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Effect of waste materials on acoustical properties of semi-dense asphalt mixtures

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ABSTRACT

Among the urban societal burdens rolling noise generation from tire pavement interaction and urban waste stand apart. Many urban waste materials can be used in pavements with comparable mechanical performance. Noise-related pavement characteristics such as porosity, sound absorption and surface texture, were measured for semi-dense low noise pavement mixtures using urban waste materials namely: recycled concrete aggregates, crumb rubber, polyethylene terephthalate and polyethylene. The results show that the use of these materials is a viable sustainable option for low noise pavements, however that may affect the noise reduction properties. With values around 0.2 at 1000 Hz, the sound absorption of all the mixtures is relatively low and the use of mean profile depth (MPD) alone is not enough to characterize the noise reduction properties. Surface texture was altered in different degrees depending on the waste material used. The results presented can aid in policy pertaining to noise abatement and waste reduction.

1. Introduction

Road traffic as a noise source is composed of two contributions namely, propulsion and rolling noise. Furthermore, at very high vehicle speeds, aerodynamic noise can play a role. However in urban areas and on motorways up to 120 km/h, this contribution is generally negligible. While propulsion noise is essentially controlled by the vehicle manufacturer, rolling noise depends on the tire and the pavement properties. Due to regulatory pressure, vehicle manufacturers have significantly reduced propulsion noise in recent decades [Qatu, 2012]. Furthermore, on the tire and pavement side improvements have been achieved. Nevertheless, for passenger cars rolling noise is now the dominant component in most operating conditions.

For a specific vehicle, propulsion noise depends mainly on the rotational speed of the engine and the engine load. On the other hand, for a given tire and pavement combination and specific environmental conditions, rolling noise mainly depends on vehicle speed. From this follows that propulsion noise dominates at low speeds whereas rolling noise becomes more relevant at higher speeds. The evolution of the ratio of the two noise components can be described by the transition speed for which both contributions add equally to total noise. SonRoad [Heutschi, 2004], the Swiss road traffic noise model that was published in 2004 and reflects the Swiss vehicle fleet from the late 1990 s, determined a transition speed of 38 km/h for passenger cars and 57 km/h for heavy vehicles. The

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recent update of the model sonROAD18 [Heutschi, et al 2018] with an updated vehicle fleet exhibits a transition speed of 21 km/h for passenger cars and 42 km/h for heavy vehicles under reference conditions (ACMR8 pavement, air temperature 10 °C). For comparison, the European model CNOSSOS-EU [Kephalopoulos et al 2012] identifies with its default parameters the transition speeds at 30 km/h for passenger cars and 75 km/h for heavy vehicles. However, it can be assumed that in a future revision of the model these transition speeds will shift to lower values [Peeters and van Blokland, 2018].

This development demonstrates that, from a noise point of view, the importance of tires and pavements has increased. This opens up significant potential for further noise reduction options. With the European Union (EU) regulation 1222/2009 [EU 1222/2009], the EU introduced a label in 2012 to characterize the properties of individual tires. It contains information about fuel efficiency, wet grip and noise of a tire and allows a customer to make a decision on a solid basis. Based on evaluation of a large tire label data base in 2014, Heutschi et al. (2016) has shown that there is only a weak correlation between noise and the other properties on the tire label. It can be concluded that quiet tires do not compromise the other domains.

In addition to the use of low noise tires, use of low noise pavements can contribute to the reduction of traffic induced noise. The relevant frequency range in which the noise-reducing effect of a pavement plays a role, extends over a band from about 500 to about 5000 Hz. A first important property is the sound absorption capacity that describes the interaction of sound waves with surfaces. At laboratory scale, in addition to the sound absorption coefficient, noise-relevant non-acoustical characteristics like surface texture, porosity and airflow resistivity are primary characterization methods used. It should be noted that porosity is a complex parameter and it contains pore size, and distribution as well as connectivity and tortuosity, all having an effect on noise reduction properties [Wang et al 2016]. Optimizing surface texture at the macro-scale was found to be important in reducing tire/road noise [Mikhailenko et al., 2020(2)]. Over the years, worldwide various pavement options have been investigated for use as low noise pavements. The developments have been in optimizing porosity such as porous asphalt (PA) [Knabben et al., 2016] or surface properties and stiffness such as poroelastic road surfaces [Goubert et al., 2019]. Wang et al (2016) investigated the influence of pore structure on acoustic absorption of porous asphalt concrete with a focus on acoustic absorption of PA that is closely related to the pore structures including porosity, pore size, pore length, and pore connectivity. The study showed that increasing pore radius has a positive effect on the absorption properties. The main challenge has been the acoustical as well as mechanical durability of such solutions. The most successful low noise pavements were found to be PA with ca 20% porosity. However only usually 15% of this porosity consisted of connected voids. The open porosity affects the airflow resistivity as well as the sound absorption properties of the pavement. Furthermore, in situ acoustical and mechanical performance of this type of pavement has been around 10 years [Bafu, 2010]. The current solution used in Switzerland is semi-dense asphalt mixtures (SDA) with a porosity of 12–16% that theoretically combines the low noise properties of PA with porosity of ca 22% but has better mechanical durability [Poulikakos et al., 2019].

Using waste materials as a substitute for virgin materials aims to mitigate the consumption of natural resources and provide new solutions to recycling end-of-life materials [Piao et al., 2020]. For the road industry, several studies have indicated that a range of waste materials, including end-of-life tires [Shirini and Imaninasab, 2016], recycled concrete aggregates [Kareem et al., 2018], waste ceramics [Muniandy et al., 2018], waste plastics [Lastra-González et al., 2016], steel slags [Qazizadeh et al., 2018], waste glass [Behbahani et al., 2015] and waste textiles [Yin and Wu, 2018], can potentially be applied for road construction. These waste materials are generally used as aggregates mostly in base or subbase courses, binder modifiers and performance enhancing additives for asphalt mixtures. Moreover, the use of some waste materials has been further accepted by the industry and been implemented widely in the field, such as the technology of rubberized asphalt concrete in California [Zhou et al., 2014], and the use of steel slag asphalt pavement in Germany [Motz and Geiseler, 2001]. These efforts revealed the opportunities for use of waste materials in asphalt pavements. Furthermore, the use of waste materials in low noise pavements provides further opportunities to reduce two societal challenges; noise and waste.

In order to quantify the noise reduction properties of pavements, some restrictions apply to laboratory measurements as these are performed during the pavement development process where only small samples as compared to a road segment can be created and investigated. The most conclusive acoustical methods in the laboratory are done with drum test rigs where the pavement is placed on a rotating drum and is in contact with a rolling tire [Kowalski et al., 2013]. This allows controlled rolling noise measurements at various speeds and microphone locations. This method requires an expensive laboratory facility and is limited in validity since its results depend on the chosen tire and unrealistic operating conditions, such as the curvature of the pavement.

