Assessing the Sustainability Characteristics of Modified Asphalt Concrete

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Abstract. The increasing concern on impacts of various sectors to sustainability has prompted the transportation sector to improve efforts on enhancing sustainability through various tools. Whilst extensive research has currently been done on various innovative pavement materials, their impact on sustainability is still yet to be properly understood and quantified, therefore a need to analyze the sustainability characteristics of various modified bituminous mixes on the sustainability of Asphalt Concrete. Asphalt Concrete consumes high volumes of natural resources and is energy intensive henceforth affecting sustainability. Warm Mix Asphalt (WMA), Crumb rubber modified Asphalt (CRMA), Reclaimed Asphalt Pavement (RAP) and Waste Plastic Asphalt (WPA) are all mixes that incorporate additives or recycled materials to negate the negative environmental impacts of conventional Asphalt Concrete and are therefore associated with improved sustainability. Sustainability indicators such as Energy Consumption, Green House Gas emissions, Human Toxicity and Cost Implications as evaluated in Life Cycle Analysis (LCA) from various literatures were used to compare the impacts of using the alternatives through relationship graphs. The results show that lowering the temperatures of production by about 19–63 °C in the case of WMA and replacing between 2 and 100% of either binder or whole mix with recycled material in the case of RAP, CRMA and WPA lowers most indicator values vis-à-vis baseline produced values, therefore achieving not only higher environmental benefits but in addition proving to be good alternatives that perform similar or better than virgin mixes. This notwithstanding, there are limits to the quantity of additives or recycled material that is used to modify the mixes due to their effect on overall mixture performance requirements. In conclusion a quantitatively based positive sustainability effect of the considered alternatives can be seen therefore proving that these alternatives when properly engineered can be used to improve sustainability goals in the road sector.

Keywords: Sustainability · Indicators · Life cycle analysis · Asphalt concrete · Modified bituminous mixes

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1 Introduction

1.1 Sustainability in the Transportation Sector

"Sustainability" is a concept that basically expresses the interest to preserve resources for the future as the practice of making the most of what is available is exercised. One of the most used definitions however is the one given by the World Commission on Environment and Development (WCED) in its 1987 report; Brundtland Commission Report that indicates that it is "the ability of humanity to ensure that it meets the needs of the present without compromising the ability of future generations to meet their own needs" (United Nations 1987). Transportation is considered to be a primary need of human beings, therefore, developing sustainable transportation facilities should be essential. Pavement construction in specific heavily consumes energy and causes Green House Gas (GHG) emissions (Pouranian and Shishehbor 2019) and therefore much emphasis has been made on the negative sustainability related impacts induced by the industry. Many efforts have been made to enhance sustainability in the pavement industry through varied methods among them is through the use of pavement material improvement. One of the world's most widely used paving material is Asphalt Concrete (AC) which constitutes of about 95% aggregates and 5% asphalt binder (Pouranian and Shishehbor 2019) which are both natural resources that are non-renewable in nature. Due to the importance of roads in facilitating economic growth, the demand for AC is presumed to continue growing, therefore the need to enhance this materials sustainability impacts. Suggested general approaches for improving this materials' sustainability include, among others, recycling of materials, use of industrial secondary products, use of innovative binders and the use of less energy consuming technologies (Florkova et al. 2021) therefore the creation of modified bituminous mixes. Researchers have suggested various mixes such as warm mix asphalt (WMA), crumb rubber modified asphalt (CRMA), waste plastic asphalt (WPA), reclaimed asphalt pavement (RAP), reclaimed asphalt shingles, vacuum tower bottoms, steel and copper blast furnace slag and glass (Bamigboye et al. 2021; Pouranian and Shishehbor 2019; Ozer et al. 2016) which mostly seem to have a positive influence of not only AC sustainability but also on its performance. This research will delve further into the concept of material improvement for enhanced sustainability with a focus on Asphalt Concrete (AC) as well as evaluate the performance and sustainability related impacts of using modified bituminous mixes.

1.2 Sustainability Through Modified Bituminous Mixes

The scope of this study will focus on WMA, CRMA, RAP and WPA. The selection was based on acceptance levels in the pavement industry as well as the benefits to enhanced sustainability they exhibit.

