

# Life cycle assessment of asphalt pavements using crumb rubber: a comparative analysis

Zhengyin Piao<sup>1,2</sup>, Moises Bueno<sup>1</sup>, Peter Mikhailenko<sup>1</sup>, Muhammad Rafiq Kakar<sup>1</sup>, Davide Biondini<sup>2</sup>, Lily Poulikakos<sup>1</sup>, Stefanie Hellweg<sup>2</sup>

<sup>1</sup> Empa, Swiss Federal Laboratories for Materials Science and Technology, Switzerland

<sup>2</sup> ETHZ, Swiss Federal Institute of Technology in Zurich, Switzerland

zhengyin.piao@empa.ch  
Lily.Poulikakos@empa.ch  
stefanie.hellweg@ifu.baug.ethz.ch

**Abstract.** Using crumb rubber (CR) as a performance enhancing additive to asphalt mixtures is an increasingly popular method to improve pavement properties and make material use of waste tires. However, the ecological benefits/losses of CR asphalt pavements have not yet been assessed in Switzerland. This study investigates the climate change impacts and cumulated energy demand as two indicators of environmental impacts for CR modified wearing courses in Swiss semi dense asphalt pavements. Mechanical tests are conducted to estimate the lifetime of wearing courses. CR comes from the waste tires otherwise incinerated in cement kilns. Life cycle assessment is employed to compare the environmental impacts of scenarios with varying degrees of CR use (from waste tires) in pavements and the current situation of conventional pavements and co-processing of waste tires in cement kilns. Inventory data are collected from previous scientific works, reports, industrial partners and the ecoinvent v3.5 database. The results show that the CR wearing courses have comparable energy demands to conventional pavements, while emitting less greenhouse gases compared to the reference system. It can be preliminarily concluded that using CR in the wearing course of SDA pavement is a potentially environmentally promising option to enhance pavement performance and make material use of waste tires in Switzerland.

**Keywords:** Life Cycle Assessment (LCA), Wearing Course, Semi Dense Asphalt (SDA) Pavement, Crumb Rubber, Dry Process.

## 1 Introduction

Production of asphalt pavements comprises a series of activities, such as materials production, construction, maintenance etc., all of which have environmental impacts. Life Cycle Assessment (LCA) can track and quantify the environmental impacts of both individual and total activities of products. It helps identify the activities with the highest environmental burdens within the life cycle of the product, or point to

hotspots and clarify the most environmentally effective strategies among various options. Such advantages make LCA a methodology frequently used to assess the environmental impacts of asphalt pavements.

The increasing number of vehicles leads to increasing amounts of tires disposed. Current solutions to disposing waste tires include the energy recovery (use tires as alternative fuels in cement kilns), chemical recovery (pyrolysis/thermolysis) and granulate recovery (shredding) [1]. Rubberized asphalt pavement is an increasingly popular method that uses the crumb rubber (CR) from waste tires. CR can be either added by wet process or dry process into asphalt mixtures. Although CR asphalt pavements have received positive feedback in other countries [2], their potential ecological benefits/losses for Switzerland are still not clarified. Therefore, in this paper we use LCA to assess the environmental performance of CR modified asphalt pavements in Switzerland. LCA allows to investigate the environmental strengths and weaknesses of using CR. Evaluations are performed through the case study of Swiss semi dense asphalt (SDA) pavements.

## 2 Materials

### 2.1 Asphalt mixtures

Three types of asphalt mixtures for the wearing courses are prepared in plant. The mix designs are based on Swiss standard SNR 640436 for SDA 4-12 (maximum particle size: 4 mm, air voids content: 10-14%) [3], and their details are shown in Table 1.

**Table 1.** Information of reference and test asphalt mixtures ([M%]: by weight of total mixture, [V%]: by volume of total mixture, PmB: polymer modified binder).

