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Evaluating the mechanical performance of Flemish bituminous mixtures containing RA by statistical analysis

Currently, reclaimed asphalt (RA) is considered as one of the most recyclable materials in the construction industry of the developed countries. The purpose of this paper is to investigate the effect of RA on manufactured mixtures in Flanders and to define a correlation between RA and mechanical performance through the statistical spectrum. In this study a statistical analysis was carried out on a dataset of 74 bituminous mixtures, certified in Flanders (2009-2016). A bivariate correlation analysis was used to determine the influential factors and the impact on the performance of mixtures. In addition, the determination of the effect of RA on major mechanical properties was evaluated by an independent-samples T-test analysis. Finally, a prediction model was fitted using the multiple linear regression analysis. The main result of the comparison within the mechanical properties showed that for this dataset the mixtures with RA exhibit at least equal mechanical properties compared to mixtures without RA. The correlation analysis provided insight on the influential factors of the mechanical properties, such as a significant linear correlation between binder properties (penetration and softening point) and mechanical properties (stiffness, fatigue and wheel rutting). Moreover, the multiple linear regression (MLR) analysis quantitatively described the influence of mix properties on mechanical properties.

Keywords: reclaimed asphalt; mechanical performance; statistical analysis;

Pearson’s correlation; multiple linear regression

1. Introduction

Several milestones have stimulated asphalt recycling over the past four decades. The main reason for the research and industry community to focus on asphalt recycling were the economic and environmental benefits. In the early days, asphalt recycling was driven exclusively by economic motives. Nowadays many countries take initiatives on promoting greener technologies, such as the green procurement policy applied by the Flemish government since 2018. According to service order MOW/AWV/2018/1, contractors who use bituminous mixtures produced in reduced temperature are entitled to a discount of 5€/ton or 12,50€/m³ (Agentschap Wegen en Verkeer, 2018).

The material extracted from old road constructions, containing bitumen and aggregates, is labelled as reclaimed asphalt (RA) under the European standard terminology (EN 13108-8:2016). The impact of RA has been studied by many researchers and the overall results show rather confidently that RA is the primary material for a green, sustainable and efficient road infrastructure (Al-Qadi, Aurangzeb, Carpenter, Pine, & Trepanier, 2012; Anthonissen, 2017; Noferini, 2016). RA is frequently incorporated to mixtures produced in reduced temperature.

Although the economic and environmental benefits of using RA are widely accepted, questions arise from the construction sector concerning the service life of recycled asphalt mixtures: where is the limit of adding RA? The durability aspects of such mixtures are explained more elaborately in section 2.2. The importance of this study is that it is possible to obtain valuable information from a statistical approach, by identifying simple parameters of the mixture design and mixture components that are significantly related to the mechanical performance of the mixture, such as fatigue, stiffness and rutting. In this paper these parameters are defined, offering firstly the opportunity of understanding better the factors influencing the mechanical performance and secondly providing with a tool to estimate the mechanical performance by fitting the available data in three models predicting the mechanical response of the mixtures.

The present study is part of a wider Ph.D. project focusing on the impact of RA on the healing and fatigue properties of bituminous mixtures, in particular mixtures designed to be used in Flanders, a region in Belgium with own specifications for road construction based on European Standards.

2. Literature review

2.1. Asphalt recycling figures

According to the European Asphalt Pavement Association (EAPA) and Eurobitume RA shows one of the highest recycling rates in the construction industry (EAPA and Eurobitume, 2011). Although rates concerning the total exploitation of the country are published annually there are no figures regards the individual usage rates in the three regions of Belgium: Flanders, Wallonia and Brussels. Figure 1 shows the evolution of asphalt production together with the exploitation of RA from 2008 till 2017 as recorded by COPRO (COntrol of PROducts), a Belgian impartial certification body in the Belgian construction sector. As it can be seen, the use of RA is stable and high throughout the years. Currently, the Belgian road construction sector shows one of the highest asphalt recycling rates in Europe (EAPA, 2017), with 57% of the newly produced asphalt mixtures containing RA in an averaging content of 44%, concerning figures published in 2017 (COPRO, 2017). As it is presented in Table 1, Belgium demonstrates the second highest average RA content in new asphalt mixtures between the countries included in this table. The table consists only of countries of which all the demonstrated data are available. The presented data are retrieved from figures published by COPRO (only for the case of Belgium) and from EAPA concerning figures of 2013, which was the most recent year with detailed rates of asphalt production and recycling.