WMA is a type of AC that is manufactured at lower temperatures than typical Hot Mix Asphalt (HMA) (produced at about 170 °C (Giunta et al. 2019)) which reduces the viscosity of the asphalt and provides complete aggregate coating at lower temperatures (EAPA 2010). Technical advantages of using this material are better compaction of the road, increased haulage transportation, paving in colder seasons, higher durability of the pavement due to the lower aging of the binder during production, improved worker welfare due to reduced fumes etc. (Giunta et al. 2019; EAPA 2010) in retrospect, WMA technologies seem to be comparable or better in performance to HMA (Pouranian and Shishehbor 2019; EAPA 2010). Environmental benefits of WMA are related with the reduction of the energy consumption which in turn cause reduction of Green House Gas (GHG) emissions that emanate from AC production (Giunta et al. 2019; EAPA 2010; Pouranian and Shishehbor 2019).

RAP is a modified bituminous mix in which a portion of recycled old pavement replaces a portion of virgin material in a new mix. This material is adopted in many countries with huge success in reduced resource consumption, cost reduction and reduced deconstruction waste (Jamshidi and White 2019). The reduction of virgin material leads to the reduction of both aggregate and binder content which causes improved sustainability parameters such as reduced global warming, energy consumption, water consumption, life cycle costs and hazardous waste generation (Jamshidi and White 2019; Pouranian and Shishehbor 2019) among others. In terms of performance, high RAP content mixes require rejuvenators otherwise they have increased cracking tendencies (Pouranian and Shishehbor 2019).

Crumb rubber (CR) is mainly obtained from mainly recycled tires and is used in replacing either binder (18–25%) or aggregates (3–5%) in a new AC mix (Pouranian and Shishehbor 2019). These mixes usually exhibit enhanced mechanical properties that result in improved service life, noise reduction, reduced maintenance cost among others (Rodríguez-Alloza et al. 2015). As a result, positive sustainability related impacts such reduction of raw material, longer service life, reduced climate change and ozone depletion among others can be seen when the materials whole life cycle is assessed (Pouranian and Shishehbor 2019; Bartolozzi et al. 2013).

WPA is a fairly new pavement innovation and so far about 12 countries have roads made from plastic waste (Good News Network 2021). Several studies have shown that these mixes generally replace between 5 and 10%, by weight of bitumen with plastic and this in turn helps improve AC performance indicators and therefore improved longevity and pavement performance (Pouranian and Shishehbor 2019). However, it is also worth noting that very few studies are available that mention the environmental aspect of using WPA due to the relatively new nature of these roads and hence forth difficulty in assessing comprehensive sustainability benefits.

1.3 Objective

This study will focus on enhancing understanding on how WMA, RAP, CRMA and WPA affect pavement performance and various sustainability assessment parameters.

To achieve this, pavement sustainability is assessed through the entire pavement life cycle (Ozer et al. 2016) as well as indicators to quantify the effects of sustainability. A typical road material life cycle constitutes various modules; material production, construction, service, maintenance and end of life (Pouranian and Shishehbor 2019) and it is critical to understand how sustainability can be affected by these phases as can be seen in Fig. 1. Thereafter comes the introduction of indicators which are quantitative or qualitative measures that allow sustainability to be quantified to assess and address certain issues (OECD 2008; Opon and Henry 2020). This indicator-based sustainability evaluation is commonly used to support various decision-making processes relating to material selection, methodology and progress assessment (Opon and Henry 2020). The approach coupled with secondary data collection as a source of data enabled the graphical representation of the effects of the four selected materials on various selected indicators.

