Sound absorption capacity of hot and warm asphaltic mixes modified with waste plastic bottles

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Abstract. Vehicular traffic is one of the noise-producing factors contributing to environmental problems. Utilizing special asphaltic mixes can help reduce noise generation. Thus, this research evaluated the sound absorption capacity (SAC) of hot mixed asphalt (HMA) and warm mixed asphalt (WMA) modified with pyrolyzed polyethylene terephthalate (PET) bottles varying at 1-17 wt. %. PET bottles were pyrolyzed at 450 °C for a 2 h retention period, obtaining pyrolyzed PET bottle (PTB). HMA and WMA were prepared with 0-17 wt. % PTB and the SAC values were tested. The results were compared to a control mix, a standard HMA or WMA without any PTB modification, to provide a baseline for the evaluation. The effects of volumetric and Marshall properties of HMA and WMA on SAC were correlated. The results revealed decreased sound levels with increasing PTB dosage in the HMA. However, WMA generated increased sound levels as PTB content increased from 1-9 wt. % but decreased after 9 wt. % of PTB substitution. HMA and WMA performed best at 11 and 7 wt. % PTB with corresponding SAC values of 78.23 and 80.53 dB compared to the control mix with 79.33 dB.

Keywords: Asphalt, Plastic Bottles, Recycling, Sound Absorption, Sustainability, Waste Management.

1. Introduction

One of the leading causes of noise pollution in cities nowadays is road traffic noise. High road traffic noise levels in affluent nations expose about 40 % of the population to health risks and sleep disturbances [1]. Vehicle technology advancements have significantly decreased engine and exhaust system noise, leaving tire and pavement noise as the primary source of road traffic noise [2]. Research indicates that at speeds exceeding 40 and 60 km h^{-1} for passenger cars and trucks, tire-pavement noise predominates over other forms of traffic noise [2]. In European countries, traffic noise is second among environmental stressors significantly influencing public health [3]. The compression of the tire tread against the pavement texture is the primary cause of rolling noise. In open-graded mixtures with high texture, less compression is experienced than in dense mixtures due to the dissipation of air gaps created during the tire/pavement interaction at this interface [4]. The totality of tire and pavement characteristics dictates the amount of noise produced and the extent to which the pavement absorbs it. The combination of noise-absorbing pavements and decreased traffic noise generation offers a promising solution to the issue of noise pollution, instilling hope for a quieter and healthier urban environment [4].

Researchers and pavement engineers have investigated various pavement-wearing course designs to lessen the noise produced by tire-pavement interaction. Nowadays, the most popular pavement application utilized globally to reduce traffic noise is porous asphalt pavement, which has been shown in studies to be an effective pavement type [5,6]. Compared to traditional dense asphaltic mixtures, porous asphaltic mix reduces noise by up to 6 dB because of its high air void content and enhanced texture and shape [7]. Epoxy-based porous asphaltic concrete also lessens hydroplaning, which improves visibility and safety during wet spells [8]. The porous asphaltic mixtures' sound absorption capacity (SAC) accounts for roughly 23–33 % of the overall tire-pavement noise reduction [6]. The sound absorption of dense-graded conventional and rubberized asphaltic mixtures did not differ significantly [5]. Nonetheless, crumb rubber can enhance sound absorption in blends with a high void percentage [4].

Among the most serious problems facing humanity are the environmental effects of global warming. Significant fuel and energy consumption leading to pollutant emissions contributes to the flexible pavement, which predominantly uses hot mixed asphalt (HMA). Conversely, warm mixed asphalt (WMA) technology was developed to meet economic, environmental, and societal needs [9]. Aggregate, asphalt binder, and filler are the three primary components of most asphaltic mixtures. Approximately 94-66 % of the weight of the mix is made up of aggregates and fillers, with asphalt binders making up the remaining 4-6 % [10]. The utilization of waste materials in asphalt modification has drawn much attention in searching for environmentally acceptable and sustainable methods in recent years.