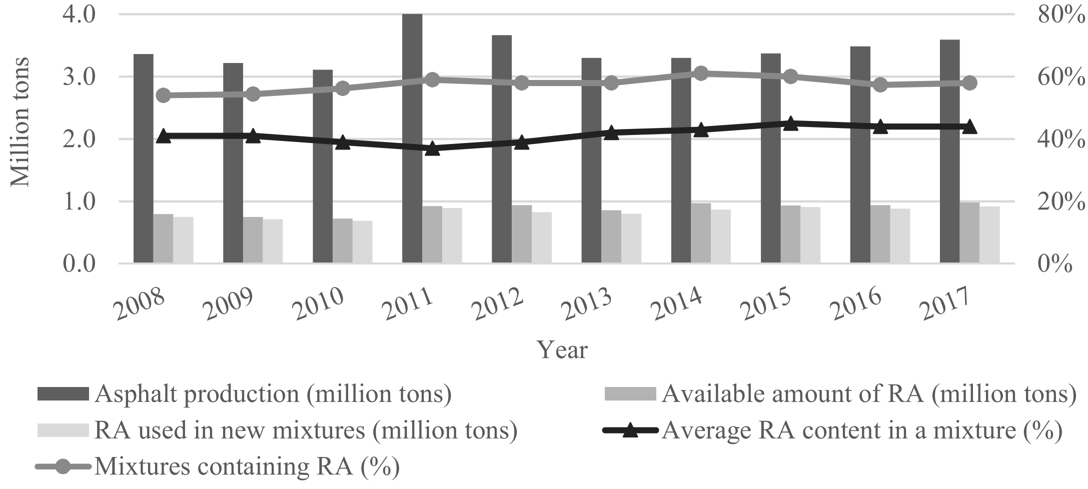

Figure 1: Asphalt production and recycling progress in Belgium based on annual reports published by COPRO (2008-2017)(COPRO, 2008-2017).

Table 1: Asphalt recycling figures in European countries (COPRO, 2014; EAPA, 2014).

	Belgium	**Sweden**	**Denmark**	**France**	**Netherlands**
Asphalt production (million tons)	3.30	7.60	3.70	35.40	9.70
Available amount of RA (million tons)	0.86	0.90	0.79	7.00	4.50
RA used in new mixtures (%)	94.0%	90.0%	83.0%	64.0%	76.0%
Mixtures containing RA (%)	58.0%	70.0%	58.0%	65.0%	70.0%
Average RA content in a mixture (%)	42.0%	15.2%	30.6%	19.5%	50.4%

2.2. International experience of durability aspects of mixtures containing RA

Many challenges appear when bituminous mixtures containing RA are being studied. When RA is added in the mixture two types of binder are 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 actual degree of blending between those (Cavalli, Partl, & Poulikakos, 2017; Mogawer et al., 2012). A life-cycle assessment (LCA) based research by Anthonissen for Flemish mixtures, concluded that the environmental benefits of adding RA in new asphalt mixtures are significant, however recommending that the mechanical performance of the final mixture has to be ensured (Anthonissen, 2017). Nowadays, it is evident that LCA and RA optimisation studies are flagship topics among the research community of bituminous materials.

Though even more researchers have studied the influence of RA on the mechanical properties, because the mechanical performance is evaluated for type testing, there is still an uncertainty whether RA can be beneficial and under which conditions. The most important findings of this preliminary review regarding laboratory or field mixtures within a variety of RA content (0-60%), showed some similarities and some contradicting cases concerning the influence of RA on the mechanical performance. According to the Flemish road regulations SB250 v3.1, air voids and resistance to water sensitivity are mixture design requirements. Besides this, three mechanical properties are required to characterise a bituminous mixture, namely stiffness, fatigue resistance and wheel rutting (Agentschap Wegen en Verkeer, 2014). Therefore, this review covers only those three mechanical properties.

It has been demonstrated that adding RA up to 20%, does not alter the properties of the final binder blend (McDaniel, Soleymani, Anderson, Turner, & Peterson, 2000; Noferini, Simone, Sangiorgi, & Mazzotta, 2017). Sabouri et al investigated mixtures from 0 till 40% RA inclusion showing that there was no significant stiffness increase when RA was added (Sabouri, Bennert, Sias Daniel, & Richard Kim, 2015). Other studies have reported that high RA content mixtures (above 40%) demonstrated higher stiffness compared to the control virgin mixtures (Lee, Denneman, & Choi, 2015; Lopes, Gabet, Bernucci, & Mouillet, 2015; West, Michael, Turochy, & Maghsoodloo, 2011).

