EVALUATION OF FLEMISH BITUMINOUS MIXTURES' PERFORMANCE CONTAINING RAP.
Statistical analysis and modelling

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ABSTRACT

Currently, reclaimed asphalt pavement (RAP) is considered as the most recyclable material in construction industry of the developed countries, presenting higher exploitation figures in compare with dominant recyclable materials, such as glass and paper. The purpose of this paper is to investigate the effect of RAP on manufactured mixtures and to define a correlation between RAP and mechanical properties through the statistical spectrum. The methodology of this study is firstly to provide an overview of the current state of recycling and the existing knowledge on the impact of recycling on pavement's performance. Secondly, we carried out a statistical analysis on a dataset containing 74 registered Flemish asphalt mixtures. A multivariate correlation analysis determined the influential factors and the impact of those on the performance of mixtures as well as to determine the effect of RAP on major mechanical properties, testing the hypothesis of equality by performing an independent-samples T-test analysis. In addition, a prediction model was fitted using the multiple linear regression analysis. The mechanical properties investigated in this study are stiffness, fatigue resistance and wheel rutting. The results are compared with the experience of researchers as described from the literature review.

Keywords: Reclaimed asphalt, correlation, regression, fatigue, stiffness

1. INTRODUCTION

Several milestones have stimulated asphalt recycling over the past four decades. After the first oil crisis in 1973, the cost of virgin materials significantly increased. Even after the crisis and the stabilization of the crude oil price, the need for recycling and reusing become common practice after 1980s [1]. Moreover, in 1997 the Kyoto protocol signed, committed the State Parties to reduce greenhouse gas emissions. As a result, the need of applying asphalt recycling become even greater. Therefore, using reusable materials and alternative practices, beneficially by economic and environmental means, was the sparkle for the research and industry community to focus on asphalt recycling.

The material extracted from old road constructions, containing bitumen and aggregates, is labelled as reclaimed asphalt (RA), under the European standards [2] terminology, or reclaimed asphalt pavement (RAP), under US terminology [3] The author from hereafter embrace the EN-established term. This study is part of a wider PhD project focused on the impact of RA on the performance of Flemish mixtures. Many researchers have studied the impact of RA and the results as well as the current exploitation figures show rather confidently that RA is the primary material for a greener, sustainable and efficient road infrastructure.

2. LITERATURE REVIEW

2.1 Asphalt Recycling Figures

Currently, Belgium shows one of the highest exploitation rates of RA in Europe. Although, rates concerned the total exploitation of the country are published annually, there are no figures regarding the individual usage rates in the three regions of Belgium: Flanders, Wallonia and Brussels. In TABLE 1, figures regards the volume of RA utilization in different countries are presented, including Belgium [4], France [5], the Netherlands [5], the USA [6] and Japan [6].

TABLE 1: Production and RA rates in different countries.

	Belgium	France	Netherlands	USA	Japan
Hot and warm mix production (10^6 tons)	3.30	35.40	9.70	331	55
Available RA amount (10^6 tons)	2.00	7.00	4.50	69.7	41.9
Exploitation of available RA in mixtures (%)	43.0%	64.0%	76.0%	91.0%	No data
Mixtures containing RA (%)	58.0%	65.0%	70.0%	No data	No data
Estimated average RA content (%)	45.0%	19.5%	50.4%	20.4%	47.0%

2.2 International experience

Many challenges appear when bituminous mixtures containing RA are being studied. When RA is added in the mixture, two types of binder will be present: the aged RA binder and the non-aged virgin binder. The interaction between the two types of binder is still under discussion, without knowing the degree of blending between those [7]. A life-cycle assessment (LCA) based research by Anthonissen [8] for Flemish mixtures, concluded that the environmental benefits of adding RA in new asphalt mixtures are significant, recommending though that the quality of the final mixture has to be ensured. Many researchers have studied the influence of RA on the mechanical properties. The most important findings of a preliminary research, regards to laboratory or field mixtures within a variety of RA content (25%-60%), showed some similarities and some contradicted cases:

- Stiffness is increased along with the addition of RA [9-10].
- Fatigue is a contradicting factor for most cases. In some cases fatigue resistance show improvements by the addition of RA [11-12]. On the other hand, West et al [13] showed that fatigue cracking propagate more rapidly, on a field study that determined long-term pavement performance.
- RA improves rutting performance because rutting is strongly connected to binder viscosity [14]. By adding a hard binder, such as the aged RA binder, the viscosity increases and as a result the rutting decreases. Laboratory tests [15-16] along with field experiences [17] support this statement.
- The majority of researchers concluded that tailored made design must be taken into account when RA is added [18-19].