Mixture	Binder content [M%]	Binder type	CR content [M%]	Void content [V%]	Bulk density [t/m <sup>3</sup> ]
Ref.	6.20	PmB	0.0	13.7	2.09
CR <sub>0.7</sub>	6.52	B 70/100	0.7	14.3	2.07
CR <sub>1.0</sub>	6.63	B 70/100	1.0	13.5	2.10

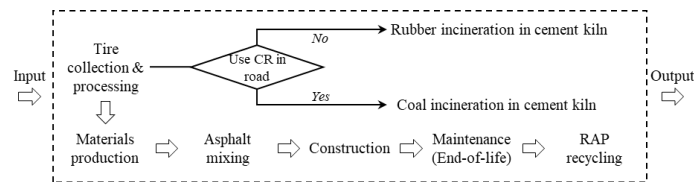
### 2.2 Mechanical performance of asphalt mixtures

To compare the mechanical performance of investigated asphalt mixtures, the cooperated study conducted the water sensitivity test (EN 12697-12) and wheel tracking test (EN 12697-22) [4]. The results showed that the indirect tensile strength ratios of all the specimens are comparable, ranging from 76 to 81%; the rutting ratio of Ref. and CR<sub>1.0</sub> are both 6.0% at 30 000 cycles, while CR<sub>0.7</sub> has less rutting ratio of 4.4% [4]. Based on the available test results, this initial study assumes that the CR wearing courses have the same service life as that of the reference. In the future study, further tests need to be employed to estimate more accurate service life.

### 3 Life Cycle Assessment

The international standard ISO 14040 divides LCA into four steps: goal and scope definition, inventory analysis, impact assessment and interpretation [5]. For the case of wearing courses, all the four steps are explained as follows:

#### 3.1 Goal and scope definition



**Fig. 1.** System boundary of LCA.

LCA is used to quantify and compare the environmental impacts of reference and CR wearing courses. The functional unit (FU) is constituted by the wearing course with the dimensions of 1 km length, 7m width and 30 cm depth. The effects of dimension, service life, traffic volume, weather and other pavement layers are assumed to be identical for all the wearing courses studied. Fig. 1 shows the system boundary, including the processes of asphalt pavements and rubber/coal incineration. It shall be noted that the maintenance is equal to end-of-life for wearing courses because both two processes demolish the used wearing courses and transport them to the recycling plant. Due to lack of reliable data of emissions, the use phase is not considered in the analysis.

The CR used in the pavements is originally incinerated in Swiss cement kilns where it replaces coal. To make a fair comparison of the current reference situation and scenarios of CR use in pavements, system expansion was used as an allocation approach. The following three scenarios are discussed for comparison:

- (1) CR wearing course with 3.0 t of rubber from waste tires + incinerating 1.4 t of rubber and 3.3 t of coal (to substitute for the diverted tires in the kiln);
- (2) CR wearing course with 4.4 t of rubber + incinerating 4.8 t of coal;
- (3) Reference wearing course + co-processing of 4.4 t of rubber in cement kilns.

Within the functional unit, 3.0 and 4.4 t of rubber account for 0.7 and 1.0% of asphalt mixtures by weight, respectively; the energies generated by 3.3 and 4.8 t of coal are equal to that produced by 3.0 and 4.8 t of rubber, respectively. The calorific values of coal and rubber are assumed to be 31.4 and 28.7 MJ/kg, respectively, and the carbon content of coal is 81% [6-7].

#### 3.2 Inventory analysis

Inventory data in this article are collected from the previous studies [6-8], report [9], industrial partners in Switzerland and ecoinvent v3.5 database (cut-off system model).

Materials production: based on the functional unit, Table 2 presents the quantity of raw materials to prepare each type of asphalt mixtures. The input/output data of base binder and polymer are obtained from the report of Eurobitume [9]. According to the industrial partner, the grinding of 1 t of waste tires produces 0.73 t of CR (rest parts of tires are steel wires and fibers) and consumes 308 kWh of electricity. The data of aggregates and electricity are determined by the ecoinvent database.

