



# High and low temperature performance of polyethylene waste plastic modified low noise asphalt mixtures

Muhammad Rafiq Kakar<sup>a,b,\*</sup>, Peter Mikhailenko<sup>a</sup>, Zhengyin Piao<sup>a,c</sup>, Lily D. Poulikakos<sup>a</sup>

<sup>a</sup> Empa, Swiss Federal Laboratories for Materials Science and Technology, Switzerland

<sup>b</sup> Bern University of Applied Sciences, Department of Architecture, Wood and Civil Engineering, Bern, Switzerland

<sup>c</sup> ETH Zurich, Institute of Environmental Engineering, Switzerland

## ARTICLE INFO

### Keywords:

Asphalt  
Polyethylene  
Waste recycling  
Semicircular bending  
Cyclic compression test

## ABSTRACT

Waste plastic in low noise asphalt mixtures can be a viable alternative to asphalt mixtures with polymer modified bitumen. The performance of low noise semi dense asphalt (SDA) mixtures with waste polyethylene (PE) plastic is investigated. The cyclic compression test (CCT) and semi-circular bending (SCB) test was used for characterization of high and low temperature performance. The CCT results revealed that the PmB mixture had shown significantly higher resistance compared to the PE mixture. However, the PE modification showed some improvements in terms of CCT loading when compared with mixtures using the same base binder without PE. The SCB test results found that on average using higher content of PE mixtures had slightly improved fracture energy and lower fracture toughness compared to asphalt mixtures using polymer modified binder (PmB). The electron microscopy images showed that the PE does not completely melt during the mixing process and exists as elastic bodies within the mixture. The findings showed that at low temperatures, both PE and binder behave elastically, whereas at higher temperatures, PE remains elastic, and binder's viscoelasticity becomes dominant. These results highlight the importance of selecting proper base binder for such modifications with waste plastic.

## 1. Introduction

Asphalt mixture production is mainly reliant on the use of natural materials such as mineral aggregates and asphalt binder. The role of asphalt binder is very important in terms of its performance as it binds the mineral aggregates and imparts strength when in service. In Switzerland, one of the main streamline strategical priority areas is to improve the sustainability of road paving materials including asphalt binder. Therefore, the idea of using alternative materials more specifically waste plastic in road construction is an option that is being explored since the current environmental perspective is alarming due to higher amounts of waste generation. This option has the potential to reduce the use of traditional polymers as modifiers and reusing waste plastics, thereby contributing to sustainability from two aspects.

In many European countries, in order to protect the environment and promote the utilization of waste materials, higher recycling rates for waste plastic are being encouraged [1–2]. Waste plastic materials can be used as an alternative for the improvement of asphalt mixtures durability [3–4]. Furthermore, it can become cost effective in terms of avoidance of repair and maintenance of road pavements as a result [5].

Also, the use of waste plastic in asphalt mixtures would on the one hand reduce the amount of binder used in asphalt mixtures, and on the other hand reduce the overall cost of the whole project [6].

Previous laboratory studies have shown that PE modified asphalt binders and mixtures perform well regarding high temperature stability [7], fatigue [8] and moisture resistance [9–10] permanent deformation [11]. However, the practical usage of PE modified asphalt in engineering projects has not been widely explored. This is reflected in the technical readiness level of ca 5–7 (within a scale of 1–9) indicating that only pilot projects have been implemented in the field [2]. The reasons are manifold, including lack of incentives, legislation and implementation knowledge. The performance issues include two main aspects: firstly, the high temperature storage stability [12–14] and secondly, some researchers believe that the addition of PE in asphalt mixtures has a negative impact on the low temperature properties [13–15].

Presently, there are no extensive studies on whether the existing low temperature performance evaluation methods are suitable for PE modified asphalt binder or mixtures and therefore, it is important to consider this aspect further. The modification of asphalt mixtures is normally classified based on two main processes: wet and the dry

\* Corresponding author.