Fatigue resistance is a property which exhibits contradicting results for most cases. In some cases, fatigue resistance show improvements with the addition of RA (Al-Qadi, et al., 2012; McDaniel, Shah, & Huber, 2012), while West et al showed that fatigue cracking propagated more rapidly according to a field study that determined long-term pavement performance (West, et al., 2011). Furthermore, Sabouri et al concluded that the inclusion of 40% RA led to reduced resistance in fatigue cracking (Sabouri, et al., 2015). A study by Mangiafico et al showed that fatigue resistance was higher for mixtures with RA from 20 till 40% and that for mixtures with 60% a small drop was observed, concluding that the optimum percentage in terms of fatigue resistance is between 20 and 40% (Mangiafico et al., 2012).

Concerning the rutting performance, the addition of RA leads to lower rutting depth. By adding a lower penetration grade binder, such as the aged RA binder, the viscosity increases and as a result the rutting decreases. Laboratory tests (Mogawer, et al., 2012; Porot, Broere, Wistuba, & Grönniger, 2017) along with field experiences (West et al., 2012) support this statement.

Two main reasons are responsible for the contradicting findings. For both stiffness and fatigue, the selection of virgin bitumen and the blending efficiency have great impact on the result. Naturally, a harder bitumen will lead to increase of stiffness in the mixture (Maupin and Diefenderfer, 2006). Therefore treating mixtures containing RA with a soft virgin binder or by adding rejuvenator can lead to stiffness decrease and improve the fatigue resistance (Zaumanis and Mallick, 2015). But in the case of insufficient blending or untreated RA, that can have inverse results (Bennert and Dongré, 2010; Mogawer, et al., 2012).

The aforementioned review covers only a selection of many studies, where the effect of RA on the most common mechanical performance properties is investigated. Many researchers claim that tailored-made design must be taken into account when RA is added in order to avoid lower performance standards (Celauro, Celauro, & Boscaino, 2010; Zhou, Hu, Das, & Scullion, 2011). Therefore, when it comes to tailored-mix design simple parameters might be used for the selection of the correct materials such as RA, virgin aggregates and virgin binder. However, in order to select the composing materials methodically-based it is necessary to understand which parameters will influence the mechanical properties, both positively or negatively.

3. Materials and methodology

In Flanders, the production of asphalt mixtures for public works must be aligned with the standard road regulations SB250 v3.1, provided and revised by the Flemish Road Agency (FRA) (Agentschap Wegen en Verkeer, 2014). Mixtures are divided into building classes from B1 (heavy traffic) to B10 (light traffic), in terms of the equivalent standard axles. According to these regulations, RA is currently prohibited for use in surface layers. Next, no restrictions are imposed for base layer mixtures except for EME mixtures. For these mixtures RA can only replace up to 20% of the binder content of the mixture (Agentschap Wegen en Verkeer, 2014).

For this paper, a dataset provided by the FRA was analysed. This dataset contains 74 certified asphalt mixtures produced for public works which were used during the period 2009-2016 in the wider area of Flanders. The three most common types of base layer mixtures in Flanders are: 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 modulus. 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 20 mm and B up to 14 mm.

Each registration case was handled as a unique observation containing the following information: Stiffness E^*(MPa), Fatigue ε_6 (μm/m), Wheel rutting Pi (%), RA content (% by mixture mass), total binder content (% by mixture mass), old binder (coming from RA) over new binder ratio (O/N in %), air voids (VA in %), final penetration of the binder blend (Pen in dmm), final softening point of the binder blend

(R&B in °C), stones (aggregates above 2mm) (%), sand (aggregates between 0.063 and 2 mm) (%) and filler fraction (aggregates below 0.063mm) (%). Additionally two categorical variables are present for each observation: the type of virgin bitumen added and the building class. The mean and standard deviation values of the mix properties and the recorded mechanical properties for each type of mixture, making the distinction between mixtures with and without RA, are presented in Table 2 and Table 3 respectively. Table 4 is a frequency table of the bitumen type used and building class for each mixture.

Table 2: Mean and standard deviation values of the mix properties per type of mixture and presence of RA.