3. MATERIALS AND METHODOLOGY

In Flanders, the production of asphalt mixtures must be aligned with the SB250 v3.1 regulations, provided and revised by the Flemish Road Agency (FRA). According to the regulations, RA is prohibited for use in surface layers and depending on the mixture and/or the type of the work (public or private) there are also limitations for base layers. Mixtures are divided in building classes from B1 to B10, as for the most demanding to the less demanding cases accordingly, in terms of the equivalent standard axles.

For this paper a dataset containing 74 registered asphalt mixtures in the wider area of Flanders were analysed, provided by the FRA. Three types of asphalt mixtures are described in this dataset: APO-A, APO-B and AVS-B. According to the Flemish Standards SB250, APO stands for asphalt mixtures with performance requirements for base courses and AVS for asphalt mixtures with increased stiffness. The corresponding types described in the European standards are AC and EME accordingly. The A and B symbols describe the maximum size of stones, namely for A stones up to 20mm and B up to 14 mm.

Each registration was handled as a unique observation containing the following information: Stiffness (MPa), Fatigue (μm/m), Wheel rutting (%), RA content (%), total binder content (%), old binder over new binder ratio (O/N) (%), air voids (VA) (%), virgin bitumen type, final penetration, softening point (R&B) (°C), stones (%), sand and filler (%). In some registrations missing values were observed, hence those measurements were not considered as part of the analysis. The objective of this research is twofold: first to shade light into the impact of RA on the major mechanical properties by statistical means and secondly to provide insight on the influential factors of those properties. Therefore, three statistical tools were used.

There are two methods in order to compare the two groups, mixtures with and mixtures without RA, of the current data. The first test is the independent-samples T-test (parametric test) and the second test is the Mann-Whitney U-test (non-parametric test). In order to perform a T-test, the assumptions of normality and outliers non-presence must be met. In this study, the normality has been assessed using as indicators the Shapiro Wilk test and graphically using the Q-Q plots. Furthermore, the presence of outliers determined graphically, using boxplots. When one of the aforementioned assumptions is violated, the Mann-Whitney U-test is used instead. Continuous dependent variables included considered stiffness, fatigue and wheel rutting. The comparison was conducted separately for all the three mixture types of the dataset: APO-A, APO-B and AVS-B. The test was performed using the statistical software SPSS ® v.24.

After the impact of RA had been assessed, the influential factors were determined. Therefore, the strength of the association, between the continuous variables was expressed by Pearson's correlation coefficient assuming a linear relationship. Moreover, a multiple linear regression (MLR) analysis provided a model for the prediction of the mechanical properties explained by the best fitted predictors, in this case properties of the mixture, composition and binder characteristics. The multivariate and the MLR analysis were conducted for all the mixtures of the dataset, to obtain one simplified model for each of the three mechanical properties. The statistical software JMP Pro ® v.12 was used for the multivariate and MLR analysis.