E-mail address: [muhammad.kakar@bfh.ch](mailto:muhammad.kakar@bfh.ch) (M. Rafiq Kakar).

mixture preparation. In the former case, the binder is modified with the waste materials first and then the modified binder is used to prepare the asphalt mixtures. In the latter case, the modification is based on the addition of waste materials directly in the mixtures [6]. During the wet process, it is important to know that the high temperature storage stability is ensured, and that the modification is homogenous in laboratory produced mixtures. An important point to be considered is if the modification is chemical or physical in nature. In a recent study by Kakar et al. (2021) [4], the results of FTIR analysis has shown that binder blended with the same waste PE as used in this study, has a physical influence rather than a chemical one. Other research groups have reported similar results [13 12 16 17 2].

The objectives of the current study are to evaluate the mechanical performance of low noise semi dense asphalt (SDA) mixtures prepared with PE waste plastic blended binders using mechanical tests. The SDA mixtures modified with waste plastics address important societal burdens in the urban environment; that of noise and waste plastics. If proven successful, such solutions can reduce noise, reuse plastic waste and reduce the use of polymers making an important contribution to sustainable pavements in the urban environment. The low and high temperature performance are used as the main performance criteria. In addition, the environmental scanning electron microscopy (ESEM) was used to trace the physical presence of waste PE in asphalt mixtures. In order to simulate the effect of base binder aging, mixtures prepared with and without PE waste used a similar blending process, so that the blending process had no bias effect. In the analysis, the compactability of both modified and non-modified mixtures were discussed. In addition, the surface texture properties that are important for the noise reduction functionality of such mixtures were evaluated using a laser texture scanner. The mechanical tests used to evaluate the low and high temperature performance of PE modified mixtures are semi-circular bending (SCB) and cyclic compression test (CCT), respectively.

## 2. Materials

Asphalt binder 70/100 with penetration of 82 (0.1 mm) and softening point of 52 °C was supplied by Q8-Research (Middle Eastern origin) and used as the base binder for PE modification. The aggregates used for the preparation of asphalt mixtures were quarried sandstone with a 25–30 % quartz content supplied by the company FAMSA (in Massongex, Switzerland) and graded for an SDA 4–16 mixture according to SN 640 436. The reference mixtures prepared with polymer modified binder (PmB 45/80–65) with penetration  $68 \text{ mm}^{-1}$  and softening point 68 °C, as PmB is a requirement for SDA mixtures according to the Swiss standards (SN 640 436) [18]. The polymer type is SBS and more details such as SBS content are not known. The waste PE material shown in Fig. 1 was obtained from a Swiss supplier and is a by-product from the recycling of packaging waste currently used as fuel in cement factories. The density of PE-shreds (0.949 g/cm<sup>3</sup>) was measured with a Helium pycnometer (Micromeritics® AccuPyc II, USA). According to Differential Scanning Calorimetry curves for this PE waste two sharp melting peaks exist; one at 110.7 °C and the other at 123.8 °C with an overall heat energy of 813.4 MJ, indicating a mix of low-density and medium density PE based on their known heat energies [4].

## 3. Methods

### 3.1. PE binder modification

The PE waste was first grinded (cf. Fig. 1) in a container partially filled with cold water at approximately 15 °C. During the grinding process, the PE-shreds were introduced at room temperature using a high shear mixer (Silverson L5M Laboratory Rotor/Stator Batch Mixer) for 5 min at a speed of 5000 rpm. After grinding, the plastic was removed from the water and laid flat on a paper towel to completely dry for at least 24 hours before it was added to the bitumen. In order to produce



Fig. 1. PE-shreds waste plastic as received from the plant (top) and after the grinding process (bottom).

the PE waste modified asphalt binder, the 70/100 base binder was pre-heated in an oven thereafter placed in an oil bath at a temperature of 170 °C. The PE shreds were then added to this heated binder using a blending speed of 3500 rpm maintained for 60 min. This was found to be sufficient to assure proper blending as assessed visually by the fact that the consistency stopped changing. The amount of PE was 5 % by mass of the base binder; more details on grinding and blending of waste plastic PE can be found in Kakar et al. (2021) [4].