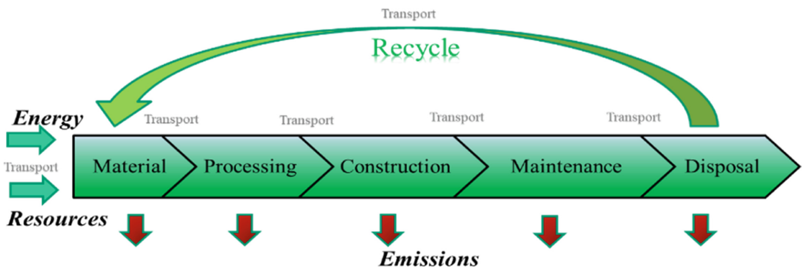

Fig. 1. Asphalt concrete life cycle and various sustainability parameters

2 Methodology

2.1 Indicator Selection

Indicator selection was the first most critical step. It was crucial that all three dimensions of sustainability (environmental, social and economic) be included in the assessment (S.R. CWA 17089:2016). Hence forth indicators were based on asphalt concrete and how it affects the three pillars of sustainability. In the assessment of various LCAs (Santero et al. 2011) found that for evaluated pavement materials, energy consumption was easily the most popular along with conventional air pollutants (e.g., Sulphur dioxide (SO_2), Nitrogen Oxide (NO_X), Carbon Monoxide (CO), particulate matter (PM)) and other greenhouse gases. (S.R. CWA 17089:2016) suggested indicators such as energy demand, global warming potential, human toxicity, cost, traffic congestion due to maintenance among others which were also considered. The indicators were thereafter revised based on availability and subjectivity as seen in Table 1 according to further availability during the data collection process.

2.2 Data Collection

Secondary data collection was the main source of data and over 150 research papers and 4 books were reviewed. The data collected was used to establish various scenarios which presented a comparison of various indicators for modified bituminous mixes vis-à-vis a conventional mix often HMA also known henceforth as the baseline. It is important to note that for every scenario the baseline HMA was varied based on the researchers' mix design parameters, thus each scenario was assessed against its own specific baseline. Final data selection was based on analytical soundness, measurability, coverage, and relevance of the indicators to the pillars of sustainability and their relationship to asphalt concrete and the modified mixes (OECD 2008).

Table 1. Indicators selected for analysis

Abbr.	Indicator	Unit	Pillar	Phase
ER	Energy requirements	MJ	Environmental, economic	Production
CO_2	Carbon dioxide	$kgCO_2$	Environmental	Production
SO_2	Sulphur dioxide	$kgSO_2$	Environmental	Production
NO_X	Nitrogen oxide	$kgNO_x$	Environmental	Production
CO	Carbon monoxide	kgCO	Environmental	Production
VOC	Volatile organic compounds	kgVOC	Environmental, social	Production
C	Production cost	Cost/unit	Economic, social	Production
GER	General energy requirements	MJ	Environmental, economic	Life cycle
GWP	Global warming potential	$kgCO_2$ eqv	Environmental	Life cycle
AP	Acidification potential	$kgSO_2$ eqv	Environmental	Life cycle
HT	Human toxicity	1,4-DB	Social, environmental	Life cycle
FFD	Fossil fuel depletion	MJ/kg	Environmental, economic	Life cycle
WLC	Whole life cost	Cost/unit	Economic, social	Life cycle
MR	Maintenance requirements	No	Economic, environmental, social	Life cycle
ISL	Increased service life	%	Economic, environmental, social	Life cycle

Other factors of consideration were data validity and uniformity in the LCA. Due to the aspect that all LCA studies were location and project dependent, this paused a challenge for the analysis of the materials. However, to curb this careful consideration of the various researchers' scopes and boundaries were considered. To enable some form of uniformity in final data, only system boundaries that covered the phases that have been highlighted in Fig. 1 were selected, studies that included extra phases such as the "use phase" which is another common phase in material oriented LCA's were not included. Most phases were similar in setting to the baseline materials with an exception to the maintenance phases of the materials where WPA and CRMA showed reduced the maintenance cycles (represented in this research as the number of overlays done over a life cycle) and increase service life (represented in this research as a percentage increase or decrease). A major factor that also increased both data validity and uniformity is that all the Life Cycle Inventories (LCI) analysis were mostly based on international environmental databases in accordance with ISO (International Organization of Standardization) standards, mostly ISO 14040. In addition to this, LCI data was mostly sourced from various established databases e.g., Ecoinvent database (Bartolozzi et al. 2013), other literatures and interviews or source-based values (Giunta et al. 2019) which was the main source of data for the production phase data. Other factors that could contribute to uniformity are the tools and methods used to do the analysis. Methods such as the ReCipe method was quite commonly used by several researchers who contributed to the results highlighted in this paper. When it came to the actual data collection at the various phases, it is worth noting that depending on the method selected for analysis, not all indicators were catered for and only applicable indicator value data relevant to the study were selected.

