Life Cycle Analysis of Low Carbon Roller Compacted Concrete Pavements

Alexandra Telford[1], Sripriya Rengaraju[1]*, Haneen Mohammed[2], Ahmed I. M. Nassar[3], and Abir Al-Tabbaa[1]

[1] Department of Civil Engineering, University of Cambridge, Cambridge, United Kingdom
[2] Department of Civil Engineering, Istinye University, Istanbul, Turkey
[3]Jean Lefebvre (UK) Ltd, United Kingdom
sr973@cam.ac.uk

Abstract. Roller compacted concrete (RCC) is a zero-slump concrete with lower ordinary Portland cement (OPC) content and water/cement, and a higher proportion of aggregates than conventional concrete. Life cycle analysis (LCA) was performed with a cradle-to-gate system boundary to compare the impacts of continuously reinforced concrete pavements (CRCP) and RCC pavements per mile of dual carriageway. RCC pavements have less than half of the environmental impact of CRCP due to lower thickness of RCC pavement lifts and lower quantity of OPC. Construction processes contributed to only a very small proportion of the total environmental load for both pavement types. In RCC pavements, notable reductions in the GWP were observed with partial replacement of cement. Compared to fly ash and ground granulated blast furnace slag, limestone calcined clay cement has the lowest CO_2e emissions for concretes with similar compressive strength, due to its shorter transport distances. The benefits of using recycled concrete aggregates and reclaimed asphalt pavement aggregates in RCC pavements were outweighed by their long transport distances. The geographic availability of materials is critical to consider when replacing OPC and natural aggregates to reduce RCC pavement environmental impacts.

Keywords: Roller compacted concrete, life cycle analysis, cement replacement, non-virgin aggregates, global warming potential, abiotic depletion.

1 Introduction

The global popularity of concrete pavements for use in high-speed applications is growing because of their longer design life over asphalt pavements due to their higher durability, stiffness, and improved performance in a range of temperatures [1-3]. Furthermore, it's important to note that concrete pavements offer a significant advantage in terms of routine maintenance costs. They have been consistently proven to be the least costly option over the long term, requiring fewer repairs and resurfacing compared to asphalt alternatives. This cost-effectiveness makes concrete pavements a highly attractive choice for sustainable and economically viable infrastructure projects worldwide [4]. However, cement contributes up to 90% of greenhouse gas emissions associated

with concrete production, with clinker attributable to 60% of UK CO_2 emissions from concrete and cement production [5]. Roller compacted concrete (RCC) pavements provide opportunities for reducing these environmental impacts due to their lower cement content. They combine the durability of conventional concrete pavements with the ease of construction of asphalt pavements using high-compaction pavers and vibratory rollers [1]. The environmental benefits could be further exploited through partial substitution of OPC with fly ash, ground granulated blast furnace slag (GGBS), and limestone calcined clay cement (LC3) and of natural aggregates with recycled concrete aggregates (RCA) and reclaimed asphalt pavement (RAP) aggregates.

Life cycle assessment (LCA) quantitatively evaluates the sustainability of producing RCC pavement over its entire life. Both one cubic metre (m^3) and one kilometre (km) of RCC pavement have been used as functional units for existing LCAs, with system boundaries ranging from cradle-to-gate to cradle-to-grave [6-9]. Studies by Hashemi et al. (2020) and Anastasiou et al. (2015) found that partially replacing OPC with fly ash (45% and 50% respectively) reduced global warming potential per m3 by 40% and per km by 60% [7,8]. Adamu et al. (2018) and Hashemi et al. (2020) also showed OPC replacement rates of 38-45% using fly ash or GGBS decreased CO_2 emissions by 39-40% [7,9]. However, long transport distances for fly ash and GGBS, discussed by Kurda et al. (2018) and Adamu et al. (2018), should not be overlooked [9,10].

LCA of RCC with the replacement of natural aggregates with RAP aggregates has been investigated by Debbarma et al. (2021) and Shi et al. (2018) with contrasting findings [11, 12]. A 50% replacement rate was shown to reduce the CO_2e emissions by 1.5% for the former and a 40% replacement rate was shown to increase the GHG by 3% for the latter. Other non-virgin aggregate replacements have been investigated by Aghayan et al. (2020), Anastasiou et al. (2015), and Adamu et al. (2018), with similar patterns of small increases or decreases in the GWP [8, 9, 13]. The impacts of mixes with non-virgin aggregates are more greatly influenced by their longer transport distances and are sensitive to differences in the assumed distances across the LCA.