### 3.2. PE modified mixture preparation

The asphalt mixtures were produced using a mixer with the capacity of approximately 4000 g using the “semi-wet” process to minimize storage stability issues. This refers to the asphalt mixing being performed soon after blending the PE in the asphalt base binder. The mixing of PE blended binder with hot aggregates (170 °C) was performed for approximately 2 min. Fig. 2 shows the gradation curve that was followed to produce all the SDA 4–16 mixture.

As mentioned in Section 1, the modification of asphalt mixtures is typically performed using the dry or wet process as shown in Fig. 3. In an earlier study by the authors Kakar et al. (2021) [4], it was shown that the PE blended asphalt binders have issues with high temperature stability. Therefore, in this study the so called semi-wet process was used, where the PE particles were blended in the binder avoiding storage as they were immediately added to the aggregates (cf. Fig. 3). All the mixtures were designed according to semi dense SDA 4–16 with a nominal

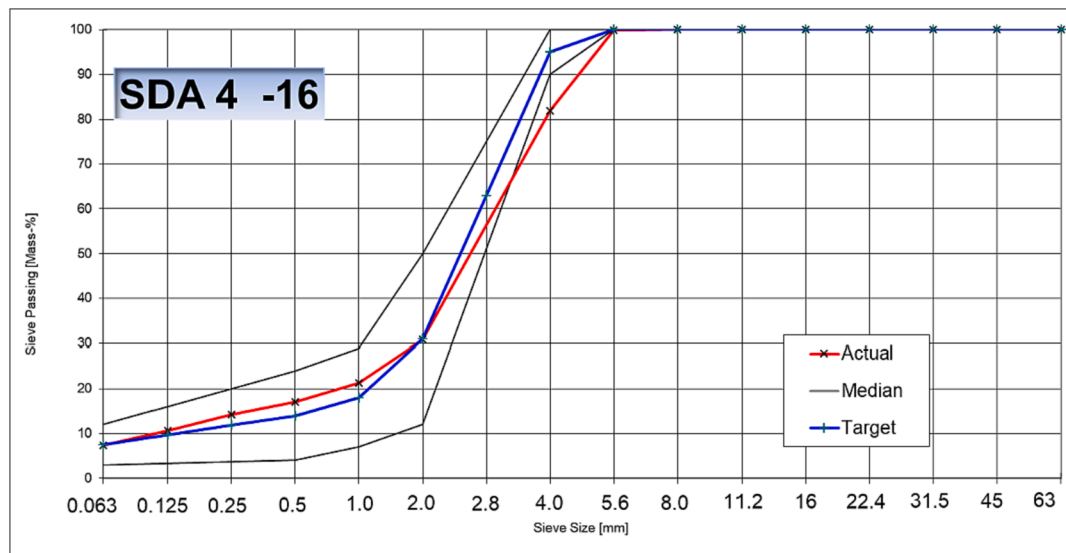


Fig. 2. Typical gradation curve of SDA 4-16 for the mixture production (SN 640 436).

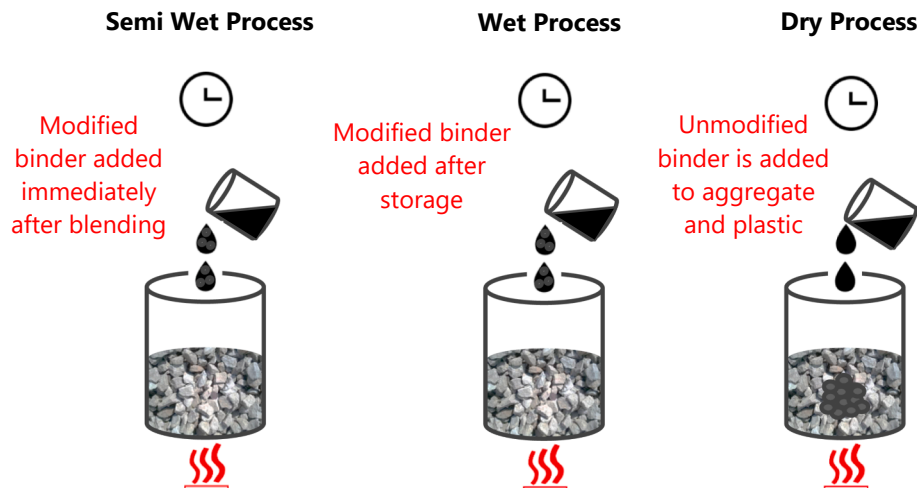


Fig. 3. Process of PE mixture preparation.

