COMPARATIVE SUSTAINABILITY EVALUATION OF MODIFIED BITUMINOUS MIXES USING DESIRABILITY FUNCTION ANALYSIS

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1. INTRODUCTION

The use of modified bituminous mixes is one of the methods in which pavement engineers have associated with improved pavement sustainability. As a result, extensive research has currently been done on various innovative pavement materials. Nevertheless, their impact on sustainability is still yet to be properly understood and quantified. Due to this, there lacks a proper framework for the sustainability improvement analysis of modifying asphalt mixes. This has therefore presented an opportunity for researchers to discover methods in which sustainability benefits of new innovative mixes can be identified, quantified, and compared to a baseline mix or to each other. This research focuses on quantifying and comparing sustainability improvements brought about by four modified bituminous mixes i.e. Warm Mix Asphalt (WMA), Reclaimed Asphalt Pavement (RAP), Crumb Rubber Modified Asphalt (CRMA) and Waste Plastic Asphalt (WPA). These are all mixes that incorporate additives or recycled materials to negate the environmental impacts of conventional Asphalt Concrete (AC) therefore increasing pavement sustainability. The sustainability assessment was done through the identification and selection of indicators as evaluated in asphalt pavement Life Cycle Analysis (LCA) studies. The comparative sustainability performance of the materials was thereafter evaluated using the desirability function analysis.

2. METHDOLOGY

2.1 Indicator Selection and evaluation

Indicator selection was based on a holistic approach (which encompasses the 3 major pillars of sustainability i.e., social, economic and environmental parameters) as well as data availability, completeness and overall subjectivity. Table 1 summarizes the 6 indicators as assessed in LCA studies that were selected to quantitatively assess the mixtures effect on AC sustainability.

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 labelled the baseline. The design mix variation in AC made it that the baselines varied for all scenarios, due to this data normalization through distance to a reference method was used to render the data comparable. This was only

Table 1: Indicators Selected for Analysis

Abbr	Indicator	Unit	Pillar	Phase	Directionality
GWP	Global Warming Potential	$kgCO_2$ eqv	Environmental	Life Cycle	(-)
C	Production Cost	Cost /unit	Economic, Social	Production	(-)
WLC	Whole Life Cost	Cost /unit	Economic, Social	Life Cycle	(-)
ISL	Increased Service Life	%	Economic, Environmental, Social	Life Cycle	(+)
MR	Maintenance Requirement	No.	Economic, Environmental, Social	Life Cycle	(-)
HT	Human Toxicity	1,4- DB	Social, Environmental	Life Cycle	(-)

considered assuming performance requirements for all mixes met or exceeded that of the baseline mix. The scenarios were then represented as a percentage increase or decrease from their own individual baseline mix.

2.3 Data Analysis

Relationship graphs were then plotted for the percentage change in indicator values against the causative indicator. The causative indicators are responsible for the change in the rest of the indicators and consist of temperature reduction for WMA, reduced virgin material for RAP and reduced bitumen content (BC) in mix for WPA and CRMA. Linear regression was then used to establish predictive relationship equations that relates the effect of the modification extent of the causative indicator to the change in indicator value considering a contribution from all the scenarios gathered from literature. The equations and the Ideal coefficient of determination (R^2) are seen in Table 2 for each indicator and material. The predictive relationship equations were then used to determine change in indicator values relative to conventional values (conv.) shown in Table 2. These were then used to comparatively analyze the sustainability performance through the desirability function analysis as outlined in [1] which uses equation 1 where d_i is the desirability for indicator Y_i, while U_i, L_i and s represent the upper and lower limits and the function index respectively. The upper and lower limits are based on the ultimate usage values (Ult.) seen in Table 2 attained from literature and the nil effect of not altering the material. Other assumptions included a linear function shape and minimization (-) or maximization (+) of indicators as described in Table 1. Lastly, the overall desirability also representing the sustainability score (SS) was computed using equation 2.