The environment and human health are at risk because of the inadequate management of waste materials [11,12]. In 2016, about 19-23 million metric tons of plastic waste entered the global aquatic ecosystem, an increase from 2010's estimate of 4.80-12.70 million [13], while its degradation releases greenhouse gases and pollutes terrestrial and marine habitats [14]. Various studies have recycled polyethylene terephthalate (PET) waste bottles, mitigating environmental pollution and promoting sustainable construction [15–17].

Pavement engineers are interested in reducing tire-pavement noise and maintaining the ability to absorb sound during service while designing asphaltic mixes. Such a mixed design is currently unavailable to assess the SAC of asphaltic mixes modified with waste PET bottles. This paper evaluates the SAC of HMA and WMA modified with pyrolyzed PET bottles (PTB). HMA and WMA were modified with 0-17 wt. % PTB and the SAC values were tested under controlled laboratory conditions. The effects of volume of voids (Vv), voids filled with bitumen (VFB), specific gravity (SG), bulk density (GM), optimum bitumen content (OBC), stability, and flow on SAC of HMA and WMA were correlated. The potential effects of PTB on SCA of asphaltic mixtures would be advantageous by providing confidence in the benefits of plastic addition, reducing waste, and promoting a healthier environment.

2. Materials and methods

2.1 Materials

The 60/70 penetration grade bitumen was sourced from Reynold Construction Company Limited, Ibadan, Nigeria. Sasobit, a commonly used WMA additive, was obtained from Asphalt Leverage Limited, Ibadan, Nigeria. Aggregates and quarry dust were sourced from a local quarry in Ede, Nigeria. Coarse aggregate (CA) (granite, ≤ 10 mm size) and fine aggregate (FA) (quarry dust, ≤ 4.75 mm size) were used as mineral aggregates, while powdered quarry dust (PQD) was used as a mineral filler (MF). The quarry dust was pulverized using an abrasion machine and sieved below 75 µm, obtaining PQD.

As post-consumer plastic wastes, the PET bottles were gathered from Adeleke University and Ara Bahnat plastic product company, Ede, Nigeria. The PET bottles were thoroughly cleaned and sorted to ensure no contaminants. As illustrated in Figure 1, the PET bottles were cut into pellets (at a 1:2 aspect ratio) using scissors to reduce their sizes, boost their surface area, and aid in pyrolysis. As shown in Figure 1, the pyrolysis reactor was used for the pyrolysis process. The reactor’s cooling and heating units were lagged to prevent heat from escaping into the surrounding area, and the samples were fed into the pyrolysis reactor at 450 ºC for 2 h to dissolve to liquid form for effective miscibility with asphalt. Table 1 displays the physical properties of the used PET bottles.

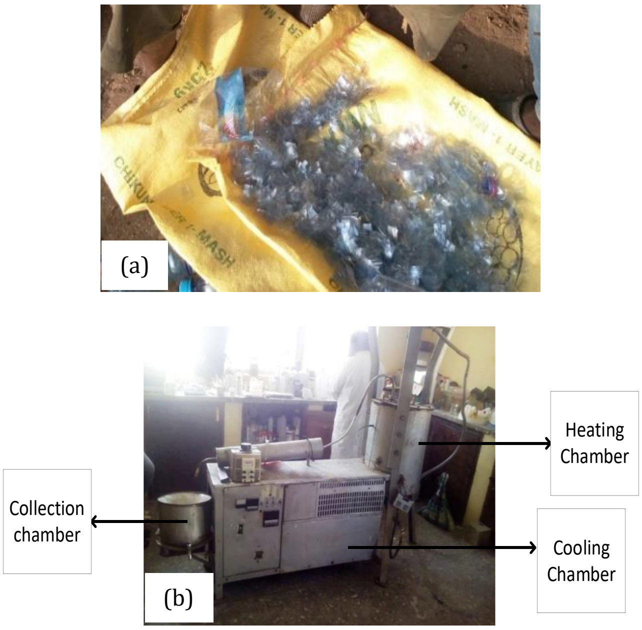

Figure 1: Material and equipment used (a) shredded PET bottles and (b) Pyrolysis reactor.