2.3 Data Analysis

Indicators should be normalized to render them comparable (OECD 2008) and therefore homogenized. Various forms of data normalization methods exist (OECD 2008), in this case, due to the presence of varying baseline materials which all the modified mixes were compared to, distance to a reference method was used and Eq. 1 was applicable. The data was then used to make graphical representations in which data was in the form of percentage increase or decrease of indicator values from values produced by the baseline, where a decrease shows an indicator contributes positively towards sustainability and vice versa for an incremental value. The only exception is the ISL indicator which shows a different directionality from the rest.

$$I_{norm} = \frac{Xm - Xb}{Xb} \times 100 \tag{1}$$

where:

I_{norm} is the Normalized indicator value (%)
X_b = Indicator value for baseline
X_m = Indicator value for modified bituminous mix.

The change in indicator values were plotted against the causative indicator (temperature reduction for WMA, reduced virgin material for RAP and reduced bitumen content in mix for WPA and CRMA) that is responsible for the change in the rest of the indicators. The results are as seen in the consequent chapter through Figs. 2, 3, 4, 5, 6, 7, 8 and 9.

3 Results and Discussion

3.1 The Effect of WMA on Selected Indicators

The result of the analysis was therefore represented in Figs. 2 and 3 which show the plotted relationship graphs. The Figures represent the several studies that used various additives to achieve a temperature reduction range of between 19 and 63 °C resulting in indicator changes ranging between a 70% reduction of NO_X produced at the production phase to a 3% increase in CO produced at the production stage. Most scenarios fall within the third quadrant implying improved sustainability due to a lowering of indicator values, this similar trend is also seen in Figs. 4, 5, 6, 7, 8 and 9 with an exception of the ISL indicator which has an opposite effect. There are however exceptions of the production cost and CO indicators which could possibly be attributed to the use of additives in the new mix. Improved sustainability for this material is due to reduced energy consumption and emissions hence lowered sustainability related impacts.

3.2 The Effect of RAP on Selected Indicators

The graphs shown in and Figs. 4 and 5 show the effects of a replacing between 10 and 100% of bitumen and aggregates with RAP which show varying impacts on indicators ranging between a 98% reduction of NOx produced during the production phase and a 4.8% increment in VOC production still at the production phase. By reducing virgin material use, large amounts of virgin materials can be spared, henceforth positively impacting the modified mixtures effect on the various indicators hence the observed elevated levels of sustainability. The positive results notwithstanding, there are still some scenarios that show that the indicators increased. Indicators such as CO_2, NO_x, CO, VOC for RAP showed a negative effect by an increase due to the use of rejuvenators in mixes and extra burden of RAP processing. However, most results still show that even with these added processes and rejuvenators an enhanced sustainability is still seen, therefore emphasising the aspect of the variability of data from the different studies assessed.

3.3 The Effect of CRMA on Selected Indicators

The effect of replacing between 5 and 25% of bitumen with crumb rubber on various indicators is shown in Figs. 6 and 7. The indicator change ranged from a 550% increase in service life to a 47% increase in CO_2 at production regardless of the small replacement ratios in a new mix. This Indicator reduction (or improvement for ISL) is influenced by bitumen consumption reduction as well as the fact that polymers have a characteristic improving the performance of AC and therefore reducing maintenance cycles and increasing service lives hence improved durability. Regardless of most indicators showing improved sustainability, some of the scenarios in Fig. 6 i.e., CO_2, SO_2 and cost indicators showed a negative effect by an increase of indicator values. The reason for this could be attributed to increased heating temperatures at production and processing of waste materials.