Apart from these methods that directly sample the acoustic field around the tire/road contact, there exist various methods to measure characteristic pavement parameters that are relevant for tire/road noise generation. An advantage is that these parameters can be measured in-situ as well as in the laboratory, and can therefore assist in the pavement design and optimization of noise reduction properties. The drawback however is that their link to the overall noise performance is vague since the involved physical mechanisms are diverse and not fully understood so far. Some of the most important pavement parameters that are also considered in this work are surface texture levels, the open porosity (connectivity), and sound absorption coefficients.

1.1. Summary of research objectives

As indicated above the research by the authors as well as others has shown that various types of waste materials are suitable as replacement for conventional road materials [Poulikakos et al 2017, 2019; Piao et al. 2021]. This is also relevant for noise reducing surface courses [Heutschi, et al. 2016; Mikhailenko et al., 2020(1), (2)]. The goal of this work is to investigate the noise-relevant characteristics of low noise SDA mixtures that are produced using alternative materials and investigate if their noise reduction properties have been affected. To date there is little research dedicated to noise reduction properties of these novel materials. The results presented can aid in policy decisions pertaining to the use of low noise pavements for the purpose of noise abatement as well as

Table 1
Material designation and properties.

Designation	Binder Type	Binder Content [%-Mass Mixture]	Type of Waste [-]	Amount of Waste [%-Mass Mixture]
SDA-Control	PmB 45/80–65	5.8	None	0
RCA-32C	PmB 45/80–65	5.8	Coarse RCA	32
RCA-64C	PmB 45/80–65	6.0	Coarse RCA	64
RCA-12S	PmB 45/80–65	5.8	Sand RCA	12
RCA-24S	PmB 45/80–65	5.8	Sand RCA	24
RCA-7F	PmB 45/80–65	5.8	Filler RCA	7
CR-2.5 (17%) voids)	PmB 45/80–65	5.8	CR	2.5
CR-2.5 (18% voids)	PmB 45/80–65	5.8	CR	2.5
PET-5.1 (22%) voids)	PmB 45/80–65	5.8	PET	5.1
PE	70/100	6.1	PE	3

waste reduction measures.

2. Materials and methodology

2.1. Materials

The work done by the authors has shown that various fractions of recycled concrete aggregates (RCA), crumb rubber (CR), polyethylene terephthalate (PET) and polyethylene (PE) could be used in asphalt concrete with comparable mechanical performance to reference materials [Kakar et al. 2020; Mikhailenko et al., 2020(1), 2020(2), 2020(3); Piao et al 2020]. All mixtures used the same gradation and are listed in Table 1 and described briefly below.

The reference or control mixture for this work was a semi-dense asphalt mixture (SDA4-16) that is used in Switzerland as the most popular low noise pavement. The quarried sandstone with a 25%-30% quartz from Massongex, Switzerland was used as control aggregates with 16 ± 2% voids content [SN 640 436]. Furthermore, maximum aggregate size was of 4 mm was used for all mixtures and polymer modified bitumen PmB 45/80–65 as reference binder.

The plastic modified mixtures were prepared with waste PE to modify a base binder 70–100 of Middle Eastern origin. The PE waste recycled from packaging was obtained from a Swiss company which is currently used as fuel in cement factories. The material received from the factory was too large to be used directly therefore, it was ground to around 1 mm before being blended with the unmodified binder 70–100. The detailed procedure of PE grinding can be found elsewhere [Kakar et al., 2020]. Finally, for the preparation of PE modified mixtures, the PE modified binder was used to prepare the mixtures using the so-called semi-wet process. The semi-wet process is defined as when the PE modified binder is added to the mixture directly after the blending process of PE with bitumen without any resting time. The mixtures were prepared using 6.1% of PE modified binder at a mixing temperature of 170 °C. This semi-wet process avoids the possible segregation of PE from the base binder 70–100.

The RCA used in this study was provided by a Swiss company in Hinwil, Switzerland. It is a concrete plant waste from the excess of various productions from Canton of Zurich. Three different fractions of RCA, 2/4, 0.125/2 and 0/0.125 mm were used as partial mineral aggregate replacement.

Both CR and PET waste materials were used as received from the suppliers and used as sand fraction substitute based on their particle size mostly ranging from 0.1 to 2 mm. The CR was supplied by a Swiss manufacturer and produced through the mechanical grinding of waste truck tires. No further treatment was done to the CR used [Loderer et al. 2018, Rodríguez-Fernández et al., 2020(1), (2)]. The PET was obtained from a Swiss company in Frauenfeld, and is mostly from recycled plastic bottles, in the form of flakes. This could be classified as “crumb PET”.

Two types of compaction methods were used in this work: Gyratory compaction and wheel compaction. The Gyratory compaction was used to prepare the Marshall specimens (100 mm diameter cylindrical shape) to the desired voids content. During the compaction process, an angle of gyration 1.25° and 600 kPa vertical pressure were applied on the mixtures. The Wheel Tracking Test (WTT) according to EN 12697–22 was first of all used to characterize the mixtures’ rutting resistance, but also to investigate the surface texture response to wheel loading. The test involves repeated passes of a loaded wheel at constant temperature of 60 °C. Specimens with dimensions 500 mm × 180 mm × 50 mm were compacted using a steel wheel. Two sets of specimens were run in parallel, loaded with a solid rubber and treadles tire, with a diameter of 200 mm and a rectangular cross profile with a width of w = (50 ± 5) mm for 30,000 passes. During the test, each cycle consists of two passes (outward and return) of the loaded wheel. Texture scanning was conducted before and after the test on the area in the wheel path.

2.2. Methods to measure noise-relevant characteristics

The laboratory characterization methods used are porosity, normal incident absorption and surface texture as described in detail below.

2.2.1. Porosity

The porosity of the compacted cylindrical mixtures was determined using the European standard method EN 12697–8 [EN 12697–8], using the maximum density [EN 12697–5] of the loose mixture and the bulk density [EN 12697–6] of the compacted specimen. The maximum density is calculated from the volume of the loose mixture without voids and from its dry mass and is measured using the volumetric option in the standard [EN 12697–5]. In this procedure, the volume of the loose mixture is measured as the displacement of toluene by the sample in a pyknometer. The bulk density of the compacted samples were determined using procedure D; bulk density by dimensions [EN 12697–6], where the sample dry mass and its dimensions are used.

2.2.2. Normal incidence sound absorption

The investigations were carried out as test series of different material samples. Only small samples of limited size were available, so that only an absorption coefficient measurement under normal incidence in the impedance tube was possible. Normal incidence refers to the assumption in the impedance tube measurement, i.e. the sound wave is considered to be a plane wave that is arriving at the normal angle to the sample's surface. This measured quantity is considered to be relevant as a characterization of the pavement properties with regard to sound generation. However it should be noted that when it comes to sound propagation to a receiver location next to the road, the absorption for grazing sound incidence is important. The sound absorption coefficient of the asphalt mixture samples was measured based on the ISO 10534–2 [ISO 10534–2] standard. The large tube setting of B&K 4206 tube was used for which the frequency range is 50 Hz to 1600 Hz. The total length of the tube is 700 mm and the inner diameter is 100 mm. Two ¼" microphones type 4187 with the open circuit sensitivity of 4 mV/Pa (-48 ± 3 dB re 1 V/Pa) at 250 Hz were used, with a frequency response characteristic of 1 Hz to 8 kHz (flush mounted). B&K pre-amplifiers type 2670 were used for these microphones (Brüel & Kjær, type 4206). The microphones were calibrated using a B&K acoustical calibrator type 4231. The sound source was a loudspeaker driver with a diameter of 80 mm. The distance between the microphones was 50 mm. The distance between the sample surface and the microphone (the one closer to the sample) was 150 mm. The distance between the loudspeaker and the microphone (the one closer to the loudspeaker) was 100 mm.