**Table 2.** Mass of raw materials to prepare the reference and test asphalt mixtures.

Mixture	Asphalt mixture [t]	Virgin aggregate [t]	Base binder [t]	Polymer [t]	CR [t]	End-of-life tire [t]
Ref.	439.6	412.3	26.3	1.0	0.0	0.0
CR <sub>0.7</sub>	434.8	403.3	28.3	0.0	3.0	4.2
CR <sub>1.0</sub>	440.8	407.2	29.2	0.0	4.4	6.0

Asphalt mixing: as mentioned in previous case study in Switzerland [8], the incorporation of CR by dry process does not increase the energy consumption of mixing; the production of 1 t of asphalt mixtures consumes 8.6 kWh of electricity and 216.3 MJ of natural gas (assuming the calorific values of natural gas is 49.4 MJ/kg [9]). The environmental impacts of natural gas are provided by the ecoinvent database; qualitative measurements from the industrial partner shows that CR plays very limited role in increasing the total emissions during mixing. Therefore, such emissions are assumed to be same for all the asphalt mixtures.

Construction: the construction of wearing course requires 1.48, 1.50, and  $1.49 \times 10^4$  MJ per FU for scenario (1)-(3), respectively [8]. These amounts of energy are consumed by pavers, materials' transfer vehicles, rollers and electricity generators, and provided by diesels (impacts of diesels are determined by ecoinvent). Due to lack of data, the emissions of asphalt mixtures during the construction are not included.

Maintenance: the use of milling machine and electricity generators consume 11.54 MJ and 4.75 MJ (from diesel) tonne of wearing courses [8]. The overlaying of new wearing course is not included because it is identical in all scenarios and therefore not relevant for the comparison.

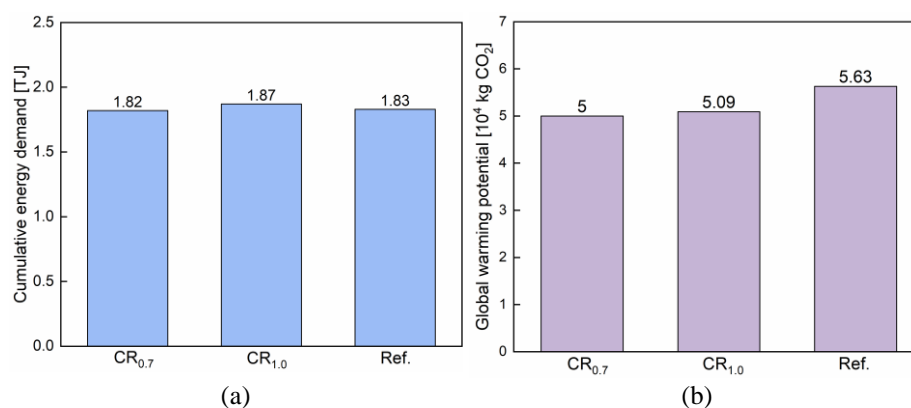
Transportation: the distances among all the relevant places (rubber manufacturer, mixing plant, construction site etc.) are based on their actual geographical locations in Switzerland or abroad, and they add up to 7.02, 7.15, and  $6.92 \times 10^4$  tkm per FU for scenario (1)-(3). A 25 t lorry is assumed to be the only method of transport, of which the impacts are provided by the ecoinvent database.

Rubber/coal incineration: the emissions of coal incineration are derived from the elemental composition of hard coal from Oberschelp et al. [6]; the impacts of rubber incineration are based on the ecoinvent.

### 3.3 Impact assessment

The impacts investigated in this article include the cumulative energy demand (CED) and global warming potential (IPCC GWP 100a). The collected data are integrated by Simapro 9.0.0.48 to quantify the target environmental impacts.