maximum aggregate size of 4 mm and target air voids of  $(16 \pm 2)\%$ . The binder content of 6.2 % were used for reference PmB mixture and non-modified binder (70/100) mixtures and 6.1 % and 6.5 % for PE blended mixtures (SN 640 436) as given in Table 1. The binder content was varied in order to allow the study of the influence of the binder on the performance. The two binder contents (6.1 % and 6.5 %) of plastic-modified asphalt mixtures were selected to study the influence of different binder contents on the performance. The binder content was slightly increased in comparison to reference, in order to compensate for any absorbed binder in the plastics.

**Table 1**  
Mixtures details and designation.

Mixture Type	Binder Content	Plastic Content	Mixture Designation	Test Performed
PmB	6.2 %	–	PmB 6.2	SCB & CCT
Non-Modified Binder	6.2 %	–	70–100 (6.2)	CCT
Plastic modified	6.1 %	5 % by mass of binder	Plastic 6.1	SCB & CCT
Plastic modified	6.5 %	5 % by mass of binder	Plastic 6.5	SCB & CCT

### 3.3. Mixture compaction

The gyratory mode of compaction was used to compact the asphalt mixtures. The compaction was performed according to the maximum number of ( $N_{max}$ ) 125 gyrations or till the required height of the compacted specimen is reached (AASHTO, 2010). During the compaction process, an angle of gyration at  $1.25^\circ$  and 600 kPa vertical force applied. The compactor was assigned to terminate compaction by either reaching the required height of the specimen or design number of gyrations. It can be seen in Fig. 4 that all of the mixtures lie within the required void content range of SDA  $(16 \pm 2)\%$  [18].

### 3.4. Compacted specimen preparation

All compacted specimens were prepared according to the Asphalt Institute Manual (MS-2) (Asphalt Institute, 2001). The mixtures were mixed at  $170^\circ\text{C}$  and subsequently compacted at  $155^\circ\text{C}$ . To simulate the short-term aging effects, all the mixtures were placed inside the oven for 2 h at compaction temperature ( $155^\circ\text{C}$ ) before compaction. After compaction, the end faces of specimens were cleaned and dried out at room temperature as shown in Fig. 5.

The ease of compaction and mechanical stability of asphalt mixtures

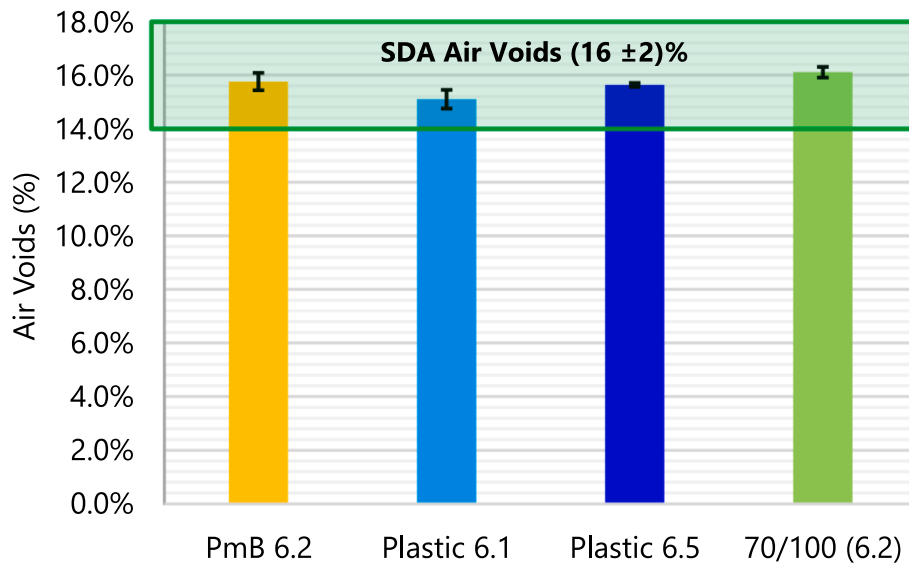


Fig. 4. Air voids of PE and PmB modified asphalt mixtures.