Although the valid frequency range of the tube measurements is 50 Hz to 1600 Hz, the range 400 to 1200 Hz is presented here, since the most relevant frequency range for road traffic noise, i.e. 500 Hz to 5000 Hz lies within this frequency range. Each sample was mounted in the tube, with two careful sealing considerations. First, the sample was wrapped with a thin but stiff tape so that it firmly fits into the impedance tube. This would help to avoid leakage of sound waves around the sample or possibly through the pores as much as possible. As was observed in some preliminary tests, not having this kind of firm sealing around samples may lead to artefacts showing a peak in the absorption coefficient at frequencies close to 300–350 Hz. Second, the gap between the sample's rim and the impedance tube was sealed using grease. The impedance measurements were done three times for each sample, while for each measurement the sample was rotated 120° and the results were averaged. This was done to account for the possible directivity effects of reflection from the random distribution of the aggregates. However, in most cases the difference in the measurements for each sample before averaging was negligible. Traffic noise shows a peak between 800 and 1200 Hz [Mikhailenko et al., 2020(2)], therefore effective reduction due to sound absorption is expected in this range.

2.2.3. Surface texture

- Texture scanning on smaller Gyratory compacted samples

The surface texture of the asphalt mixture samples was measured with an Ames Engineering 9400HD 3D laser scanner. The tests were conducted on 6 cylindrical asphalt samples with a diameter of 100 mm of each type. The test was done by placing the sample horizontally under the device and conducting a 50x50 mm area scan. The resolutions were 0.005 mm vertically, 0.006 mm along the length of the scan and 0.025 mm for the width. A total of 2000 scan lines were recorded for each area scan and used to calculate the average mean profile depth (MPD), skewness (R_{sk}), kurtosis (R_{ku}) and length/area ratio via the Ames software. The MPD is an indicator of the pavement macrotexture range and was calculated by removing wavelengths below 2.5 mm as prescribed by ISO 13473–1 [ISO 13473-1]. However, the maximum scan line was limited to 50 mm due to the size of the samples, which was less than the 100 mm minimum prescribed. The skewness is an indicator of how far the texture profile is positive (>0) or negative, with a negative skewness contributing less to vibration and noise generation [Mikhailenko et al., 2020(2)]. The skewness is calculated from the root mean squared (RMS) of the profile as in Eqs. (1) and (2) [ISO 13473–2].

$$RMS = \sqrt{\frac{1}{l}\int_0^l Z^2(x)dx} \qquad [1]$$

$$R_{sk} = \frac{1}{RMS^3}\left[\frac{1}{l}\int_0^l Z^3(x)dx\right] \qquad [2]$$

Where *Z(x)* is the ordinate value relative to the position in the profile and *l* is the evaluation length.

Furthermore, 200 of the scan lines were used to calculate the texture level ($L_{TX,\lambda}$) in decibels as a function of texture wavelengths, λ, by taking the 1/3 octave band power spectral density (PSD) graphs for each scanline and by using Eq. (3) derived from ISO 13473–4.

Table 2
Porosity and Texture Parameters for Gyratory compacted Samples.

Sample	Porosity [%] mean	Porosity [%] *Std Dev*	MPD [mm] mean	MPD [mm] *Std Dev*	Rsk mean	Rsk *Std Dev*
Control SDA 4	15.7	*0.1*	0.727	*0.047*	−1.378	*0.049*
RCA-32C	16.1	*0.2*	0.592	*0.048*	−1.406	*0.115*
RCA-64C	17.0	*0.2*	0.474	*0.065*	−1.462	*0.088*
RCA-12S	16.0	*0.4*	0.683	*0.029*	−1.348	*0.061*
RCA-24S	16.2	*0.2*	0.619	*0.047*	−1.397	*0.072*
RCA-7F	15.9	*0.1*	0.806	*0.067*	−1.299	*0.129*
CR-2.5	18.0	*0.3*	0.507	*0.028*	−1.572	*0.064*
CR-2.5 Post Load	17.0	*0.2*	0.447	*0.034*	−1.726	*0.132*
PET-5.1	21.9	*1.2*	0.752	*0.033*	−1.322	*0.028*
PE-Binder	*15.1*	*0.3*	0.826	*0.190*	−1.386	*0.503*

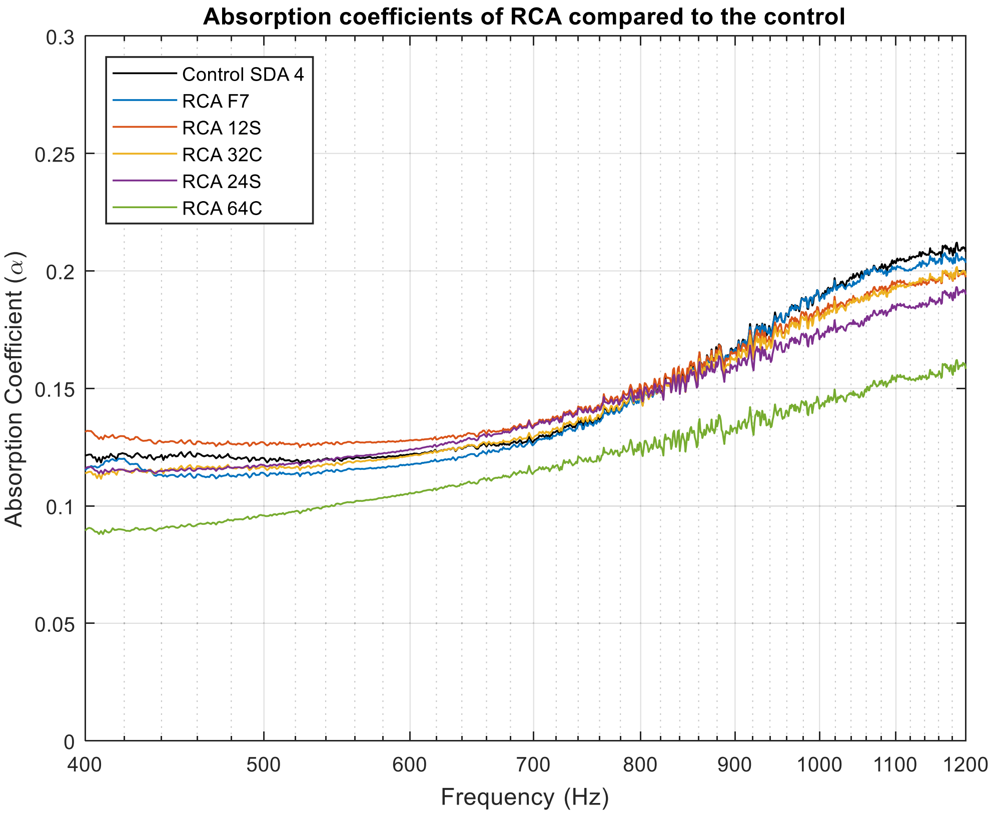

Fig. 1. Sound absorption as a function of frequency for the five investigated RCA modified mixtures and a control SDA.