## 4 Results and interpretation



**Fig. 2.** Quantitative results of (a) cumulative energy demand and (b) global warming potential within the life cycle of reference and CR modified wearing courses. Scenario (1): CR<sub>0.7</sub>, Scenario (2): CR<sub>0.7</sub>, Scenario (3): Ref.

Quantitative results of CED and GWP for all the scenarios are shown in Fig. 2. It can be seen that the CED values between the reference and CR wearing courses are quite comparable, implying that the use of CR in both wearing courses and cement kilns have few differences in energy consumption. However, the emissions of greenhouse gases (GHG) from CR wearing courses are lower than that of the reference. Table 3 compares the GHG emissions of all scenarios in different phases. The largest gap of GHG emissions between reference and CR wearing courses is in the binder preparation. The reason is that the reference wearing courses use polymer modified binder, in which the production of polymer release huge amount of GHG. While the CR wearing courses use base binder, which eliminates the GHG cause by polymer production.

**Table 3.** GHG emissions of scenario (1)-(3) in different phases [ $10^3$ kg CO<sub>2</sub>].

Mixture	Aggregates & CR preparation	Binder preparation	Mixing	Construction & Maintenance	Coal / Rubber incineration	Transport
CR <sub>0.7</sub>	1.58	14.30	6.45	1.98	14.2	11.50
CR <sub>1.0</sub>	1.64	14.80	6.54	2.00	14.3	11.70
Ref <sub>1.0</sub>	1.52	21.14	6.52	1.99	13.8	11.30

## 5 Conclusion

This study employs LCA to compare the environmental impacts of reference and CR wearing courses in Swiss SDA pavements. Asphalt mixtures are prepared in plant and mechanical tests are conducted to investigate the mechanical performance of reference and CR mixtures. CR comes from waste tires that are originally incinerated in cement kilns. The analyzed scenarios include both the rubber/coal incineration and the life cycle of wearing courses. The results showed that the cumulative energy demands are comparable between the reference and CR wearing courses, while the climate change impacts of CR wearing courses are lower than that of the reference. The main reason is the greenhouse gas emissions caused by polymer production in the life cycle of reference wearing courses. From the environmental point of view, the results present a high potentials of CR as an alternative performance enhancing material of wearing courses and alternative method to dispose of waste tires in Switzerland.

## 6 Acknowledgement

This project has been supported by the Swiss National Science Foundation (SNF) grant No. 5211.01569. The cooperation of industrial partners from the companies TRS, Ammann, FBB and Weibel are greatly appreciated.

## References

1. Lo Presti, D.: Recycled Tyre Rubber Modified Bitumens for road asphalt mixtures: A literature review. *Construction and Building Materials* 49, 863-881 (2013).
2. ETRMA.: End-of-life Tyre Report 2015. European Tyre & Rubber Manufacturers' Association, (2016).
3. VSS SNR 640 436.: Semi-dense mixtures and pavements - Definition, requirements, design and implementation (in German and French). VSS Schweizerischer Verband der Strassen- und Verkehrsfachleute, Zurich, Switzerland, (2015).
4. Poulidakos, L.D., Bueno, M.: Laboratory scale performance of plant produced crumb rubber modified mixtures with dry process. (In preparation).
5. ISO 14040.: Environmental management-Life cycle assessment-Principles and framework. International Standard Organization, Geneva, Switzerland, (2006).
6. Oberschelp, C., Pfister, S., Raptis, C., Hellweg, S.: Global emission hotspots of coal power generation. *Nature Sustainability* 2(2), 113 (2019).
7. Pipilikaki, P., Katsioti, M., Papageorgiou, D., Fragoulis, D., Chaniotakis, E.: Use of tire derived fuel in clinker burning. *Cement and Concrete Composites* 27(7), 843-847 (2005).
8. Birrer, N.: Life cycle assessment of alternative asphalt pavements (master thesis). ETH Zurich, (2019).
9. Eurobitume.: Life cycle inventory: bitumen. European Association of Bitumen Producers, (2012).