shows the summary of the total impacts for each of the EOL treatments.

Table 5 shows the percentage share of each of the life cycle stages on the total impacts.

Table 4. Summary of the total impacts for each of the EOL treatments for 1 ln-km

Surface Treatment	GWP [kg CO_{2-e}]	POCP [kg O_{3-e}]	PM2.5 [kg]	PED (total), Fuel [MJ]	PED (non-ren), Fuel [MJ]	PED (non-ren), Non-Fuel [MJ]
CIR (10 cm milled + Mech. Stab.) w. 2.5 cm of HMA OL	1.64E+04	3.15E+03	1.09E+01	6.26E+05	6.20E+05	3.57E+05
CIR (10 cm milled + Mech. Stab.) w. Chip Seal	7.65E+03	2.23E+03	5.83E+00	4.01E+05	3.97E+05	1.62E+07
FDR (25 cm milled + no stabilization) w. 6 cm RHMA OL	4.20E+04	6.20E+03	2.74E+01	2.01E+06	1.98E+06	9.64E+07
FDR (25 cm milled + 4% AE + 1% PC) w. 6 cm RHMA OL	1.16E+05	1.52E+04	7.57E+01	6.67E+06	6.59E+06	3.11E+08
FDR (25 cm milled + 3% FA + 1% PC) w. 6 cm RHMA OL	1.02E+05	1.33E+04	6.60E+01	5.45E+06	5.40E+06	2.57E+08
FDR (25 cm milled + 2% PC) w. 6 cm RHMA OL	9.87E+04	9.48E+03	4.96E+01	2.27E+06	2.23E+06	9.64E+07
FDR (25 cm milled + 4% PC) w. 6 cm RHMA OL	1.55E+05	1.28E+04	7.19E+01	2.54E+06	2.48E+06	9.64E+07
FDR (25 cm milled + 6% PC) w. 6 cm RHMA OL	2.12E+05	1.60E+04	9.41E+01	2.81E+06	2.73E+06	9.64E+07
HMA Overlay (7.5 cm)	3.80E+04	4.48E+03	2.39E+01	1.72E+06	1.71E+06	3.57E+05
HMA Mill & Fill (10 cm)	5.13E+04	6.24E+03	3.23E+01	2.31E+06	2.28E+06	3.57E+05

Table 5. Share of each of the life cycle stages of the total impacts for each of the EOL treatments

Item	Life Cycle Stage	GWP [kg $CO_{2\text{-}e}$]	POCP [kg $O_{3\text{-}e}$]	PM2.5 [kg]	PED (total), Fuel [MJ]	PED (non-ren), Fuel [MJ]
CIR (10 cm milled + Mech. Stab.) w. 2.5 cm of HMA OL	Material	64%	31%	64%	87%	87%
	Transport	8%	7%	4%	3%	3%
	Construction	27%	62%	32%	10%	10%
	Total	100%	100%	100%	100%	100%
CIR (10 cm milled + Mech. Stab.) w. Chip Seal	Material	48%	27%	50%	86%	86%
	Transport	6%	3%	3%	2%	2%
	Construction	46%	70%	48%	12%	12%
	Total	100%	100%	100%	100%	100%
FDR (25 cm milled + no stabilization) w. 6 cm RHMA OL	Material	79%	53%	81%	94%	94%
	Transport	8%	9%	4%	2%	2%
	Construction	13%	39%	16%	4%	4%
	Total	100%	100%	100%	100%	100%
FDR (25 cm milled + 4% AE + 1% PC) w. 6 cm RHMA OL	Material	92%	80%	93%	98%	98%
	Transport	3%	4%	2%	1%	1%
	Construction	5%	16%	6%	1%	1%
	Total	100%	100%	100%	100%	100%
FDR (25 cm milled + 3% FA + 1% PC) w. 6 cm RHMA OL	Material	91%	77%	92%	98%	98%
	Transport	4%	5%	2%	1%	1%
	Construction	5%	18%	6%	1%	1%
	Total	100%	100%	100%	100%	100%
FDR (25 cm milled + 2% PC) w. 6 cm RHMA OL	Material	91%	69%	89%	94%	94%
	Transport	4%	6%	2%	2%	2%
	Construction	6%	25%	9%	3%	3%
	Total	100%	100%	100%	100%	100%
FDR (25 cm milled + 4% PC) w. 6 cm RHMA OL	Material	94%	76%	92%	95%	95%
	Transport	2%	5%	2%	2%	2%
	Construction	4%	19%	6%	3%	3%
	Total	100%	100%	100%	100%	100%
FDR (25 cm milled + 6% PC) w. 6 cm RHMA OL	Material	95%	81%	94%	95%	95%
	Transport	2%	4%	1%	2%	2%
	Construction	3%	15%	5%	3%	3%
	Total	100%	100%	100%	100%	100%
HMA Overlay (7.5 cm)	Material	84%	65%	88%	95%	95%
	Transport	11%	15%	6%	3%	3%
	Construction	6%	21%	7%	2%	2%
	Total	100%	100%	100%	100%	100%
HMA Mill & Fill (10 cm)	Material	83%	62%	86%	95%	94%
	Transport	11%	14%	5%	3%	3%
	Construction	7%	24%	8%	2%	2%
	Total	100%	100%	100%	100%	100%