Table 1: Physical properties of PET bottles.

Property	**Details**
Plastic type	Pelletized plastic water bottles
Plastic material	Polyethylene Terephthalate (PET)
Size (mm)	15-25
Density (gcm^{-3})	1.38
Melting point (^{o}C)	260

2.2 Methods

2.2.1 Mixed design

A suitable wearing course mix was designed per the Federal Ministry of Works and Housing (FMWH) [18], consisting of 35 % of 10 mm CA and 65 % of FA. This mixed design ensures an ideal balance of particle sizes, promoting improved performance and durability of the resulting asphalt mixes. This design considered the specific properties and proportions of the sampled aggregates. The mixed design proportions are presented in Table 2.

Table 2: Mixed design

BS sieve (mm)	**Materials percentage passing**			**Range of materials/sieve**		**Total blend**	**Average specification**	**FMWH specification**	
				35 %	**65 %**			**Upper**	**Lower**
	CA (10mm)	**FA (QD)**	**MF (PQD)**	**10 mm**	**QD**				
20	100	100	100	35	65	100	100	100	100
14	100	100	100	35	65	100	92.50	85	100
9.50	71.70	100	100	25.10	65	90.10	83.50	75	92
6.30	18.80	100	98	6.60	65	71.60	73.50	65	82
2.36	1.90	85.73	92	0.70	55.70	56.40	57.50	50	65
1.18	1.30	67.02	81.80	0.40	43.60	44	43.50	36	51
0.600	1.20	49.63	61.10	0.40	32.30	32.70	33	26	40
0.300	1.20	33.38	25.50	0.40	21.70	22.10	24	18	30
0.150	10	19.68	6	3.50	12.80	16.30	18.50	13	24
0.075	1	17.22	4.10	0.34	11.20	11.50	10.50	7	14

2.2.2 Preparation of optimum bitumen content

Approximately 1200 g of a mix consisting of various percentages of aggregates and mineral fillers, as specified by the mixed proportion, were blended and placed on the hot plate for each Marshall sample following the Asphalt Institute manual series MS-2 (AI) [19] and ASTM D 1559-89 [20]. The PTB was measured and mixed with the bitumen at a rate of 1-17 % at intervals of 2 %, with a sample container with no PTB addition serving as the control. Sasobit was added at a weighted rate of 3 % bitumen to create a modified warm mixed specimen. The detailed mixed samples are displayed in Table 3. Hot and warm blends were heated to 110 and 155 ^{o}C. The mixing was done in no more than 15 minutes to avoid temperature losses. The mixtures were compacted to super-pave standards with a 4.54 kg rammer that impacted the sample 75 times at the top and bottom, falling freely from a height of 457 mm. The hot and warm mixed specimens demonstrated the best performances of optimum bitumen contents (OBC) at 6.70 and 5.40 %, with PTB dosages at 11 and 7 %. These resulted in maximum Marshall stability and flow of 54 kN and 2.60 mm for HMA and 54.67 kN and 2.18 mm for WMA.

Table 3: Detailed sample preparation.

S/N	Property	Constituents
1	Hot bitumen blend (HBB)	Dissolved PTB + bitumen
2	Warm bitumen blend (WBB)	Dissolved PTB + bitumen + 3 % Sasobit
3	Hot mixed asphalt (HMA)	HBB + aggregates + mineral filler
4	Warm mixed asphalt (WMA)	WBB + aggregates + mineral filler

2.2.3 Experimental tests

The HBB and WBB underwent tests per ASTM specifications to determine their ductility at 25 ºC [21], penetration at 25 ºC, 100 g, and 5 s [22], softening point [23], flash point [24], fire point [24], specific gravity at 25 ºC [25], and viscosity [26]. After 30 minutes of curing in hot water at 60 ºC, the samples were taken from curing tubs and allowed to cool for 2 minutes, and the Marshall characteristics of HMA and WMA were tested. The Marshall stability and flow of HMA and WMA samples were determined following ASTM D 6927 [27]. Volumetric properties of HMA and WMA, such as BD, VV, and VFB, were determined per AI methods [19].