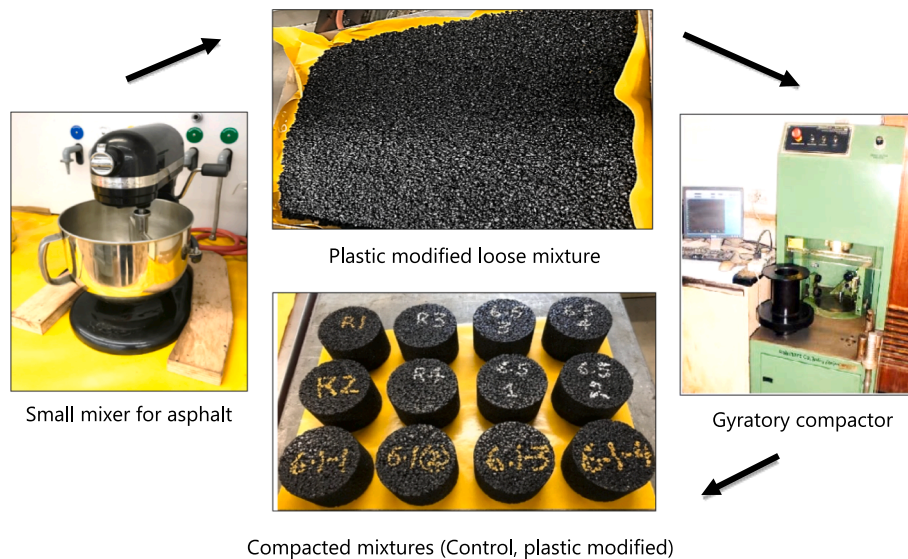


Fig. 5. Mixture and compacted specimens.

was evaluated based on the gyration compaction energy. A porous asphalt version [19] of the Compaction Energy Index (CEI) [20] was determined as the area under the densification curve between the relative density corresponding to the 8th gyration and the density at 92 % of the maximum theoretical density ( $G_{mm}$ ).

### 3.5. Cyclic compression tests

The cyclic compression test was performed as per the European Standards EN 12697-25 [21] method A2. The test offers a method to evaluate the performance with respect to permanent deformation of asphalt mixtures at high temperature (50 °C). The duration of the haversine loading cycle was 1.7 s with a rest period of 1.5 s. The 100 mm diameter and 60 mm height specimens were conditioned in the climatic chamber at the test temperature of 50 °C for at least 4 h before the tests. The top and bottom surfaces of the test specimens were polished to achieve even and plane parallel faces that is perpendicular to the cylinder axis. The specimen was placed between two plane parallel loading plates, so that the compressive stress was distributed evenly through a

plate over the top of the sample as shown in Fig. 6a, with upper and lower stresses of 0.35 MPa and 0.025 MPa, respectively. Two replicates of specimens were used per mixture variant for cyclic compression test. The creep curve shows the cumulative axial strain, in %, of the test specimen as a function of the number of loading cycles. Three stages as shown in Fig. 6b can be generally identified in the creep curve. In stage 1 or the initial part, the slope of the curve decreases with the number of loading cycles; in stage 2 which is the middle part of the creep the slope of the curve is constant and can be expressed by the creep rate,  $f_c$ . The exact turning point of the creep curve lies within this stage; in stage 3, the last part of the curve, the slope increases with increasing number of loading cycles. If the sample fails early, one or more stages may be absent. The cumulative axial permanent strain  $\epsilon_n$ , from the creep curve expressed in percent (%), as a function of the number of load applications can be calculated using Eq. (1). The test is ended when 10,000 cycles are reached or the Cumulative axial strain  $\epsilon_n$  has reached 40 %.