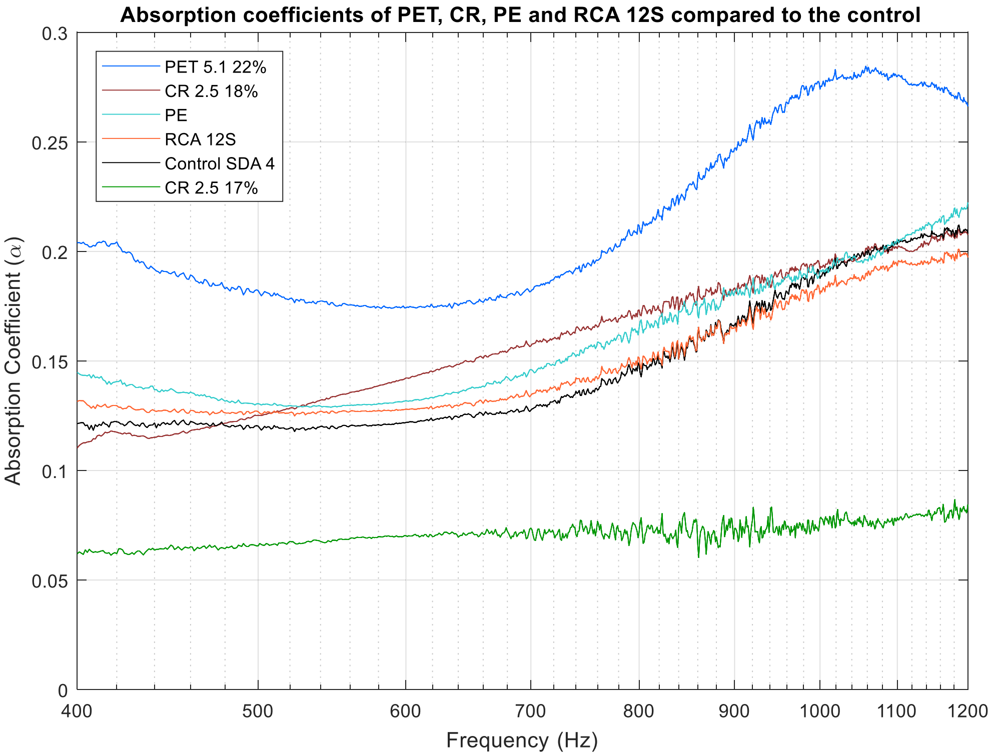

Fig. 2. Sound absorption as a function of frequency for a representative sample of four waste material modified mixture and the control SDA.

$$L_{TX,\lambda} = 10\log\left(\frac{Z_{p,\lambda}0.232/\lambda}{a_{\text{ref}}^{2}}\right)[\text{dB}] \quad [3]$$

Where $Z_{p,\lambda}$ is the 1/3 octave band PSD amplitude for a certain texture wavelength band,λ ; $0.232/\lambda$ is the corresponding bandwidth; and a_{ref} is the reference value of the surface profile amplitude (equal to 10^{-6} m according to ISO 13473–4). Given the sample sizes and the resolution of the scanner, L_{TX} was analyzed for texture wavelengths of 0.05–50 mm. ISO 13473–4 advises that the maximum texture wavelength analyzed, λ_{max} be much smaller than the evaluation length, l. In this case, $\lambda_{max} = l = 50$ mm. Given that ISO 13473–4 is written for laser scanners pulled by a car driving on the road, a high evaluation length is easier to realize than with laboratory samples. However, the modified laboratory method employed here is more precise than the field method prescribed as it is standstill and not attached to a moving vehicle.

o Texture scanning on larger samples with effects of wheel loading

The test was conducted on the rutting samples described previously, with a 100 × 50 mm area scanned for pre-test samples and a 100 × 25 mm scan in the middle of the wheel path for the post-rutting samples. The resolutions were 0.005 mm vertically, 0.006 mm along the length of the scan and 0.025 mm for the width. A total of 250 scan lines were conducted for each area scan and the L_{TX} was analyzed for texture wavelengths of 0.05–100 mm.

3. Results

3.1. Volumetric properties and compaction

Table 2 shows the porosity of all materials investigated. According to the Swiss standards a porosity between 14 and 18 percent is required for this type of semi-dense asphalt mixture samples [SN 640 436]. All the investigated materials were compacted to a certain height using the gyratory compactor as discussed in the materials section to obtain a porosity of ca 16% and therefore fulfilled this requirement except PET-5.1. This mixture produced with 5.1% of PET waste was very difficult to compact and therefore it had a much higher porosity than required. Additionally, both the CR and PET samples experience elastic rebound after the compaction affecting their porosity as listed in Table 2. The discussion of texture parameters of MPD and Rsk is provided in Section 3.3.

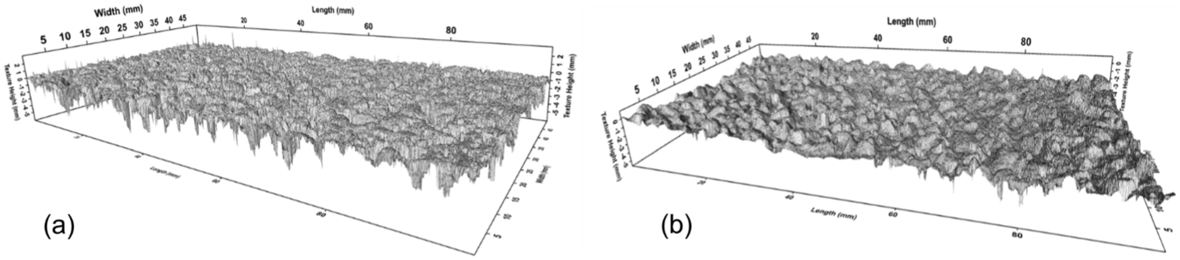

Fig. 3. Laser scanning profile (100x50 mm) of control sample before (a) and after (b) wheel loading.