This paper aims to quantify the environmental impacts of RCC pavements and the effect of low carbon substitutions on GWP and abiotic depletion (ADP) of fossil fuels.

2 Experimental Program

OpenLCA, an open access, robust tool for conducting LCA was used to determine the environmental impacts of RCC pavements. CML 2001 1A Baseline mid-point impact assessment method was used for impact assessment. The main environmental impacts were the GWP over 100 years and the abiotic depletion (ADP) of fossil fuels.

2.1 Life Cycle Analysis ISO 14040

The functional unit considered was one mile of dual carriageway with a minimum target compressive strength of 40 MPa at 28 days for the concrete mixes analysed [14,15]. The system boundaries were cradle-to-gate with a construction phase accounting for the fuel, energy, and water inputs of the processes. The inventory consisted of supply-

chain data from the Ecoinvent 3.7 Database and information obtained from the literature and Environmental Product Declarations (EPDs). The provider regions were chosen to be the UK, then Europe or a European country, with the Rest of the World average as a last resort. Table 1 shows the mix pairs of similar strength obtained from the literature, allowing for more valid comparisons of percentage change of impacts. The pavement width of 21.1 m was designed per DMRB CD 127 guidelines [16]. Following DMRB CD 226 and 224, the lift thicknesses were designed to be 270 mm and 200 mm for CRCP and RCC pavements respectively [14,17]. For transport, single trip distances were obtained from various literature and are detailed in Table 2. Machine specifications were used to obtain the required information about the construction processes to enable the impacts of these processes to be calculated.

Table 1. Concrete design mixes used in LCA analysis.

Substitution	Literature	Mix
Reference RCC	Mohammed (2018) [18]	Granite mix
Reference OPC	Zimmerman & Lehký (2014) [19]	C40/50
RCC with fly ash	Tangtermsirikul et al. (2004) [20]	RCCP:31 & RCCP: 17
RCC with GGBS	Afroughsabet (2021) [21]	RCC REF & LCC RCC
RCC with LC^3	Dhandapani et al. (2018) [22]	Mohammed (2018) in proportions [17]
RCC with RAP aggregate	Mahdavi et al. (2021) [23]	R0 & R25
RCC with RCA	Nehar et al. (2022) [24]	100% NA & 25% RA

Table 2. Transport distances of materials.

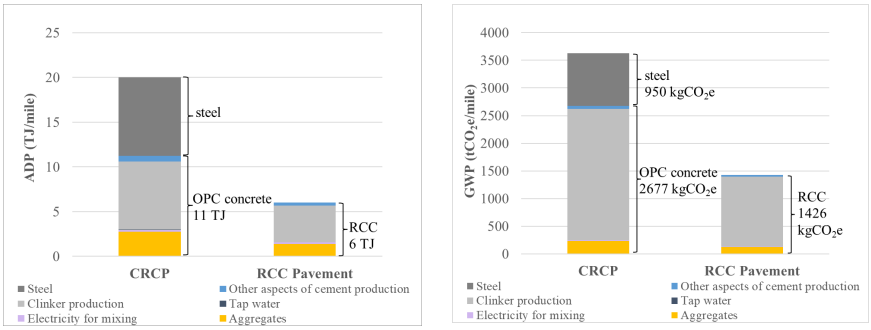
Material	Distance (km)
Portland cement	105
Fly ash	155
GGBS	220
LC^3	110
Natural aggregates	55
Non-virgin aggregates	140
Reinforcing steel	250
Concrete	12

3 Results and discussion

3.1 RCC pavements vs CRCP

Fig. 1 (a) and (b) show that RCC pavements have a lower environmental impact per mile across all processes within the system boundaries. The concrete mix accounts for

85% of the GWP for RCC pavements and 93% of CRCP. The difference is attributable to the smaller required thickness and lower cement content of RCC pavement lifts for the same design parameters as CRCP. The impacts of construction account for 0.05% and 0.1% of the GWP and ADP respectively for RCC pavements. Transport of constituents accounts for a higher percentage of the overall environmental impacts for the ADP than for the GWP, of which 85% of the constituent transport impacts are due to aggregate. The findings align with Hashemi et al. (2020) and Adamu et al. (2018) when considering the same boundaries and functional units [7, 9].