	Presence of RA	**RA (%)**	**Stones (%)**	**Sand (%)**	**Filler (%)**	**Binder content (%)**	**O/N (%)**	**VA (%)**	**Pen (dmm)**	**R&B (°C)**
APO-A	Y	47.4 ± 10.8	58.3 ± 1.6	34.9 ± 1.6	6.7 ± 0.6	4.6 ± 0.2	55.9 ± 13.7	5.3 ± 1.3	33.4 ± 5.8	57.1 ± 2.7
	N	-	57.7 ± 1.6	35.5 ± 2.1	6.8 ± 0.7	4.6 ± 0.1	-	5.7 ± 1.3	45.0 ± 16.6	52.5 ± 6.2
APO-B	Y	46.0 ± 7.5	58.7 ± 3.3	34.6 ± 3.2	6.7 ± 0.5	4.7 ± 0.3	54.6 ± 9.5	7.2 ± 1.3	31.3 ± 6.0	58.3 ± 3.76
	N	-	58.0 ± 1.3	35.2 ± 1.5	6.8 ± 0.5	4.7 ± 0.1	-	6.7 ± 1.6	46.8 ± 17.5	52.5 ± 6.3
AVS-B	Y	21.2 ± 3.1	63.6 ± 5.0	28.7 ± 6.4	7.1 ± 0.9	5.8 ± 0.7	19.6 ± 0.7	4.5 ± 0.8	17.8 ± 2.2	65.8 ± 3.0
	N	-	56.0 ± 5.6	37.5 ± 5.9	6.4 ± 0.3	5.8 ± 0.3	-	5.5 ± 1.2	18.0 ± 5.2	64.2 ± 2.6

Table 3: Mean and standard deviation values of the mechanical properties per type of mixture and presence of RA.

	Presence of RA	**Stiffness (MPa)**	**Fatigue (µm/m)**	**Wheel Rutting (%)**
APO-A	Y	14227.8 ± 1757.8	105.8 ± 11.8	3.2 ± 1.5
	N	12753.0 ± 2372.3	89.2 ± 9.6	5.1 ± 1.3
APO-B	Y	13787.8 ± 2825.6	112.8 ± 25.4	3.2 ± 1.2
	N	12963.9 ± 2348.6	93.3 ± 20.2	4.8 ± 1.5
AVS-B	Y	14468.2 ± 1604.1	140.3 ± 16.5	3.0 ± 0.9
	N	14077.3 ± 2273.2	131.7 ± 27.3	4.3 [*1]

[*1] Single observation

Table 4: Frequency table of virgin bitumen type addition and building class per type of mixture and presence of RA.

		Virgin bitumen (pen. grade)						**Building class**			
	Presence of RA	***10/20***	***15/25***	***35/50***	***50/70***	***70/100***	***100/150***	***B1***	***B3***	***B4***	***B6***
APO-A	Y	-	-	26.1%	47.8%	17.4%	8.7%	82.6%	8.7%	-	8.7%
	N	16.7%	-	33.3%	50.0%	-	-	66.6%	16.6%	16.6%	-
APO-B	Y	6.3%	6.3%	37.5%	37.5%	12.5%	-	82.4%	11.8%	-	5.8%
	N	16.7%	-	33.3%	50.0%	-	-	50.0%	50.0%	-	-
AVS-B	Y	47.1%	47.1%	-	5.9%	-	-	83.3%	5.6%	5.6%	5.6%
	N	50.0%	50.0%	-	-	-	-	100.0%	-	-	-

The abovementioned mechanical properties were executed and reported as described in SB250 v3.1, by external certified laboratories. The dynamic modulus E* and the limiting strain value ε_6, which describes the fatigue resistance at 10^6 cycles, were determined by 2-Point Bending (2PB) tests conforming to EN 12697-26:2012 Annex A and EN 12697-24:2012 Annex A accordingly. The recorded dynamic modulus was determined as the mean value of at least 4 trapezoidal specimens (the number varies from 4 to 22 per laboratory) which were subjected to a strain-controlled test (50 μm/m) at 15 °C and 10 Hz. The fatigue resistance was measured at 15 °C and 30 Hz, at three replicates and three different strain levels until failure (stiffness reduction of 50%). After the completion of the tests the fatigue line was designed and from the mathematical representation of the fatigue line, the ε_6 can be calculated. The wheel rutting depth Pi was determined as the average rut depth of two asphalt slab replicates, according to EN 12697-22+A1:2007.

The objective of this research is twofold: first to qualitatively assess 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:

i. To compare groups, the independent T-test or Mann-Whitney U-test.
ii. To define the influential factors, the Pearson's r correlation coefficient.
iii. To model the mechanical properties according to the mixtures properties, the multiple linear regression analysis.

3.1. Differences between groups

In order to compare the difference between two groups in this dataset (mixtures with RA and mixtures without RA) two common statistical test methods exist. The first test is the independent-samples T-test (parametric test) (Norušis, 2006) and the second test is the Mann-Whitney U-test (non-parametric test) (Mann and Whitney, 1947). In order to perform a T-test, the assumptions of normality and outliers non-presence must be met. When one of the aforementioned assumptions is violated, the Mann-Whitney U-test is used instead. In this study, the normality has been assessed using as indicators the Shapiro-Wilk test (Shapiro and Wilk, 1965) and graphically using the Q-Q plots (quantile-quantile plot) (Ghasemi and Zahediasl, 2012). Furthermore, the presence of outliers was determined graphically, using boxplots. Stiffness, fatigue and wheel rutting properties of each mixture were considered as continuous dependent variables. The difference between the mixtures with RA and mixtures without RA for the three mechanical properties was investigated separately for the three mixture types of the dataset, i.e. APO-A, APO-B and AVS-B. The analysis was performed using the statistical software SPSS ® v.24.