3.4 The Effect of WPA on Selected Indicators

The contribution of improved sustainability due to waste plastic follows the same principles as those of CRMA and is shown in Figs. 8 and 9. This is due to the fact that they are both polymers. The results show the effect of 2–12% of bitumen with waste plastic to a new mix. These effects range from an increment of 281% of the service life and an 800% increase in cost of production albeit some lack of data for some indicators under consideration. Like all the other materials, some scenarios in the cost of production, energy consumption, CO_2 and SO_2 indicators showed a negative effect to sustainability mainly attributed to increased processing of waste materials.

3.5 Overall Effect of Modified Mixes on Selected Indicators

There was a common observation that for all the scenarios and indicators, the whole life cycle assessment showed no negative effects on sustainability indicators, therefore furthering the aspect of the effectiveness of analysing the whole life cycle in order to realise the full benefits/detriments of a material. Another interesting trend that can be

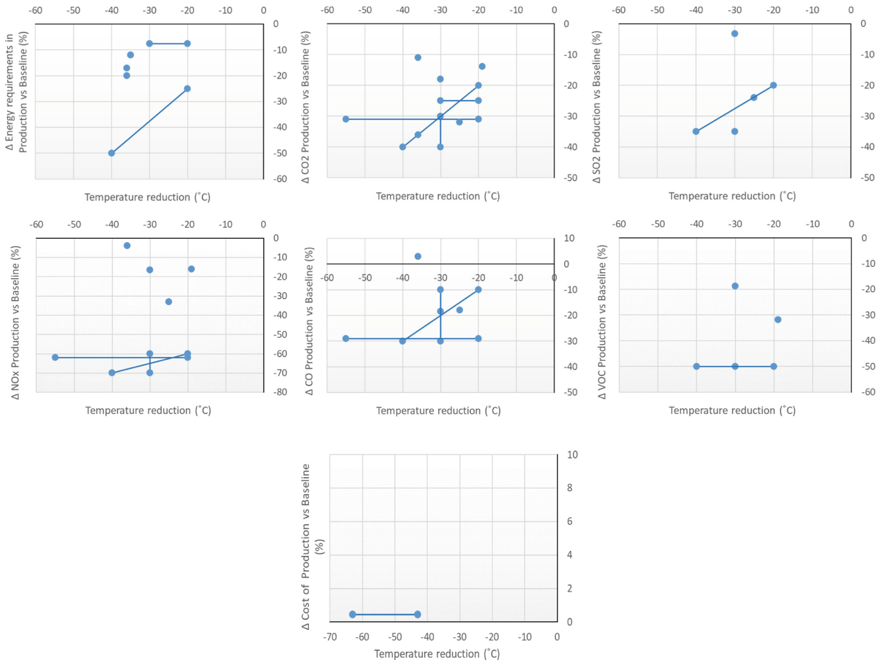

Fig. 2. Relationship graphs for various indicators versus reduced temperature in mix in production phase—WMA

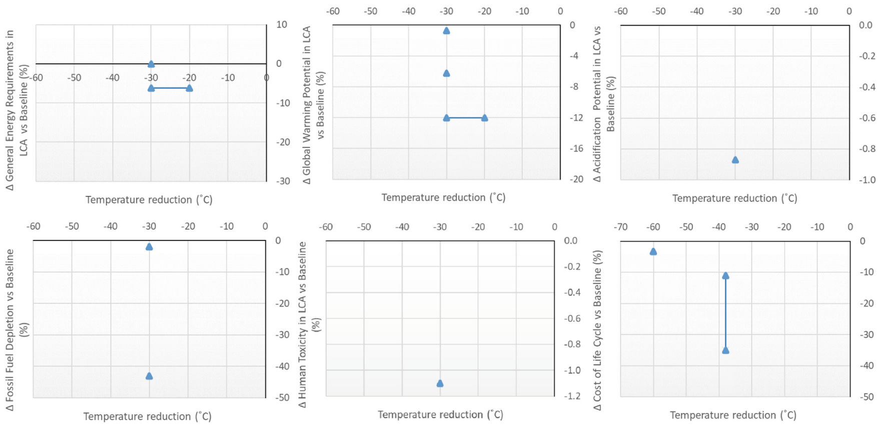

Fig. 3. Relationship graphs for various indicators versus reduced temperature in mix in whole life cycle—WMA

seen is that as the causative indicators' values rise, the more the reduction of indicator value, alluding to the fact the more the better. Mix performance is however crucial and the biggest limiting factor to this and therefore proper engineering and plant management should be highly adhered to.