The results indicate that the material production stage is dominant in all of the impact categories for all the EOL treatments material except for POCP of CIR treatments where the construction stage is the main source of the impacts. Transportation has the lowest share of the impacts in all categories for all the in-place recycling treatments but this is not the case for the conventional rehabilitation methods in which construction and transportation have close shares in most categories.

Between the treatments, the GWP for one ln-km ranged between 7.65e3 and 2.12e5 kg of $CO_{2\text{-}e}$. The contribution of the material production stage to GWP ranged between 48% and 95%.

Photochemical ozone creation potential, indicator of smog formation, was the only category in which material production stage was not the dominant source of emission across all the treatments. This indicator varied between 2.23e3 to 1.60e4 kg of $O_{3\text{-}e}$ and the material production share of the total emissions in this category ranged between 27% and 81%. The construction stage POCP were higher than those of the material production stage only for the CIR treatments, with values of 62% and 70% for CIR with HMA overlay and CIR with chip seal overlay, respectively.

PM2.5 emissions for all the treatments was mainly due to the material production stage, ranging from 5.83 to 94.1 kg for one ln-km of treatment and a range of 50% to 94% share of the total. For the CIR treatments, construction activities had the largest share among all treatments, between 32% and 48%.

Total primary energy demand for all treatments ranged between 3.97e5 to 4.77e6 MJ for one ln-km of pavement and was mainly due to the material production stage, with a share of 87% to 95% across all the treatments.

3.1 *Sensitivity Analysis on the Transportation Distance*

A sensitivity analysis was conducted on travel distance to see how it impacts the final results. The model was run under 80 and 160 km for the transport distance and the percent increases in each of the impact categories were calculated for each of the EOL treatments. As Table 6 shows, the increase in emissions are higher for the conventional methods where more materials are transported to the site, therefore the total impacts of those treatments are more affected by the transportation distance. The increase for the POCP is highest, 15%, for the HMA overlay.

Table 6. Increase in total impacts as the transport distance is increased from 80 to 160 km

Surface Treatment	GWP [kg CO2e]	POCP [kg O3e]	PM2.5 [kg]	PED (total), Fuel [MJ]	PED (non-ren), Fuel [MJ]
CIR (10 cm milled + Mech. Stab.) w. 2.5 cm of HMA OL	8%	7%	4%	3%	3%
CIR (10 cm milled + Mech. Stab.) w. Chip Seal	6%	3%	3%	2%	2%
FDR (25 cm milled + no stabilization) w. 6 cm RHMA OL	8%	9%	4%	2%	2%
FDR (25 cm milled + 4% AE + 1% PC) w. 6 cm RHMA OL	3%	1%	0%	1%	1%
FDR (25 cm milled + 3% FA + 1% PC) w. 6 cm RHMA OL	4%	1%	0%	2%	2%
FDR (25 cm milled + 2% PC) w. 6 cm RHMA OL	4%	6%	2%	2%	2%
FDR (25 cm milled + 4% PC) w. 6 cm RHMA OL	3%	5%	2%	2%	2%
FDR (25 cm milled + 6% PC) w. 6 cm RHMA OL	2%	4%	1%	2%	2%
HMA Overlay (7.5 cm)	11%	15%	6%	3%	3%
HMA Mill & Fill (10 cm)	11%	14%	5%	3%	3%

4 CONCLUSIONS AND FUTURE WORKS

This study was conducted to benchmark the environmental impacts of some of the common EOL treatments used in California for flexible pavements at their end of service life. The system boundary consists of material production, transport to the site, and construction activities and does not include the other life cycle stages such as use stage, maintenance and rehabilitation in the future, and traffic delays during construction. Ten treatments were considered consisting of eight in-place recycling (CIR and FDR with different stabilization methods and wearing courses on top) and two conventional treatments (HMA overlay and HMA mill-and-fill).