3.2. Bivariate correlation analysis

To determine the influential factors between a set of continuous variables, a bivariate correlation analysis method was used. Therefore, the strength of the association between the continuous variables was expressed by Pearson's r correlation coefficient examining first the existence of a linear relationship (Wang, 2013). This method is appropriate since both dependent (stiffness, fatigue and wheel rutting) and independent variables (RA content, stones, sand, filler, binder content, O/N, VA, pen and R&B) were considered as continuous and normally distributed variables. The Pearson's correlation coefficient was determined to examine the correlation between mechanical properties and mix properties within the whole dataset. After the establishment of the most significant correlations, the strength of the association was examined. Table 5 shows the different scales of the strength of the correlation between two continuous variables according to the coefficient r value, as proposed by Cohen (Cohen, 1988).

Table 5: Interpreting of the correlation by strength of association.

Strength of Association	**Coefficient, r (±)**
Weak	$0.0 < r \leq 0.3$
Moderate	$0.3 < r \leq 0.5$
Strong	$0.5 < r \leq 1.0$

3.3. Modelling of the mechanical performance

A multiple linear regression (MLR) analysis provided the models for the prediction of the mechanical properties explained by the best fitted predictors, in this case properties of the mixture, composition and binder characteristics (Eberly, 2007). Based on the MLR analysis a regression model can be obtained to predict a dependent variable, using the most efficient selection of input variables. In addition this method also takes into account the interaction between the input variables. The mechanical performance of asphalt mixtures depends on various factors, i.e. mix properties. Therefore this method permits the incorporation of multiple variables simultaneously compared to a simple linear regression analysis, which would only consider these factors individually. The MLR analysis was conducted for all the mixtures of the dataset, APO and EME, to obtain one simplified model for each of the three mechanical properties. The statistical software JMP Pro ® was used for the bivariate correlation analysis and MLR analysis.

4. Results of the statistical analysis

4.1. Independent samples T-test and Mann-Whitney U test

From the nine (9) tested pairs (three mechanical properties on three different mixtures) only three cases had significant differences ($p<0.05$), the fatigue and wheel rutting resistance between APO-A mixtures with and without the inclusion of RA and wheel rutting resistance between APO-B mixtures. Table 6 summarizes which pairs were significantly different and the tests conducted.

In this section, only information concerning the statistically significant cases, are presented. During the first step of this analysis the distribution of the studied data was evaluated. It was found that the mean fatigue resistance (ε_6) for APO-A mixtures with RA (105.76 ± 11.85 μm/m) was significantly higher than mixtures without RA (89.17 ± 9.60 μm/m) by 16.6 μm/m, as assessed by the T-test (Table 7 and Figure 2). The large standard deviation between the two groups (± 11.85 and 9.60 μm/m) stem from the difference in building class of the mixtures, which for both groups varies from B1 to B6 (as seen in Table 4). The median value of rutting depth of APO-A mixtures with RA (2.86 %) was significantly lower than mixtures without RA (4.68 %) by 1.82 %, as assessed by the U-test (Table 8 and Figure 3). Lastly, the median value of rutting depth of APO-B mixtures with RA (3.36%) was significantly lower than mixtures without RA (4.69 %) by 1.33 %, as assessed by the U-test (Table 9 and Figure 4).

By comparing the results of this section with the literature findings, the statements of increased stiffness are not confirmed. For AVS-B mixtures the amount of RA is limited to 20% and as shown by the literature findings no alteration in mechanical properties are expected for up to 20% inclusion of RA. The results for stiffness and fatigue of AVS-B mixtures in this study, are in line with the literature. For APO-A and APO-B mixtures with RA, the shift in softer binders selection (see Table 4) led to a compensation of the stiffness modulus. In contrast with some literature studies there was no significant difference in stiffness when RA is used. For the same reason (treatment with higher penetration grade binders) the fatigue resistance of APO-A mixtures with RA was improved by 16.6 µm/m compared to the mixtures without. For both APO-A and -B mixtures the wheel rutting depth was lower for mixtures with RA. The comparison between AVS-B with and without RA was not possible due to lack of observations for the group without RA (only one wheel rutting depth recording).

Table 6: Summary of statistically significant different pairs and test applied.