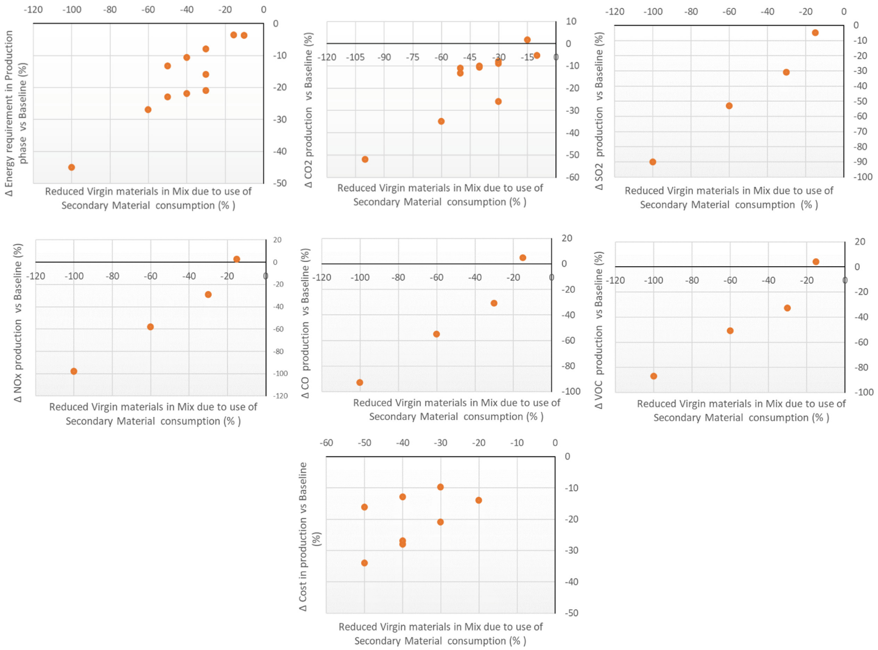

Fig. 4. Relationship graphs for various indicators versus reduced virgin material in mix in production phase—RAP

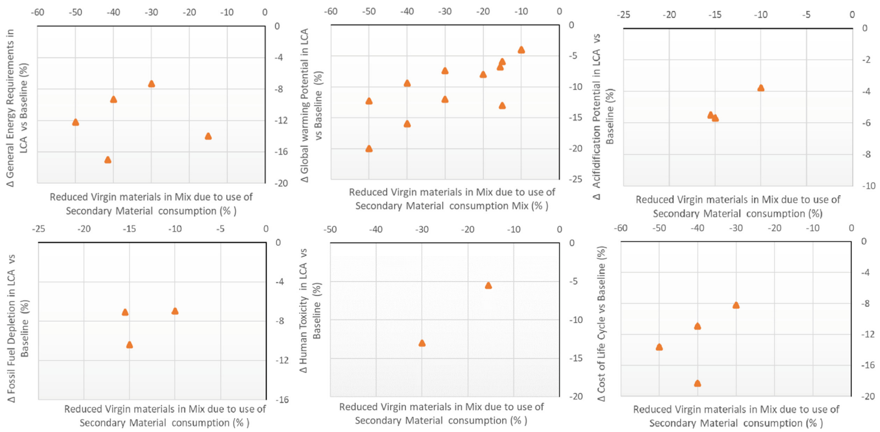

Fig. 5. Relationship graphs for various indicators versus reduced virgin material in mix in whole life cycle—RAP

Important to also note was the effect of the various modified materials to the actual improved performance and durability of the mix. A good example is how CRMA and WPA influenced the maintenance and service life of the asphalt material, hence forth in most cases they reported reduced maintenance cycles and increased service life as