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Table 2: Predictive relationship equations and R^2 values

	GWP		C		WLC		ISL		MR		HT		Conv. value	Ult. value
	Eqn (y)	R^2	Eqn (y)	R^2	Eqn (y)	R^2	Eqn (y)	R^2	Eqn (y)	R^2	Eqn (y)	R^2		
WMA	0.261x	0.643	-0.008x	0.966	0.261x	0.429	-	-	-	-	0.037x	1	-30° C	-75° C
CRMA	2.024x	0.915	-0.018x	0.001	3.943x	1	-9.565x	0.941	3.038x	0.827	1.146x	0.637	-20% BC	-25% BC
RAP	0.356x	0.931	0.536x	0.899	0.317x	0.941	-	-	-	-	0.417x	0.994	-20% AC	-70% AC
WPA	1.152x	0.449	0.577x	0.069	3.269x	0.962	-15.337x	0.774	7.142x	0.8	3.603x	1	-8% BC	-15% BC

$$d_i = \begin{cases} 0.9 & if\ \ Y_i < L_i \\ 0.8\left(\dfrac{Y_i - U_i}{L_i - U_i}\right)^s + 0.1 & If\ \ L_i \le Y_i \le U_i \\ 0.1 & if\ \ Y_i > U_i \end{cases}$$

$$or$$

$$d_i = \begin{cases} 0.1 & if\ \ Y_i < L_i \\ 0.8\left(\dfrac{Y_i - L_i}{U_i - L_i}\right)^s + 0.1 & If\ \ L_i \le Y_i \le U_i \\ 0.9 & if\ \ Y_i > U_i \end{cases} \quad (1)$$

$$SS = \prod_{i=1}^{n} (d_i)^{\frac{1}{n}} \quad (2)$$

3. RESULTS AND DISCUSSION

Based on the data collected from all the comparative scenarios found and assessed, it is first noted that all these materials when evaluated throughout their life cycle showed total positive effects in terms of a reduction of indicator value for all indicators except for the ISL indicator which has an opposite directionality. This means that any of the materials under consideration have environmental, social, and economic sustainability advantages over using conventional mixes. Once this was established, the next step was to compare the four materials using the desirability function to establish which material has the overall best sustainability improvement from a baseline scenario. It is important to note that data used to establish the predictive equations was based on values obtained from actual field and experiment-based data or researchers' assumed scenarios. The conventional and ultimate values used for desirability calculations were however based on various countries or product specifications as well as suggestions in literature on optimum modification limits therefore bringing into context a result based on actual mix performance.

Table 3: Desirability analysis results of modified mixes

	GWP	C	WLC	ISL	MR	HT	*SS*
WMA	0.22	0.10	0.16	0.10	0.10	0.12	0.19
CRMA	0.74	0.10	0.74	0.74	0.55	0.44	0.46
RAP	0.21	0.33	0.15	0.10	0.10	0.22	0.17
WPA	0.25	0.20	0.31	0.51	0.53	0.53	0.36

The result of the desirability analysis is as seen in Table 3 shows that CRMA is the most desirable mix, followed by WPA, WMA and RAP consecutively. This is possibly attributed to three factors; (1) CRMA and WPA both increase service life and reduce maintenance which are both aspects that WMA and RAP do not contribute to, (2) conventional figures closer in value to the optimum values produce better desirability scores than ones that are distanced out and henceforth the conventional value selection determines the results, and (3) most CRMA regression equations produce higher benefits compared to the other materials due to high recorded benefits compared to the other alternative materials under consideration. A notable point to also consider in this study is that comparative data was quite scarce and increasing the scenarios could have a notable effect on the equations. This notwithstanding, the results of this study show that the use of CRMA is overall the best sustainable modified mix with an overall sustainability score of 0.46 and performs the best when ranked against WPA, RAP and WMA.

4. CONCLUSIONS

This paper shows the comparative analysis of four modified bituminous mixes which all outperformed conventional mixes in sustainability assessment as cited in literature. Based on the scenario and indicators selected for this study it was seen that CRMA was the most desirable mix and therefore the most recommended modified mix. Overall, it can be concluded that bituminous mixes have sustainability related benefits over conventional mixes depending on the extent of modification implemented and using these mixes could improve pavement sustainability. It also relays the desirability function analysis as a useful tool that can be used to determine comparative analysis of various modified mixes.

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REFERENCES

[1] Henry, M., Opon J. and Vios, N.A. (2021). Sustainability Evaluation of Concrete Materials Utilizing the Desirability Approach with Varying Function shapes. *Journal of Advanced Concrete Technology*. 19(7), pp.771-784.