	APO-A	**APO-B**	**AVS-B**
Significant difference between **stiffness** of mixtures with and without **RA**	T-test	T-test	T-test
	No	No	No
Significant difference between **fatigue** of mixtures with and without **RA**	T-test	T-test	U-test
	Yes	No	No
Significant difference between **wheel rutting** of mixtures with and without **RA**	T-test	U-test	-
	Yes	Yes	-

Table 7: Fatigue T-test results of APO-A mixtures.

APO-A	**RA**	**M**	**SD**	**T-test**
	Not included	89.17	9.60	t(27) = -3.157, p = 0.004
	Included	105.76	11.85	

Table 8: Wheel rutting U-test results of APO-A mixtures.

APO-A	**RA**	**Medians**	**Mann-Whitney U test**		
	Not included	4.68	U	z	p
	Included	2.86	19	-2.18	0.028

Table 9: Wheel rutting U-test results of APO-B mixtures.

APO-B	**RA**	**Medians**	**Mann-Whitney U test**		
	Not included	4.69	U	z	p
	Included	3.36	15	-2.064	0.04

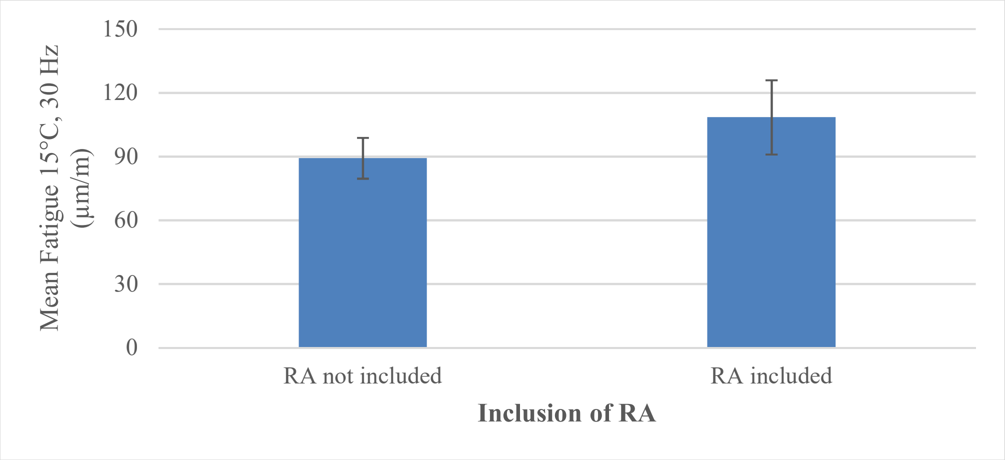

Figure 2: APO-A Fatigue mean values.

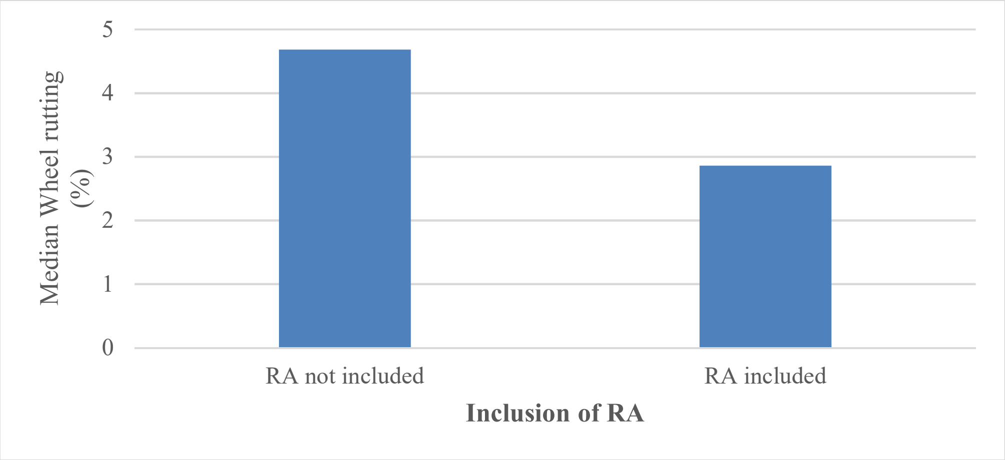

Figure 3: APO-A wheel rutting median values.