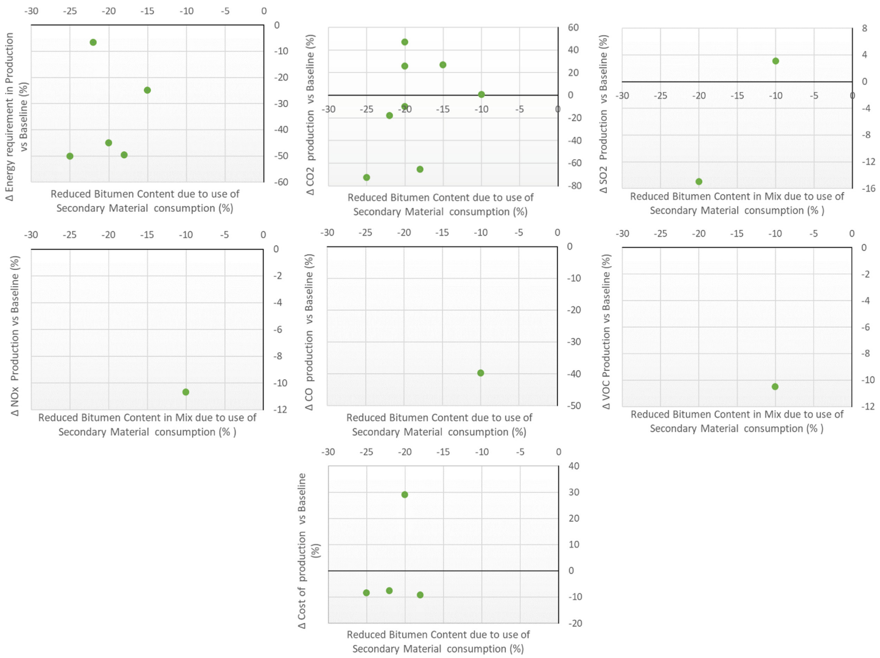

Fig. 6. Relationship graphs for various indicators versus reduced virgin material in mix in production phase—CRMA

seen in Figs. 7 and 8. This is contrary RAP and WMA mixtures seem to be engineered to perform the same as a normal mix therefore have the same maintenance and service life schedules as a normal HMA. This proves that these mixes do not only contribute to sustainability, but also improved durability and performance parameters of the material.

4 Conclusions

The findings of this research show that these modified mixes do indeed improve sustainability and to what extent they affect some social, economic, and environmental parameters of sustainability as well as the importance of assessing these materials in a life cycle scenario. The use of modified bituminous mixes is beneficial in improving pavement sustainability, advocating for responsible consumption, and encouraging innovations in the industry and therefore more considerations should be given by policy and decision makers regarding their adoption. This research also shows that a good way to quantitatively assess sustainability is through indicators and not only their use but a comparison effect to baseline scenarios. This is an easy way to help the world better understand sustainability improvement or lack thereof.

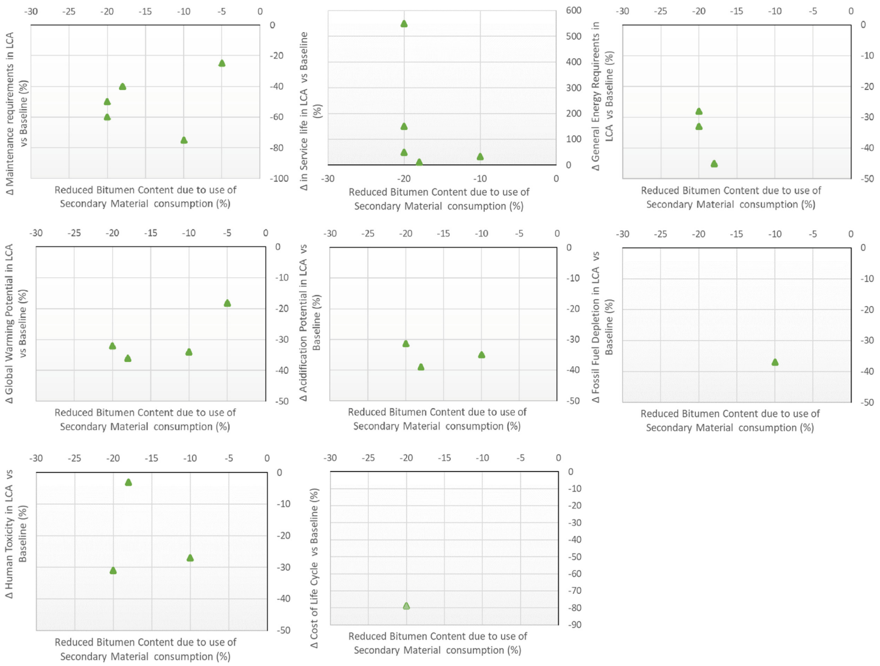

Fig. 7. Relationship graphs for various indicators versus reduced virgin material in mix in whole life cycle—CRMA