4. RESULTS

4.1 Independent sample T-test

First, to test whether the mean value of a continuous outcome variable differs between mixtures with and mixtures without RA, we carried out an independent-samples T-test (parametric) or a Mann-Whitney U test (non-parametric). In TABLE 2, the test results are presented. Summarizing the outcomes, significant differences ($p<0.05$) were tracked for the following cases:

- The mean (M) fatigue resistance for APO-A mixtures with RA (105.76 ± 11.85 μm/m) is significantly higher than mixtures without RA (89.17 ± 9.60 μm/m) by 16.6 μm/m, as assessed by the T-test: $t(27) = -3.157$, $p = 0.004$ (TABLE 2 and FIGURE 1).
- The median value of wheel rutting for APO-A mixtures with RA (2.86 %) is significantly lower than mixtures without RA (4.68 %) by 1.82 %, as assessed by the U-test: U = 19, z = - 2.18, $p = 0.028$ (TABLE 2 and FIGURE 2).
- The mean (M) wheel rutting for APO-B mixtures with RA (3.23 ± 1.22 %) is significantly lower than mixtures without RA (4.78 ± 1.53 %) by 1.55 %, as assessed by the T-test: $t(19) = 2.340$, $p = 0.030$ (TABLE 2 and FIGURE 3).

TABLE 2: T-test and U-test for mixtures with and without RA

APO-A	RA	M	SD	T-test	
Fatigue (μm/m)	Without	89.17	9.60	t(27)= -3.157, p = 0.004	
	With	105.76	11.85		
APO-A	**RA**	**Medians**	**Mann-Whitney U test**		
			U	z	p
Wheel Rutting (%)	Without	4.68			
	With	2.86	19.00	-2.18	0.028
APO-B	**RA**	**M**	**SD**	**T-test**	
Wheel Rutting (%)	Without	4.78	1.53	t(19)= 2.340, p = 0.030	
	With	3.23	1.221		

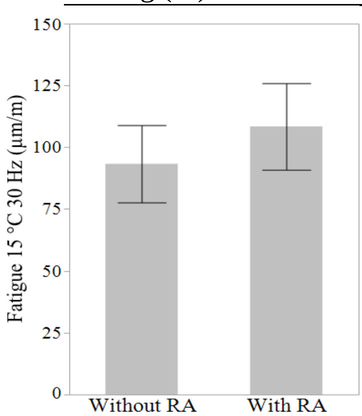

FIGURE 1: APO-A Fatigue mean values

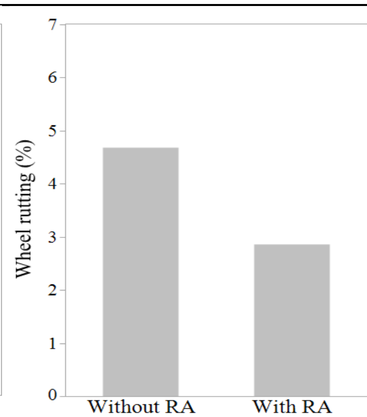

FIGURE 2: APO-A wheel rutting median values

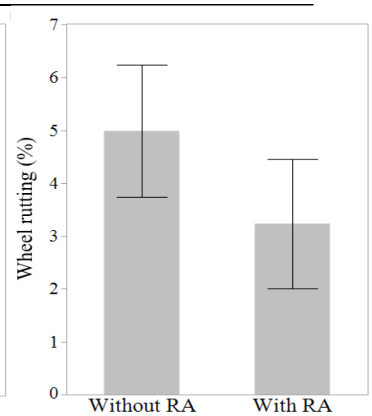

FIGURE 3: APO-B wheel rutting mean values

4.2 Multivariate correlations

The multivariate analysis provide information about the strength of the relation between the continuous variables. For the purpose of this research, the Pearson correlation analysis was used, to determine the strength and direction of a linear relationship between continuous variables. Therefore, the correlation between mechanical properties, i.e. stiffness (E*), fatigue (ε_6) and wheel rutting (Pi), and material properties were. In TABLE 3 the Pearson's correlation coefficients *r* can be found, including only the statistical significant pairs.