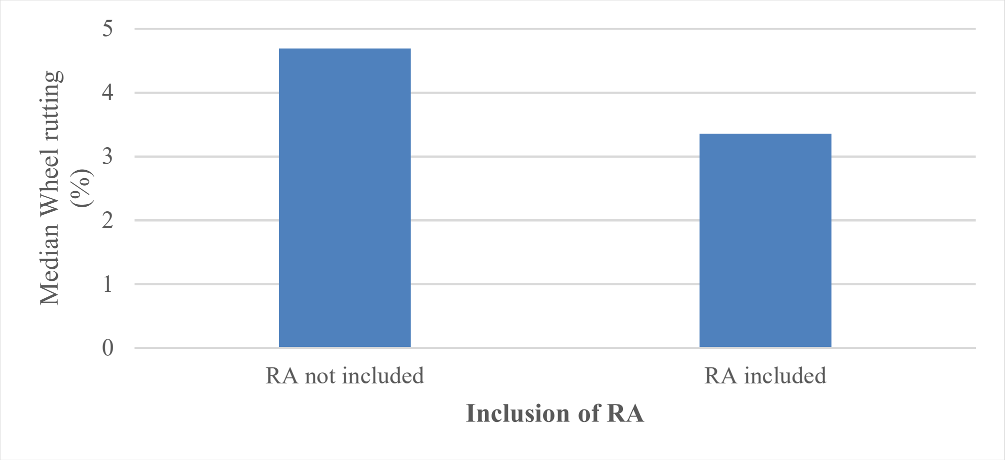

Figure 4: APO-B wheel rutting median values.

4.2. Pearson's correlation coefficient

Pearson's correlation coefficients (r) were calculated to express the strength and direction of a linear relationship between mechanical properties, including stiffness (E*), fatigue (ε6) and wheel rutting (Pi), and material properties. In Table 10, Pearson's correlation coefficients are shown. The statistically significant pairs ($p<0.05$) are highlighted with an asterisk. The table provides information about the strength of the relation between the continuous variables. From a statistical point of view and based on Cohen's interpretation of the correlations strength, the following conclusions can be drawn:

- There is a moderate correlation between: E* and Pen, E* and R&B, ε6 and stones, ε6 and sand, ε6 and VA, P_i and RA, P_i and stones, P_i and sand, P_i and O/N.
- There is a strong correlation between: ε6 and binder content, ε6 and Pen, ε6 and R&B, P_i and Pen, P_i and R&B.
- No weak correlations were found among the significant pairs. On the other hand, the non-significant pairs exhibited only weak correlations.

Two main observations can be drawn from these results. First that the binder properties are strongly correlated to all three mechanical properties of this study. Therefore the binder selection has a moderate to strong influence on the results of the mechanical properties. Second, RA has also a moderate or strong effect on the mechanical properties. Although the analysis showed a direct correlation only between P_i and RA, the binder properties of RA are integrated on the Pen and R&B of the final blend and those are significantly correlated with all three mechanical properties.

An important recommendation can be stated here concerning the selection of the RA material. Since RA replaces besides aggregates also an adequate amount of the virgin binder, an improper blend design might mislead the mix design and consequently provide with low performance mixtures. Therefore it is recommended that extra binder tests should be taken into account, such as rheological tests defining the complex modulus G* in an adequate temperature and frequency range, providing that way a comprehensive understanding of the material's response and eventually selection and design.

Table 10: Pearson's correlation matrix.

		RA (%)	**Stones (%)**	**Sand (%)**	**Filler (%)**	**Binder content (%)**	**O/N (%)**	**VA (%)**	**Pen (dmm)**	**R&B (°C)**
E* (MPa)	r	0.205	0.118	-0.196	0.267	0.096	0.219	-0.159	-0.416 *	0.320 *
	p	0.161	0.423	0.181	0.066	0.515	0.136	0.281	0.003	0.027
ε_6 (μm/m)	r	0.041	0.482 *	-0.450 *	0.093	0.623 *	-0.062	-0.417 *	-0.625 *	0.601 *
	p	0.781	0.001	0.001	0.530	<.0001	0.674	0.003	<.0001	<.0001
P_i (%)	r	-0.373 *	-0.369 *	0.365 *	-0.139	-0.106	-0.374 *	0.029	0.549 *	-0.574 *
	p	0.009	0.010	0.011	0.348	0.475	0.009	0.843	<.0001	<.0001

* for $p<0.05$

4.3. Multiple linear regression

To model the relation between the three mechanical properties (stiffness, fatigue, wheel rutting) and the material properties, multiple linear regression models were fitted. First, all the available continuous variables concerning the mixture properties were included as independent variables to predict the mechanical properties. This model was simplified using stepwise backwards elimination . The main results of the analysis are:

- Stiffness was linearly fitted in function of percentage of stones, sand and penetration value of the final blend (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 11. The prediction expression is Eq. (1).
- Fatigue was linearly fitted in function of percentage of RA and total binder content (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 12. The prediction expression is Eq. (2).
- Wheel rutting was linearly fitted in function of percentage of old over new binder content and penetration value of the final blend (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 13. The prediction expression is Eq. (3).