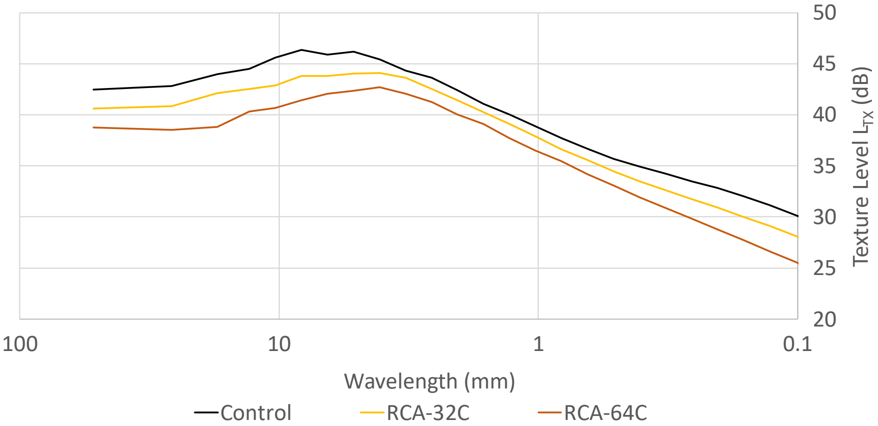

Fig. 4. Effect of Coarse RCA Replacement on Texture Level of Gyratory Samples.

3.2. *Normal incidence sound absorption coefficient values*

Fig. 1 and Fig. 2 show the measured normal-incidence sound absorption coefficient curves for the control and RCA as well as for, PE, PET and CR mixtures respectively. For each type of material six measurements were made, the plots show the mean and the standard deviation were below 0.02. Fig. 2 shows the absorption of representative of these materials for the sake of comparison. From these measurements it is apparent that with values around 0.2 at 1000 Hz, in an absolute sense, the sound absorption of all the SDA samples is relatively low. It can be seen from Fig. 1 that the absorption of all RCA modified mixtures were similar to the control SDA. The mixture with the most amount of coarse RCA (RCA 64C) had the smallest amount of absorption in comparison to the rest. Although as shown in Table 2, this mixture had a slightly higher porosity (17%). This leads to the conclusion that in addition to porosity the connectivity of voids plays an important role, i.e. the open porosity [Wang et al. 2016]. The absorption values shown in Fig. 2 indicate that PET with the highest porosity (22%) also had the highest absorption. From the two CR mixtures investigated, the CR with higher porosity also had higher absorption that was similar to the control. The comparison of the materials investigated shown in Fig. 2 indicates that 1) sound absorption values of the SDA mixtures are relatively low and 2) the use of waste materials for the most part did not compromise the noise absorption properties of the mixtures when compared to the control SDA.

3.3. *Surface texture*

As discussed above various waste modified mixtures were investigated. The interaction between these waste additives and the standard components could have an inherent effect on the noise relevant mixture properties such as voids and surface texture. An additional parameter affecting the surface texture is the compaction of the samples. The two compaction methods discussed in the methods section use different types of energy to compact. The gyratory compaction uses a kneading action whereas the steel roller compactor uses a rolling action. In addition once the pavement is laid it has to withstand traffic loads. Therefore an additional parameter is the surface texture under the wheel path that changes over time in comparison to that outside of the wheel path. Fig. 3 shows the laser scanning profile of the sample before and after exposure to wheel loads; it can be qualitatively seen that the profile is reduced after exposure to wheel loading.

However for comparison purposes, the texture parameters of all of the gyratory compacted samples shown in Table 2 are used. The MPD expressed in mm represents the texture amplitude in a single value, and is a complement to the texture level spectra discussed later. The Rsk represents whether the texture has a positive (>0) or negative profile, with a negative texture less susceptible to vibration, and therefore noise generation [Mikhailenko et al., 2020(2)]. MPD values between 0.826 mm for PE and 0.447 mm for CR

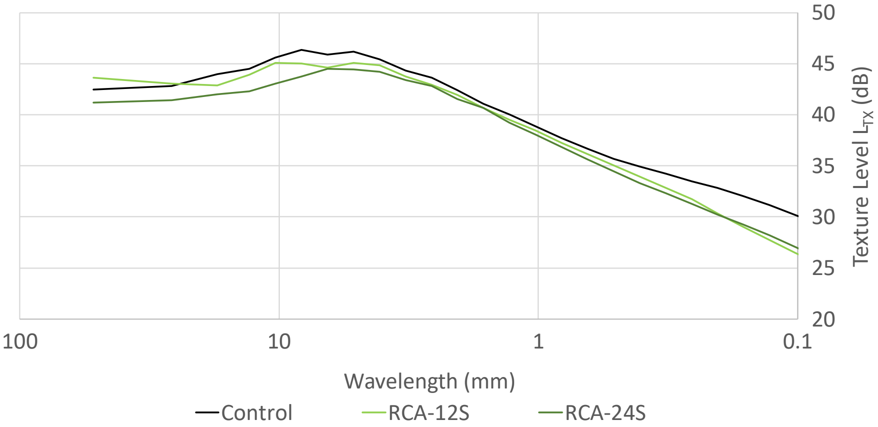

Fig. 5. Effect of RCA Sand Replacement on Texture Level of Gyratory Samples.

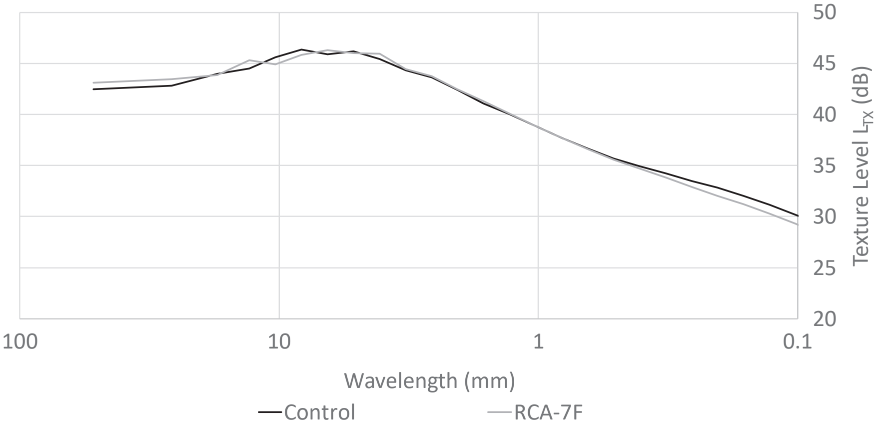

Fig. 6. Effect of RCA Filler Replacement on Texture Level of Gyratory compacted Samples.

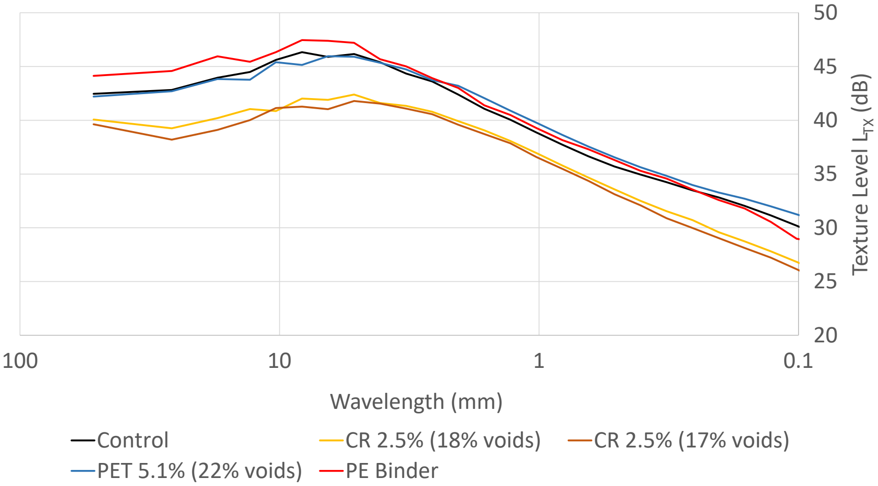

Fig. 7. Effect of CR and PET Sand Replacement, along with PE Binder Replacement on Texture Level of Gyratory compacted Samples.