2.4 Sound absorption capacity

The sound absorption capacity (SAC) of HMA and WMA samples was tested using a sound absorption apparatus (SL 4010) shown in Figure 2. A hollow shape was made in the specimen to accommodate the apparatus for the sound test. A sound source was created to ensure no interference from the surroundings, achieved by carrying out the test behind a closed door. The sound was then played at constant volume; reading was taken and designated as the initial sound level. The initial sound level (ISL) was measured using the sound level equipment before being placed on the asphalt test sample. After that, the device was set on the hollow section, and the sound continued to play at the same volume. The final sound level (FSL) was determined by taking a reading as well. Hence, the SAC (in dB) was calculated using Equation (1):

$$SAC = \frac{ISL - FSL}{ISL} \times 100 \quad (1)$$

Figure 2: Sound absorption apparatus.

3. Results and Discussion

3.1 HBB and WBB

Table 4 presents the properties of HBB and WBB. The findings showed that the penetration in HBB and WBB reduced as the PTB dosage increased because the PTB particles stiffened the asphaltic binder, decreasing penetration. These results align with earlier research that found decreased penetration as waste polymer and byproducts increased [28]. Nonetheless, 5–9 % and 3–11 % PTB dosages met the 60–70 mm penetration requirement for HBB and WBB, indicating the feasibility of PTB in enhancing HBB and WBB penetration capability. Unlike HBB, the softening, flash, and fire points of WBB decreased as PTB content increased. These can be ascribed to Sasobit's addition to WBB, lowering the temperature at which bitumen generates sufficient vapour to ignite [29]. The exhibition of higher thermal performance in HBB than that of WBB can be related to the presence of PTB, which increased the temperature required for the modified asphalt to generate ignitable vapors [30]. Ultimately, 3-5 % and 1-11 % PTB dosages in HBB and WBB met the specified softening points of 48-56 °C. Furthermore, all blends met the minimum flash and fire points of 250 °C, except 15 and 17 % PTB dosages of WBB. This demonstrates an acceptable range of safety standards for handling and transportation.

Table 4: Properties of HBB and WBB.

Property	**Bitumen blend**	**PTB dosage (%)**										**Standard**	
		0	**1**	**3**	**5**	**7**	**9**	**11**	**13**	**15**	**17**	**FMWH**	**ASTM**
Penetration (mm)	HBB	77	75	73	70	67	61	56	52	45	40	60-70	60-70
	WBB		71	69	68	68	64	61	58	52	49		
Softening point (°C)	HBB	47	53	57	59	62	67	72	78	84	94	48-56	48-56
	WBB		54	51	51	51	50	49	46	44	42		
Ductility (cm)	HBB	107	105	104	104	102	100	98	87	72	59	≥ 100	≥ 100
	WBB		106	105	105	103	101	99	91	85	76		
Viscosity (s)	HBB	76	78	79	82	84	86	88	90	96	98	-	≥ 70
	WBB		75	74	74	73	73	72	70	65	65		
Flash point (°C)	HBB	255	256	262	267	276	279	286	290	295	298	≥ 250	≥ 250
	WBB		251	251	251	250	250	250	249	245	244		
Fire point (°C)	HBB	308	311	316	319	321	325	329	336	344	346	≥ 250	≥ 250
	WBB		307	306	306	305	305	305	303	302	302		
Specific gravity	HBB	0.96	0.96	0.97	0.98	0.99	1.00	1.01	1.01	1.02	1.03	1.01-1.06	0.97-1.06
	WBB		0.98	0.99	1	1.01	1.01	1.02	1.03	1.03	1.03		

The ductility of HBB and WBB, as shown in Table 4, decreased with increasing PTB content. However, the results revealed that WBB was more ductile than HBB, indicating a WBB's ability to undergo significant deformation before fracture. This supports previous research that found warm, high-density polyethylene-asphalt concrete mixed with Nano clay had more ductility than hot samples [31]. Ultimately, it can be inferred that 1-9 % PTB dosage fulfilled the minimum ductility value of 100 cm recommended by FMWH[18] and ASTM [21].