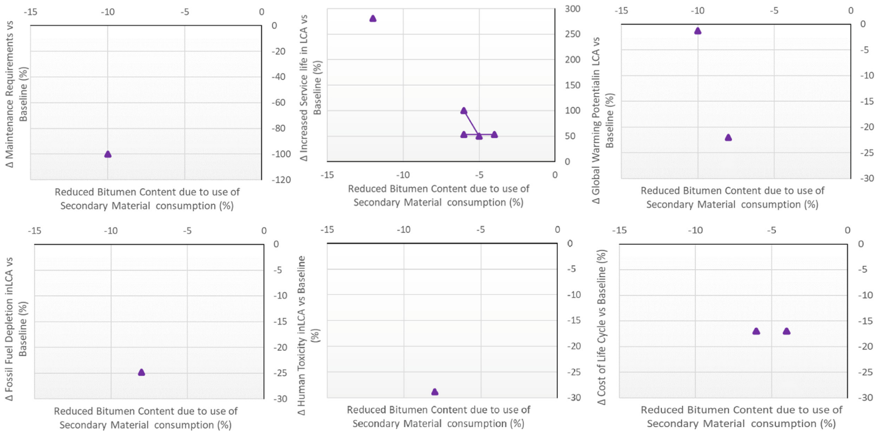

Fig. 8. Relationship graphs for various indicators versus reduced virgin material in mix in whole life cycle—WPA

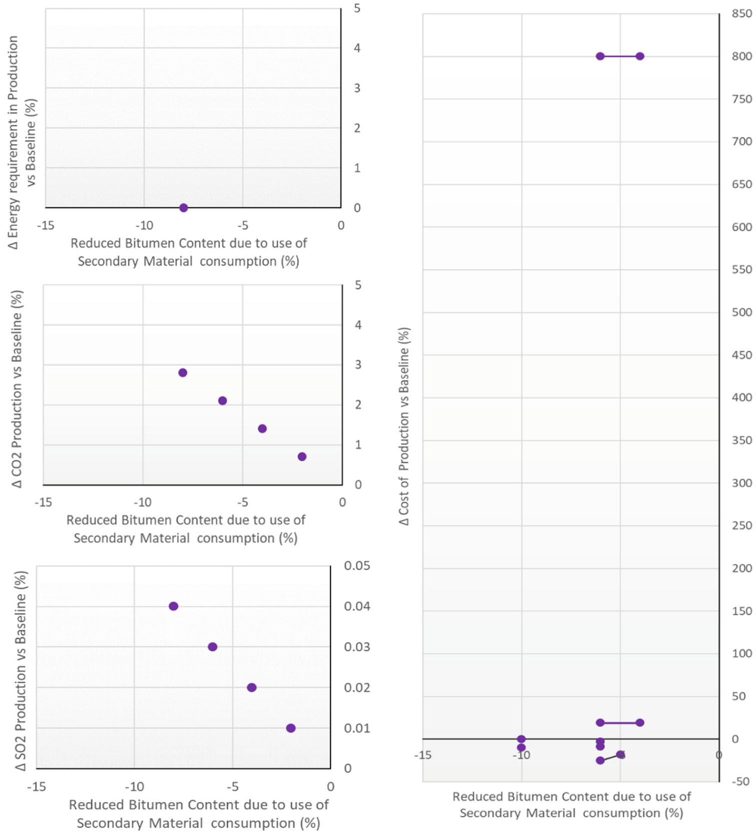

Fig. 9. Relationship graphs for various indicators versus reduced virgin material in mix in production phase—WPA

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