Table 3
Texture Parameters for Wheel-Tracking compacted Samples after Compaction.

Sample	Porosity [%] mean	Std Dev [%]	MPD [mm] mean	Std Dev [mm]	Rsk mean	*Std Dev*
SDA 4 Control	15.2	0.2	0.801	0.048	−1.356	0.113
RCA-32C	17.3	0.0	0.656	0.057	−1.524	0.063
RCA-63C			Sample Failed Compaction			
RCA-12S	17.1	0.1	0.753	0.036	−1.464	0.179
RCA-24S	19.1	0.6	0.685	0.011	−1.537	0.092
RCA-7F	16.1	*	0.700	0.029	−1.334	0.020

*Single samples tested.

Table 4
Effect of Wheel Track Wearing on Texture Parameters.

Sample	%difference after Rutting		%difference from Controlbefore Rutting		%difference from Control in Wheel path	
	MPD	Rsk	MPD	Rsk	MPD	Rsk
SDA 4 Control	+25.4	−98.4				
RCA-32C	+22.8	−104.6	−18.2	+12.3	−18.1	−501.9
RCA-12C	+7.3	−105.1	−6.0	+8.0	−20.4	−515.2
RCA-24S	+17.7	−103.7	−14.5	−13.3	−19.9	−408.1
RCA-7F	+18.8	−102.6	−12.6	−1.7	−15.7	−269.9

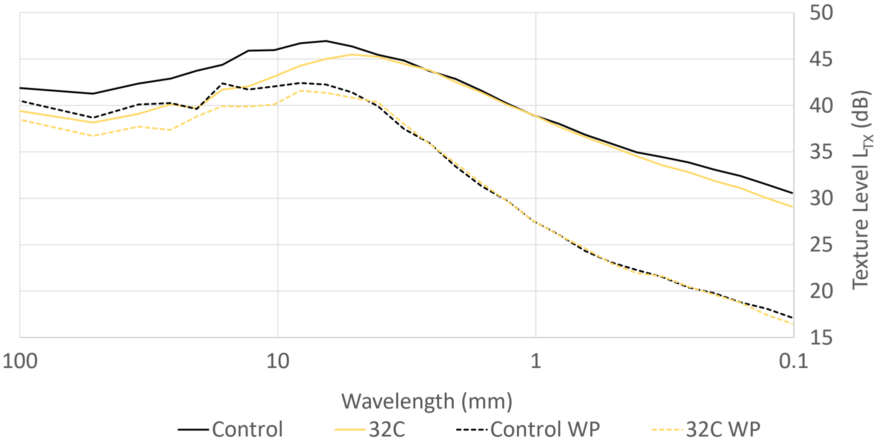

Fig. 8. Effect of Coarse RCA Replacement on Texture Level of Wheel Tracking compacted Samples showing lower texture level of the pavement under the wheel path (WP = Wheel Path).

mixtures were measured with the reference SDA being in between at 0.727 mm. These are within the range of in situ measurements of SDA mixtures reported in Bühlmann et al. (2017). However the MPD values tend to reduce with aging as reported in Bühlmann et al. (2017). The influence of MPD on the tire/pavement noise is frequency dependent and is not clear [Vázquez et al., 2020]. The skewness values were all negative indicating a negative profile ranging from −1.299 for RCA to −1.726 for CR with the control at −1.378. There are three main effects of the waste materials replacement on the MPD and Rsk of the control sample. The first is a similar result to the control in the PET replacement, where it should be noted, that the air voids content (porosity) is the highest, showing the predominance of material type in these properties. The second is a decrease in MPD and the skewness being more negative, especially with the CR replacement (at 2.5% of the aggregates). The replacement by the RCA coarse and sand at much higher contents also reduces the MPD and skewness. The replacement by RCA filler seems to increase the MPD, but this may be an outlier based on the results with roller compaction presented in Table 2. The MPD for the samples with PE modified binder also have a higher MPD than the control, but with similar values in skewness.

Fig. 4 and Fig. 5 show the effects of coarse and sand RCA replacement on texture level spectra respectively. Both replacement levels seem to lead to a general reduction in the texture level in comparison to the control SDA. The coarse RCA seem to have a higher effect on the macrotexture (8–50 mm) while the sand RCA seems to have a larger effect on the microtexture (0.1–1 mm). RCA filler (Fig. 6) shows that the texture level is not affected by this replacement.

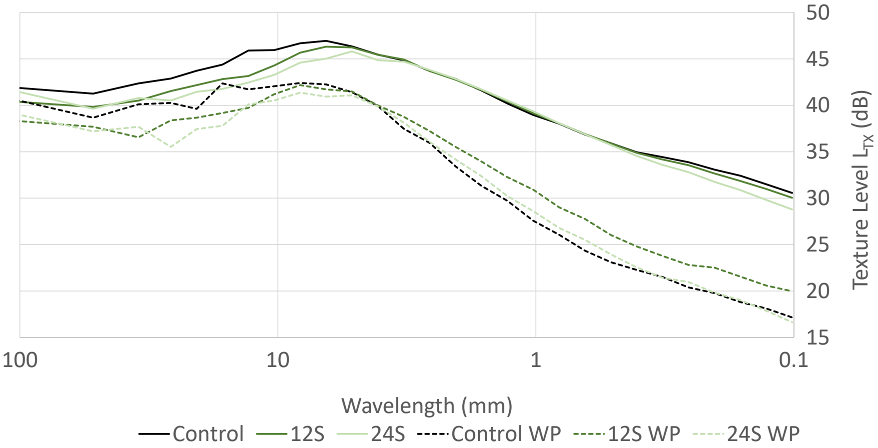

Fig. 9. Effect of RCA Sand Replacement on Texture Level of Wheel Tracking compacted Samples showing lower texture level of the pavement under the wheel path (WP = Wheel Path).