TABLE 3: Pearson's correlation analysis report

		RA (%)	*Stones (%)*	*Sand (%)*	*VA (%)*	*O/N (%)*	*Total binder content (%)*	*Penetration (dmm)*	*Softening point (°C)*
E* (MPa)	r	-	-	-	-	-	-	-0.416	0.320
ε_6 (µm/m)	r	-	0.482	-0.450	-0.417	-	0.623	-0.625	0.601
P_i (%)	r	-0.373	-0.369	0.365	-	-0.374	-	0.549	-0.574

4.3 Multiple linear regression

Multiple linear regression model was fitted to predict the three major mechanical properties using as predictors material properties. First, all the available variables, concerning the mixture properties, were entered and then the final model was determined containing only the significant predictors ($p<0.05$), following the backwards elimination procedure. The results of the analysis are:

- Stiffness was significantly predicted by the MLR model: $F(3,69)=7.339$, $p=0.0002$, adj. $R^2 = 0.210$. The regression coefficients and standard errors of the final predictors are presented in TABLE 5. The prediction expression is Eq. (1).
- Fatigue was significantly predicted by the MLR model: $F(2,71)=33.293$, $p=<.0001$, adj. $R^2 = 0.469$. The regression coefficients and standard errors of the final predictors are presented in TABLE 4. The prediction expression is Eq. (2).
- Wheel rutting was significantly predicted by the MLR model: $F(2,60)=21.962$, $p=<.0001$, adj. $R^2 = 0.403$. The regression coefficients and standard errors of the final predictors are presented in TABLE 6. The prediction expression is Eq. (3).

TABLE 5: Report of MLR analysis for stiffness

Variable	*B*	SE_B	*p*
Intercept	57658.678	16612.880	0.001
Stones	-474.051	190.789	0.015
Sand	-396.196	161.905	0.017
Penetration	-73.209	19.969	0.001

TABLE 4: Report of MLR analysis for fatigue

Variable	*B*	SE_B	*p*
Intercept	-64.997	22.293	0.005
RA	0.412	0.114	0.001
Binder content	33.812	4.151	<.0001

TABLE 6: Report of MLR analysis for wheel rutting

Variable	B	SE_B	p
Intercept	2.224	0.444	<.0001
O/N	-0.020	0.006	0.001
Penetration	0.064	0.012	0.0001

$$Stiffness = 57652.678 - 474.051 * (stones\ \%) - 396.196 * (sand\ \%) - 73.209 * (penetration) \quad (1)$$

$$Fatigue = -64.997 + 0.412 * (RA\ \%) + 33.812 * (binder\ content) \quad (2)$$

$$Wheel\ rutting = 2.224 - 0.020 * (O/N) + 0.064 * (penetration) \quad (3)$$

5. DISCUSSION AND CONCLUSIONS

In this work, mixtures produced in the wider area of Flanders were statistically investigated. During the first phase, the impact of RA on the three aforementioned mechanical properties was assessed. After that, a correlation was investigated between the material properties and the mechanical properties. The following conclusions have been derived from the current study:

- The analysed dataset consisted of mixtures that already met the performance requirements. Therefore, the potential benefits of RA are studied on properly designed mixtures. That was examined during the T-test/U-test analysis. In three outcome variables, wheel rutting and fatigue on APO-A mixtures and wheel rutting of APO-B mixtures, were significantly different when RA was added. For the other cases, no significant differences were traced.
- The T-tests/U-tests showed that the stiffness modulus does not change when moderate or high amount of RA is added, across all the mixtures. This result does not contradict the literature findings about improved stiffness when RA is implemented.
- The addition of RA has a negative linear correlation to the mixtures' wheel rutting. These results as well as the T-test result are fully in line with the international experience, as concluded by the literature review.
- The multivariate analysis also showed that the binder properties of the mixtures, i.e. penetration and softening point, significantly influence the current mechanical properties. Since RA replaces an adequate amount of the virgin binder, an improper blend design might mislead the mix design and consequently provide with low performance mixtures.
- Using the MLR analysis, three simple linear models were fitted. The adjusted R^2 of the models (0.210, 0.469 and 0.403) indicate that the data are rather spread around the regression line. Although, those models cannot accurately predict the mechanical properties, they can provide an insight into which factors mainly affect the mechanical properties.

The current results of this study indicated the impact that RA and other material properties have on the final behaviour of the mixture. Further research is needed in order to solidify the developed models. The examined dataset is annually updated, providing with the opportunity of creating an archive of manufactured mixtures in the Flemish region.

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