There are large variabilities between treatments in each of the impact categories studied in this research but as discussed earlier due to limited scope of the study and the fact that the system boundary of the study does not include all life cycle stages, no comparison can be made between treatments until the full life cycle is assessed, including performance in the use stage and subsequent EOL.

The results show that for all treatments and all impact categories that material production is the main contributing factor, the only exception being POCP of CIR treatments in which construction had a larger share of the total impacts. The findings of this study provides an estimate of the environmental impacts of alternative EOL treatments for flexible pavements in California and the percentage share of each of the life cycle stages considered.

From a pavement management perspective, it is ideal to have an LCA tool that can supplement the life cycle cost analysis in comparing possible alternatives for pavements at their EOL. The findings of this study cannot provide such information as the system boundary defined in the goal and scope definition is not inclusive of the whole life cycle of the treatments, and therefore comparing treatments is not possible. There are unsolved questions regarding:

- How does pavement surface roughness, which directly affects vehicle fuel consumption, change with time under each treatment?
- How does cracking initiation and propagation, that determines future maintenance and rehabilitation frequency and the section service life, differ between alternatives?

What is needed for modeling the use stage, future maintenance and rehabilitation frequencies, and service life of each treatment, is performance models. At this point the effect of recycling treatments on the performance of the section is not fully understood. The next stage of this study will focus on developing the performance models for the common EOL treatments in California so that fair comparison can be made between alternatives. Figure 2 shows how these prediction models will be used to provide the required information for completing the LCA model to conduct a comparative LCA study between EOL treatments. The LCA study to be done in the next step of this project will follow the flowchart presented in Figure 3.

The final step will be to combine the LCA and life cycle costs for the alternative treatments to provide recommendations to Caltrans and local governments.

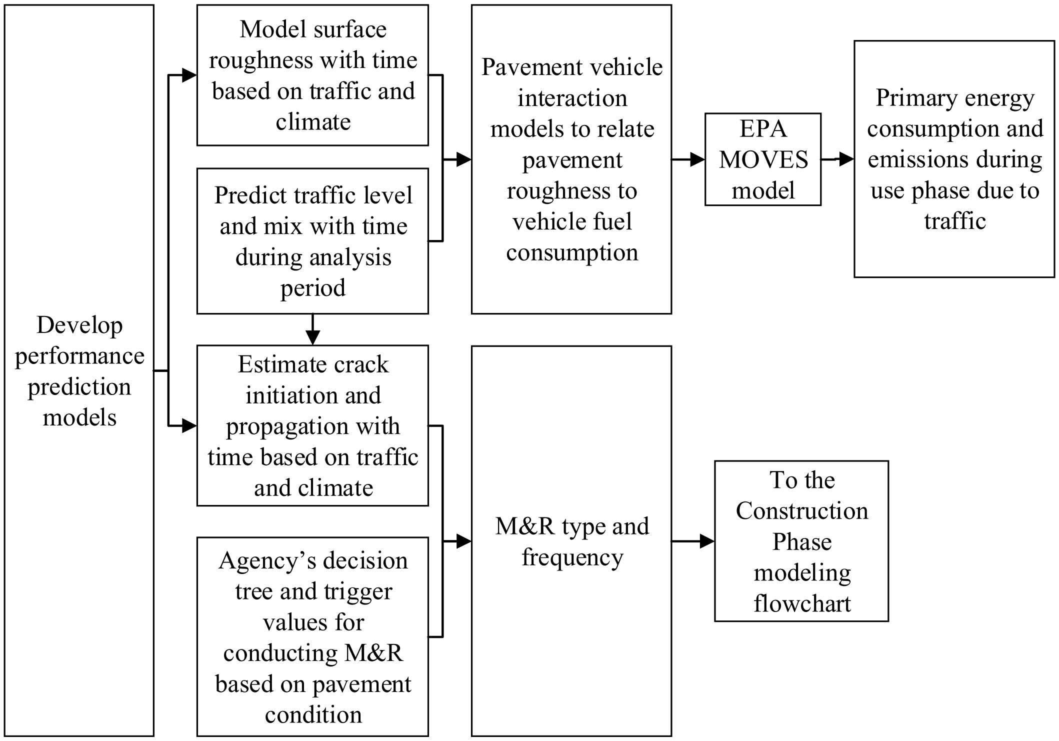

Figure 2. Flowchart of implications of developing the performance models to complete the LCA model for doing comparative LCA between EOL treatments