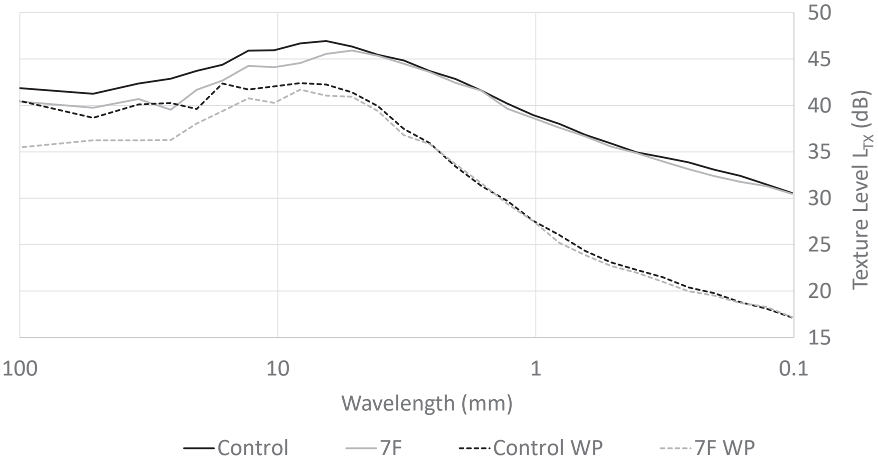

Fig. 10. Effect of RCA Filler Replacement on Texture Level of Wheel Tracking compacted Samples showing lower texture level of the pavement under the wheel path (WP = Wheel Path).

The effects of CR, PET and PE replacement on texture levels are shown in Fig. 7. Here, it can be seen that CR replacement significantly reduces the texture level as shown with the MPD. This effect does not seem to change significantly from 18 to 17% air void difference resulting from the post-compaction pressure on the latter sample. On the other hand, despite the PET sample having 6% more air voids (porosity) than the control, the texture level was not significantly affected as shown also with the MPD. No significant texture difference was noticed with PE binder used as well.

In addition to cylindrical 100 mm diameter gyratory compacted samples, larger plates of the same RCA mixtures were tested, where larger scan areas were possible (Table 3). The effect of the RCA replacement revealed a similar trend to the one of the gyratory compaction, with RCA replacement encouraging lower MPD and more negative skewness. The RCA filler sample was lower than the control this time in MPD while remaining the same in skewness.

In addition to the texture measurements after compaction the texture of the wheel path after the wheel track rutting test were also measured and compared to the texture before loading (Table 4). The effect of the wheel passes leads to an increase in the MPD and a more negative skewness for all of the samples. The MPD of the RCA samples decreases at about the samples proportion as the control, while the skewness is significantly more negative in the wheel path for the sand and coarse RCA samples and somewhat for the RCA filler.

The change in texture with RCA replacement and wheel track loading was also evaluated in terms of texture levels (Fig. 8, Fig. 9, Fig. 10). All of the samples show a substantial decrease in the microtexture within the wavelength range of 0.1–1 mm after the wheel track loading, which bring the control and RCA samples to the same level. The macrotexture (wavelength range 8–100 mm) however, remains higher for the control before and after the loading.

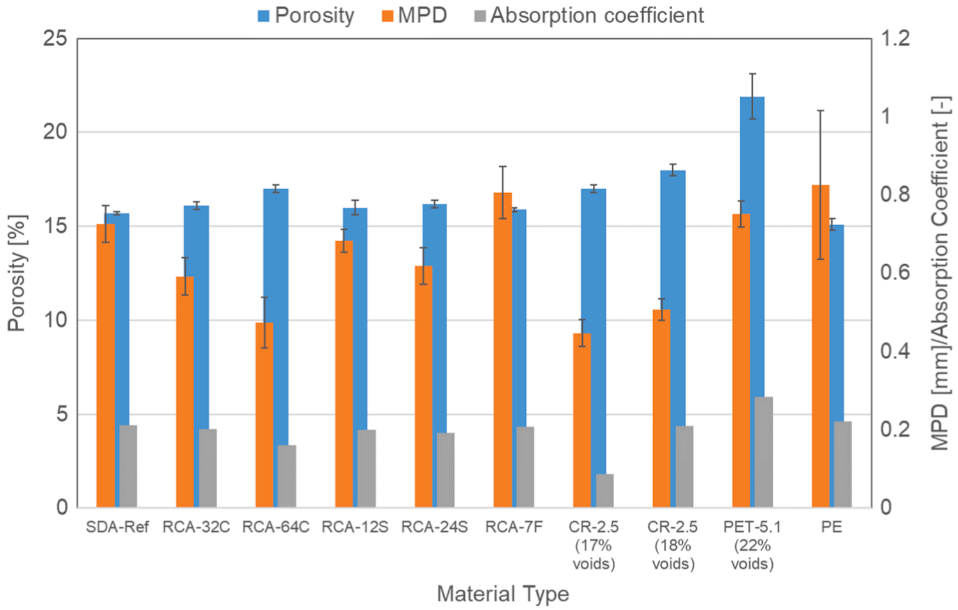

Fig. 11. Porosity, MPD and sound Absorption for the materials investigated.

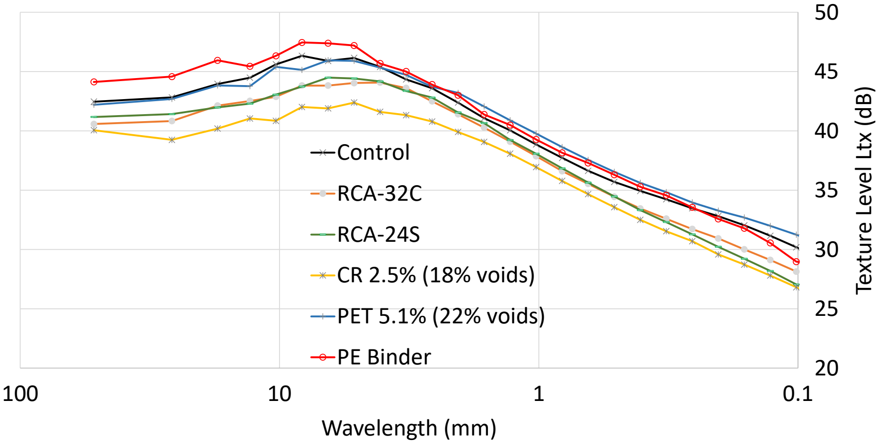

Fig. 12. Texture Level of Gyratory compacted Samples with Various Waste Material Replacement.

3.4. Discussion

Fig. 11 summarizes the measured parameters that affect the noise reduction properties of asphalt mixtures namely, porosity, MPD and sound absorption for all samples investigated. The maximum absorption obtained in the frequency range 800 and 1200 Hz is shown in Fig. 11. As discussed in the previous section, with the exception of the PET samples, the compaction using the gyratory compactor to the same porosity allows to isolate the effect of the waste addition and/or replacement. The results show that the different waste materials led to similar porosity and absorption indicators but very different values for the MPD as shown in Fig. 11. Furthermore the texture level is significantly reduced in comparison to the reference for all tested waste materials when aggregates substitution was done (Fig. 12). This is apparent with the PE modified mixture, which did not have any aggregate substitution and therefore similar texture level to the control mixture. The waste material with the highest effect on absorption and texture level and MPD was the CR modified mixture whereas the material least affected was the PET and PE modified mixture. This difference due to aggregate substitution can be attributed to the physical properties of the particular aggregates, such as CR which contains elastomers in comparison to the rigid natural sand. The data shown in Fig. 13 indicated a very weak correlation ($R^2 \approx 0.21$) between sound absorption and porosity for these samples. Sound absorption is affected primarily by connected porosity to the surface of the samples. Therefore, the results show that the connectivity is low in the case of the SDA mixtures examined here. Furthermore it should be noted that the porosities investigated here were kept at a narrow range in order to observe the effect of waste materials on the sound absorption.