Viscosity measures the thickness and flow resistance of bitumen. From Table 4, HBB samples were more dense than the control mix. Nonetheless, WBB was less dense than the control due to the 3 % Sasobit addition to WBB. The viscosity increased for HBB in Table 4 from 78 to 98 s, with a 20 s difference for 1–17 % PPB level. However, WBB demonstrated a drop in viscosity between 75 and 65 s, differing by 10 s at 1–17 % PPB dosage from the control bitumen, which had a viscosity of 76 s. These findings align with the rheological characteristics of warm asphalt mix modified with surfactant and foaming additions. This markedly enhanced the foamed bitumen, attaining 69 s at a foaming Evotherm-DAT level of 6 % [32]. Thus, except for 15 and 17 % PTB dosage, the PTB demonstrated the potential to improve the performance of bituminous mixes, satisfying 70 s minimum viscosity.

Specific gravity is a significant property that affects the overall density and volumetric parameters of bituminous mixes. As indicated in Table 4, the specific gravity of HBB and WBB were within the required specifications of 1.01-1.06 [18] and 0.97-1.06 [25], maintaining the intended performance and quality benchmarks.

3.2 Sound absorption capacity

Figure 3 shows the level of sound absorption of HMA and WMA in relation to the PTB substitution. Figure 4 displays the correlation between sound level and Marshall properties of HMA and WMA. From Figure 3, the sound level of HMA decreased with increasing PTB dosage compared to the control mix. In addition, Figure 3 reveals that more sound was absorbed by HMA at 3, 13, and 15 % PTB dosages, representing about a 3 % decrease in sound level compared to the control (unmodified) mix. It can be observed from Figure 4 (a) that HMA's sound level exhibited a moderate correlation with flow (0.33), signifying an improved sound absorption capacity with moderately increased flow. However, there was a moderate negative correlation (-0.37) between sound level and SG and a strong negative correlation between sound level and OBC (-0.70). Statistically, these results showed that the flow had the highest positive correlation (0.33), and OBC had the highest negative correlation. This suggests that, due to the positive collinear relationship between the two, an increase in Marshall flow could likely increase sound level [33]. Conversely, OBC has the strongest negative collinear relation with sound level, which could increase the absorption capacity [33].

In comparison to the control (unmodified) mix, which had a sound level of 79.33 dB, the analysis of the WMA in Figure 3 revealed that the sound level increased from 79.33 to 80.53 dB as the PTB content increased from 3 to 9 %. However, adding 9-17 % PTB dosage to WMA reduces the sound levels by approximately 1-4 % compared to the control mix. Moreover, 13 % PTB dosage generated the best SAC for WMA, emitting a sound level of 76.60 dB, 3.56 % lower than the control sample. The correlation analysis shown in Figure 4 (b) indicated that Marshall flow and volume of voids (Vv) had a negatively negligible relation (-0.27) and moderate correlation (-0.37) with WMA's sound level. These indicate that Marshall flow and Vv had no significant impact on the sound absorption capacity of WMA. This is because Sasobit was added to WMA, which showed superior binder dispersion and void filling, indicating increased cohesion and resistance to moisture damage.

Conversely, previous research confirmed that the percentage of void volume influences the sound absorption coefficient of asphaltic mixes. The sound absorption capacity increases with the increasing percentage of void volume [5]. The rubberized open-graded friction course was found to have a lower absorption peak than the rubberized porous coat due to its low percentage of air voids, even though the proportion of void volume was equal [5]. Similarly, a strong correlation of 0.94 R^2 was shown in the relationship between the maximum sound absorption coefficient and the percentage of air voids. In other words, the coefficient showed that the maximum sound absorption rises by 0.04 for every unit increase in the percentage of air void content [4,34]. Figure 4 (b) shows a positively moderated correlation (0.39) between the VFB and sound level, suggesting an enhanced SAC with moderate VFB. Similarly, there was a strong positive association (0.64) between the sound levels of WMA and OBC. This indicated that a higher OBC increased WMA's ability to absorb sound. The specific gravity (SG), as shown in Figure 4 (b), yielded the strongest negative collinear relation (-0.65) with sound level. This demonstrated that a lower SG led to a higher SAC. This finding supports relevant research showing that a lower specific gravity denotes a porous asphalt mixture with higher air voids [4].