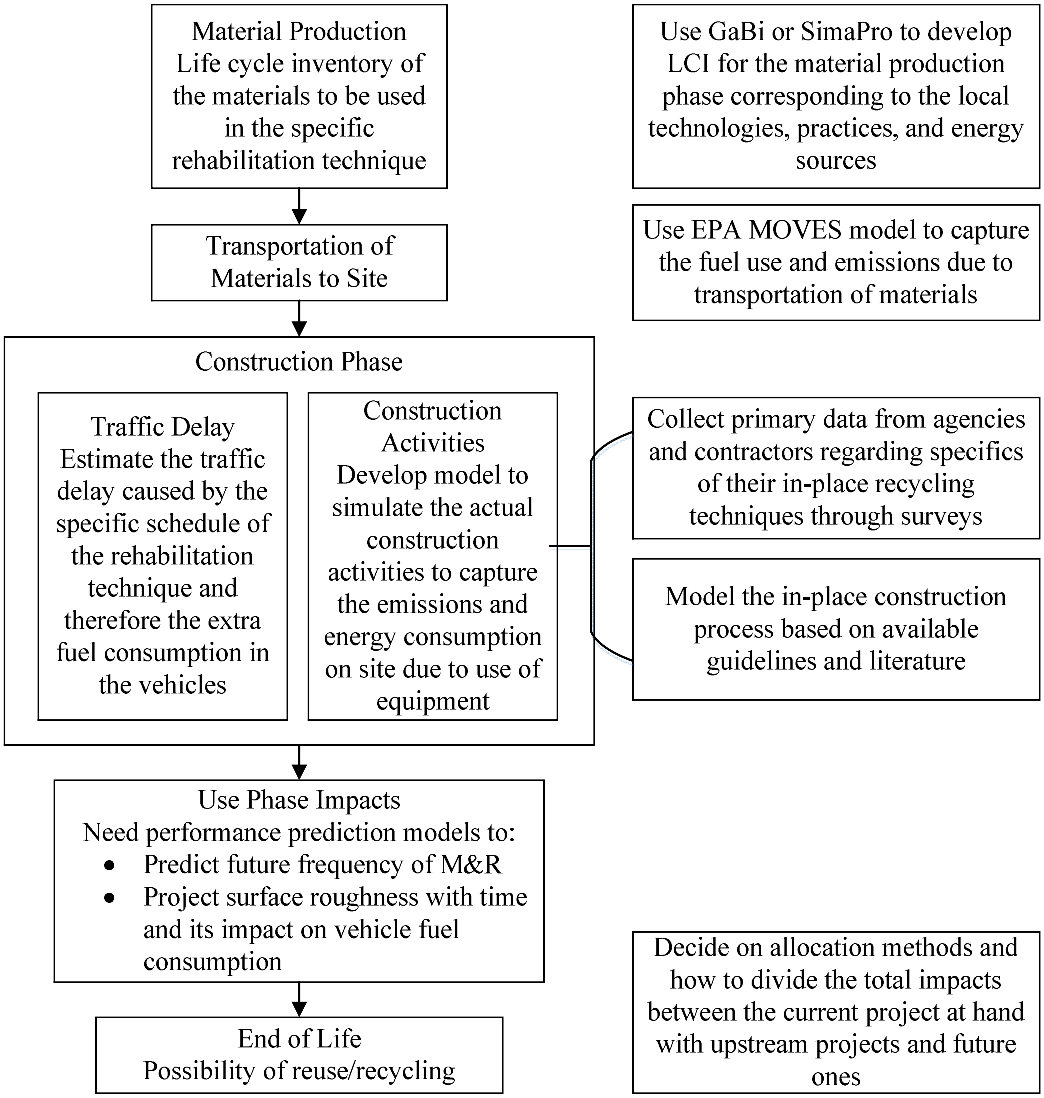

Figure 3. Flowchart of the approach to be used in the comparative LCA study between the EOL treatments.

5 ACKNOWLEDGEMENTS

The research presented in this paper was requested and sponsored by the California Department of Transportation (Caltrans). Caltrans sponsorship of that work is gratefully acknowledged. Special thanks are for Nick Burmas, Joe Holland, and Deepak Maskey for their support for and contributions to this research project. The contents of this paper reflect the views of the authors and do not necessarily reflect the official views or policies of the State of California, or the Federal Highway Administration.

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