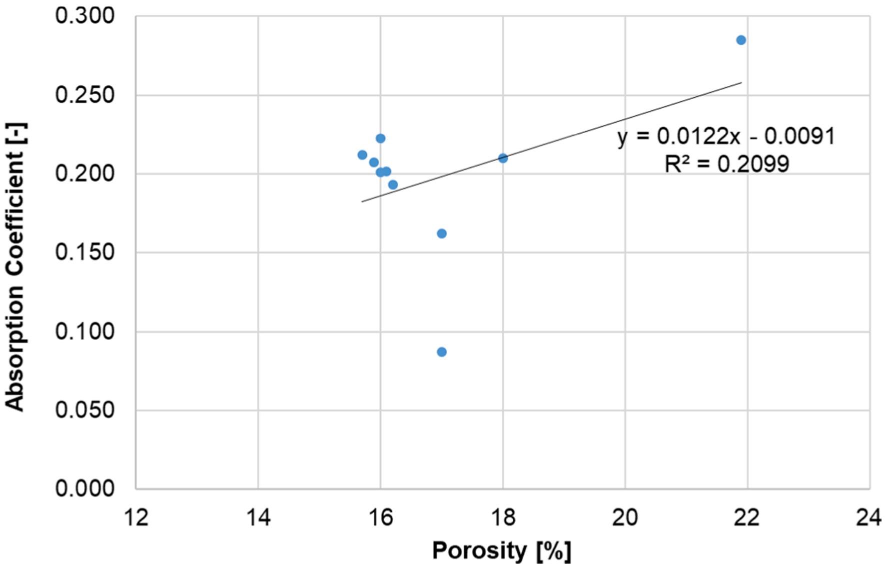

Fig. 13. Overall correlation of sound absorption and porosity.

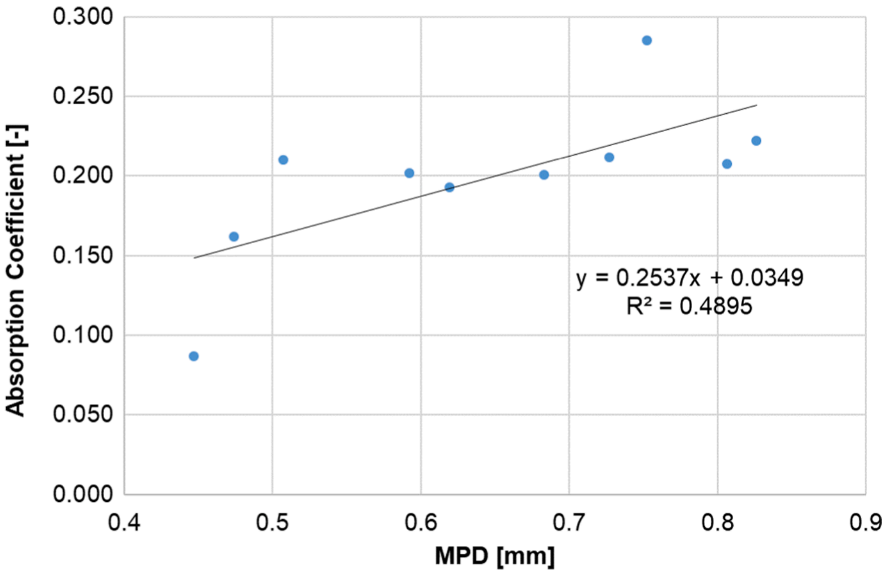

Fig. 14. Overall correlation between sound absorption and MPD.

Similarly, the data shown in Fig. 14 indicated a slightly better correlation ($R^2 \approx 0.48$) between sound absorption and MPD for these samples.

Bühlmann and Hammer (2017) have shown that semi-dense asphalt mixtures require a different standardization approach which cannot primarily rely on void content as a target measure as it leads to large acoustic variability. Their experimental results showed that all well-performing surfaces show low airflow-noise; implying well-connected voids; and low filler & sand content. The latter was deemed as most important factors regarding acoustic long-term performance as high filler and/or sand content can block pores from the surface and directly impact the low noise performance.

4. Conclusions

Various types of waste materials were used in the production of semi-dense asphalt mixtures normally used as low noise pavements. As shown in section 1, these mixtures have shown comparable mechanical performance to control mixtures containing no waste materials. For several mixtures noise-relevant characteristics namely porosity, sound absorption and surface texture were investigated. The following observations were made:

- With values around 0.2 at 1000 Hz frequency, in an absolute sense, the sound absorption of all the SDA samples is relatively low, leading to the conclusion that sound absorption is not the main noise reduction mechanism for these types of asphalt mixtures.
- A very weak correlation between sound absorption and porosity was found, leading to the conclusion that pore connectivity to pavement surface should be measured that would be the more relevant pavement property for sound absorption.
- A slightly better correlation between sound absorption and MPD was found.
- The comparison of the materials investigated indicates that the use of waste materials for the most part did not compromise the sound absorption properties of the mixtures when compared to the control SDA. One exception was observed in the case of CR. The CR replacement at the relatively high levels used here, affected the sound absorption properties. Even with higher percentage of voids the absorption values were similar or lower than the other mixtures.
- The mixtures containing PET had similar texture level in comparison to the control SDA although the PET mixture had a higher porosity, leading to the conclusion that the material type had a stronger effect on the surface texture than porosity.
- The mixtures containing waste materials showed a decrease in MPD, more negative skewness, especially with the CR replacement (at 2.5% of the aggregates), indicating a texture favorable for lower noise.
- Absorption of all RCA modified mixtures were similar to the control SDA. The texture level was not affected by RCA filler replacement.
- Both control and waste mixtures show a large decrease in the microtexture amplitude after the wheel track loading. No significant effect of the added waste material could be measured.
- The texture level was most affected with the CR modified mixture whereas less effect was observed with the PET modified mixture.
- The investigated samples indicate MPD alone as a measure for noise reduction of asphalt pavements is not enough and there are other parameters that should be also considered.

The results showed that the predominant noise reduction property in SDA mixtures, studied in this work, is surface texture. The use of waste materials did affect some of the acoustic properties of these mixtures primarily in terms of reducing the macrotexture amplitude. The results presented can aid in policy decisions pertaining to noise abatement as well as waste reduction. In future research other noise relevant parameters such as pore connectivity, tortuosity, flow resistivity and elasticity should be investigated. The work presented here aimed at predicting in-situ acoustic performance using laboratory parameters however this needs to be validated using in situ data including acoustic aging that is an important parameter that needs to be further investigated. Traffic noise is the result of the interaction of tires with the pavement, our research provided some information on the pavement side that can be used for an initial selection process. Ultimately measurements of the tire pavement interaction can provide the needed information for pavement selection. This can be done with in situ measurements or testing rigs that can simulate this interaction.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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