Contrary to earlier research, which found no discernible variations in sound absorption between the rubberized dense asphalt mix and the conventional dense asphalt mix (0.05 and 0.03 %). The results obtained herein suggest that the use of PTB and Sasobit in HMA and WMA has a significant effect on sound absorption because the difference between the asphaltic mixtures (HMA and WMA) and control (unmodified) mixture varied between 1-4 %.

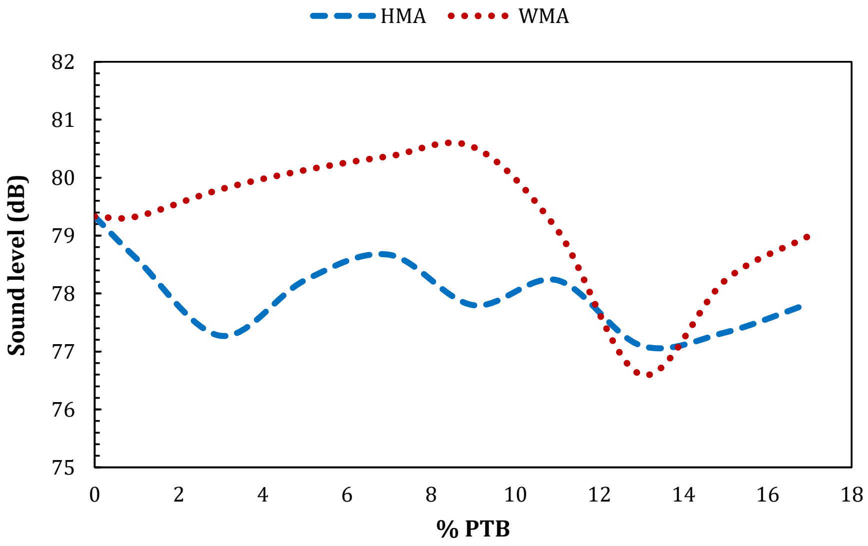

Figure 3: Effects of PET on the sound absorption capacity of HMA and WMA.