According to the defined models, all three mechanical properties are influenced directly or indirectly by the presence of RA binder. This is in accordance with the findings from the correlations described in section 4.2. The resulted R^2 for all three models is rather weak. This indication should not be interpreted as an inadequate result. Even though the model might not accurately predict the mechanical properties, it can provide an indication of the main influential variables and direction of the relationship with the mechanical properties, positive or negative. For instance, for 1 % increase of the sand fraction stiffness is expected to decrease by 396 MPa, if stones and penetration remain constant. Similar conclusions can be drawn also from the Pearson's correlation coefficient. The main difference is that the MLR analysis consider all the independent variables and their interactions, while the bivariate analysis as a pairwise method takes into account each time one mix property in function to one mechanical property.

In this study only continuous variables were incorporated. It is possible that important categorical variables are missing, such as type of aggregates or virgin bitumen type, which can influence the model parameters.

Table 11: 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 12: 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 13: 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

$$\begin{aligned} Stiffness\ (MPa) = 57652.678 - 478.051 * (Stones\ (\%)) \\ - 396.196 * (Sand(\%)) - 73.209 * (Penetration\ (dmm)) \end{aligned} \tag{1}$$

$$\begin{aligned} Fatigue\ (\mu\mathrm{m/m}) = -64.997\ +\ 0.412 * \big(RA\ (\%)\big) \\ +\ 33.812 * (Binder\ content(\%)) \end{aligned} \tag{2}$$

$$Wheel\ rutting\ (\%) = 2.224 - 0.020 * (O/N(\%)) + 0.064 * (Penetration\ (dmm)) \tag{3}$$

5. Discussion and conclusions

In this work, mixtures certified by FRA and produced for public works were statistically investigated. During the first step, the impact of RA on the three required mechanical properties (stiffness, fatigue resistance and wheel rutting) was assessed. Secondly, the correlation between the material properties and the mechanical properties was investigated. Thirdly, three models were determined for the prediction of the mechanical properties explained by the significant predictors. The following main conclusions have been derived from each analysis:

T-test/U-test analysis:

- Wheel rutting depth and fatigue on APO-A mixtures were significantly different when RA was added.
- Wheel rutting of APO-B mixtures, were significantly different when RA was added.
- The T-tests and U-tests showed that the stiffness modulus E* does not change when RA is added, across all the mixtures. This result is not in line with the literature findings about increased stiffness when RA is implemented due to virgin bitumen compensation.
- For the other cases, no significant differences were traced.
- Overall, at least equal mechanical properties are demonstrated between the two studied groups, mixtures with RA and mixtures without RA.

Pearson's correlation coefficient:

- The binder properties of the mixtures, i.e. penetration and softening point, significantly influence the studied mechanical properties.
- The addition of RA has a negative linear correlation to the mixtures' wheel rutting, meaning that the addition of RA lowers the rutting depth of the mixture. These results together with the T-test/U-test results, are in accordance with the literature review where it is described that RA improves the rutting resistance of asphalt mixtures.

MLR analysis:

- According to the defined models, all three mechanical properties are influenced negatively or positively by the presence of RA binder. This is expressed either directly by the percentage of RA and by the O/N index or indirectly by the penetration, since it is expressed by the penetration of the binder blend between the aged and virgin binder.
- 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 analysed dataset consisted of mixtures that already met the performance requirements. Therefore, the potential benefits of RA were studied on properly designed mixtures. It is important to comment here that when mechanical properties are compared between different asphalt mixtures or between groups with and without RA, certain compensation steps must be taken into account in order to have comparable groups. For example when the binder content is higher or when the binder penetration of the blend is higher, this may lead to better fatigue results, without having though explicitly comparable mixtures in terms of binder properties. In this study the distinction between the different virgin bitumen types was not taken into account during the T-test and U-test, since the goal was to evaluate the effect of RA and the number of registered cases was not sufficient for a more elaborate analysis. As a future work it is recommended that through a follow-up study the abovementioned matter will be addressed.

The current results of this study indicated that RA and other material properties influence the final performance behaviour of the mixture. Further research and extra data of material properties are needed in order to solidify the developed models, since potentially important parameters are missing, mainly aggregate properties such as shape, texture and adhesion properties. The examined dataset is annually updated, providing with the opportunity of creating an archive of manufactured mixtures in the Flemish region. Furthermore, a larger dataset will allow to study the influence of RA between lower and higher concentration ranges, between similar building classes and to model the mechanical properties between the mixture types separately.

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