(a) (b)

Fig. 1. Comparison of ADP and GWP of CRCP and RCC pavements

3.2 Ordinary Portland cement replacement

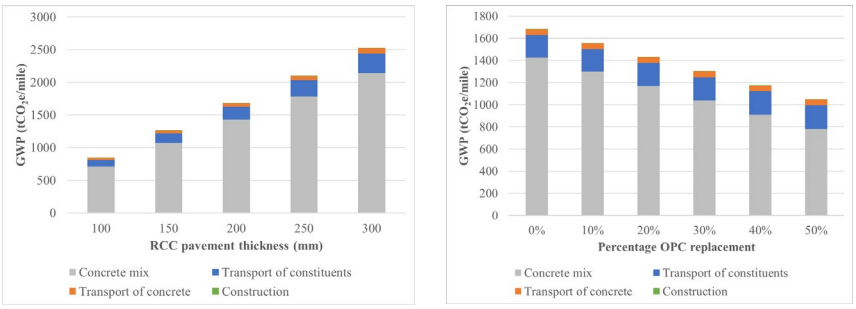
Substitution of OPC saw a 30-40% reduction in the GWP and a 6-24% reduction in the ADP depending on the material. LC3 with 50% replacement of OPC saw the greatest savings in the GWP per kilogram of OPC substituted when compared to the fly ash and GGBS mixes. However, as this mix was only hypothetical, it requires testing before it can be proposed for high-speed pavement applications. For the ADP, 50% fly ash substitution of OPC saw the overall greatest reductions per kilogram of OPC replaced, compared to GGBS and LC3. For both GWP and ADP, the mixes using fly ash and GGBS resulted in an increase in the environmental impacts due to constituent transport distance being 1.5 and 2 times longer than that of OPC respectively, which is in alignment with literature [7, 8].

3.3 Natural aggregate replacement

Natural aggregate replacement with RAP/RCA aggregates saw a small increase in the GWP (0.1%) and ADP (1%). Whilst there is a reduction in the environmental impacts associated with the concrete mixes in both substitutions, these are outweighed by the increase in the impacts associated with constituent transport for the system boundaries and assumptions made in this analysis. The longer transport distances of these non-virgin aggregates assumed 2.5 times that of virgin aggregates, cause this overall marginal increase in the impacts due to RCC pavements.

3.4 Sensitivity analysis

The LCA showed that the environmental impacts of RCC pavements are most sensitive to the pavement lift thickness as they are directly proportional (See Fig. 2(a)). RCC pavements are also greatly influenced by the percentage of OPC replacement, with an overall decrease in the GWP of 12.7 tCO_2e/mile per percentage replacement of OPC (See Fig. 2(b)). This is compared to natural aggregate replacement where there is an overall increase in the GWP of 0.78 tCO_2e/mile per percentage substitution. Hence, it can be concluded that impacts are insensitive to changes in natural aggregate replacement rate for RCC pavements.



(a) (b)

Fig. 2. Effect of pavement thickness and OPC replacement on GWP

Finally, the sensitivity to transport distances was analysed. Overall, there was very little change in the total environmental impacts when the assumed transport distances for OPC, aggregates, and concrete were separately adjusted. The GWP and ADP were affected most by changes in the aggregate transport distance, however, this was still relatively insignificant compared to the variations in the total environmental load due to changes in the lift thickness and OPC replacement rate.

4 Conclusions

Based on the LCA the following conclusions about RCC pavements are made:

1) RCC has a GWP and ADP less than half that of conventional concrete pavements, providing a viable solution to reduce the environmental impacts.
2) Replacement of OPC with SCMs can reduce the GWP of RCC pavements by 30-40% per mile of dual carriageway, with LC3 providing the greatest savings.
3) Natural aggregate replacement with RCA and RAP aggregates increases the environmental load of RCC pavements by 0.1-2.5% per mile of dual carriageway demonstrating the impact of long transport distances of nonvirgin constituent.
4) RCC pavement impacts are directly proportional to the pavement lift thickness and are also heavily impacted by changes in the OPC replacement rate.

In general, the geographic availability of materials is an important consideration to reduce the environmental impacts of RCC pavements in addition to low clinker content.

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