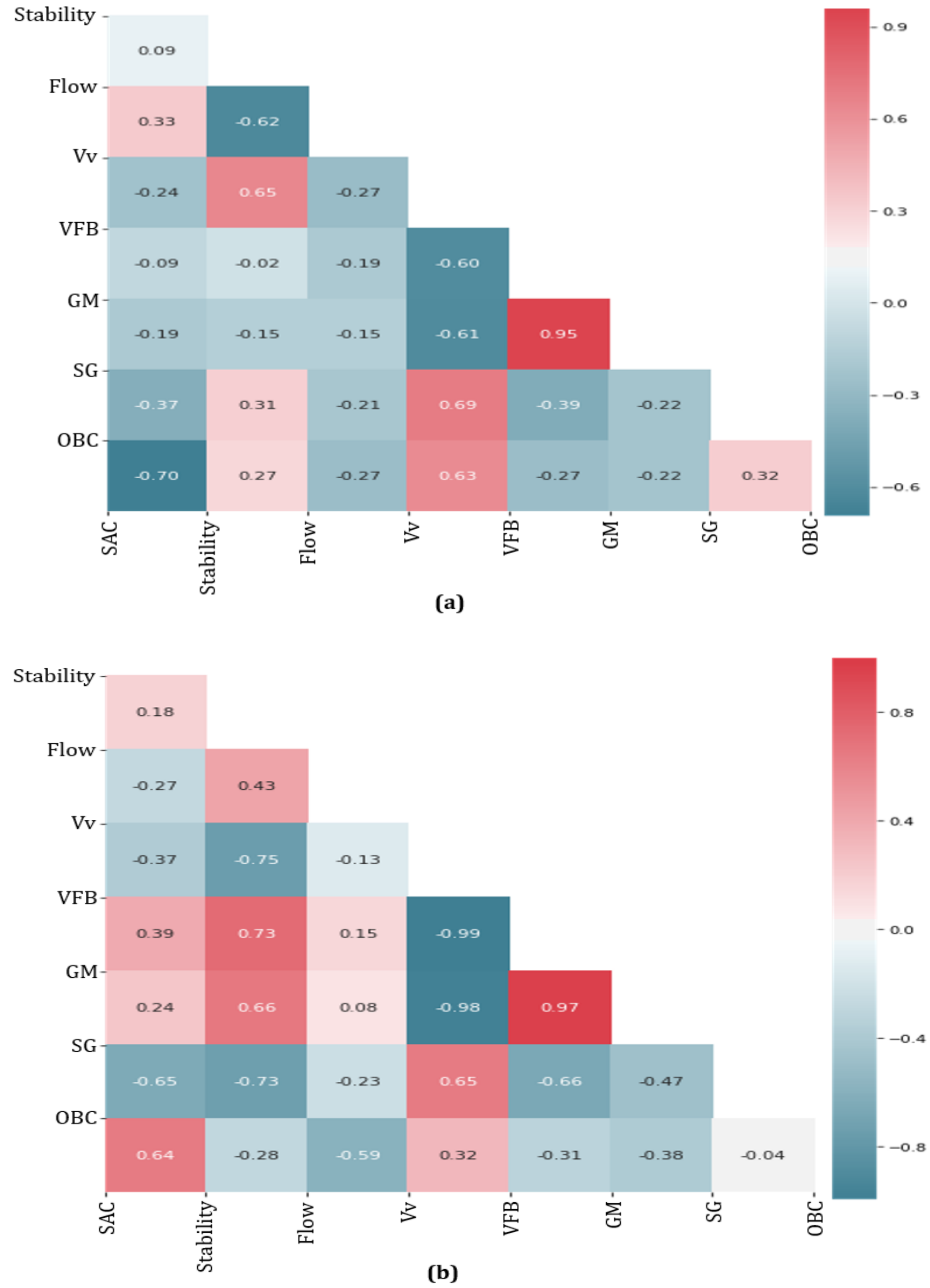

Figure 4: Correlation coefficients showing the relationship between the sound absorption capacity and the asphaltic mixes for (a) HMA and (b) WMA.

4. Conclusion and Recommendation

This research investigated the sound absorption capacity (SAC) of HMA and WMA modified with 0-17 wt. % PTB dosage. The physical properties of hot and warm blended bitumen were evaluated. Similarly, the effects of HMA and WMA's volumetric and Marshal properties on SAC were examined. Based on the research's findings, the following inferences can be made:

PTB exhibited a good modifier with the necessary mechanical and physical qualities, meeting the standard requirements for asphaltic mixtures. HMA and WMA demonstrated optimum bitumen contents (OBC) at 6.70 and 5.40 % with PTB dosages of 11 and 7 %, resulting in maximum Marshall stability and flow of 54 kN and 2.60 mm for HMA and 54.67 kN and 2.18 mm for WMA. There was a 1-3 % decrease in sound level as HMA's PTD dosage increased from 1-17 wt. %, signifying about 2 % decrease at OBC. However, the sound level in WMA increased by approximately 1-2 % as PTD dosage with 3 % Sasobit increased from 1-9 wt. %. At OBC, WMA generated about a 2 % increase in sound level. Nonetheless, from 11-17 wt. % substitution levels, the WMA's sound level decreased by about 1-4 %.

This research demonstrates that PTB is a good modifier for enhancing the sound absorption capacity of asphaltic mixes. However, incorporating Sasobit as an additive in WMA must be optimized to guarantee an improved SAC. Even with these promising findings, more investigation is required to comprehend the mechanisms responsible for the generation and spread of the tire-pavement noise in the experimental sections where PET waste bottles were added as a pyrolyzed modifier, as it relates to the characteristics of the road surface.

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