$$\epsilon_n = \frac{(un)}{ti} \cdot 100 \quad (1)$$



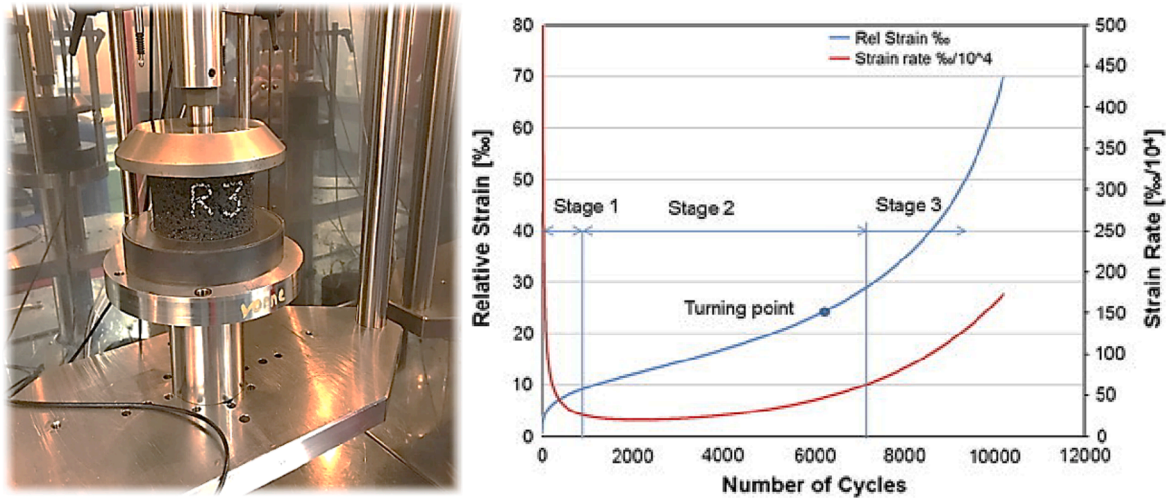


Fig. 6. a) Cyclic compression test setup b) three stages and turning point of the cyclic compression test [22].

where,

$\epsilon_n$  = the cumulative axial strain of the test specimen after  $n$  loading cycles, in percent (%).

$u_n$  = is the cumulative permanent deformation of the test specimen after  $n$  loading cycles.

$t_i$  = is the initial thickness of the test specimen in mm.

### 3.6. Semi circular bending test

One of the testing methods commonly used to assess fracture of asphalt pavement is the semi-circular bending (SCB) test [23]. This test was originally developed for determining the fracture resistance [24] and it has been reported as a simple but useful testing method for mixture design and quality control of asphalt mixtures [25].

The standard SCB test requires 150 mm diameter specimens, however in this study the authors have used 100 mm diameter specimens due to the limitation in producing the modified materials. In Bui and Saleh (2021) [26], it was suggested that the SCB test on non-standardized specimens of 100 mm diameter do not show significant differences in the results compared to 150 mm diameter standard test specimens. The test was performed at 0 °C in accordance with the European standard EN 12697-44 [27]. Two replicates of specimens were tested using SCB test. During the test, specimens were loaded with a loading strip moving at a rate of 5 mm/min. The schematic in Fig. 7 shows the preparation of the specimens and the dimensions for the 3.5 by 10 mm notch.

### 3.7. Environmental scanning electron microscopy (ESEM)

The microstructure of PE modified mixtures was investigated using the ESEM. Specimens with dimensions of  $30 \times 30 \times 10 \text{ mm}^3$  were cut from the center of compacted cylindrical specimens. The samples were impregnated with epoxy resin and polished following the method

described in a previous study by Poulikakos & Partl (2010) [28]. The ESEM was an FEI Quanta 650 by Thermo Fisher using a low vacuum mode at 0.8 mbar. The ESEM micrographs are the result of the interaction of the electron beam with the surface atoms of the sample. Elements with a high atomic number, such as silicon that is present in aggregates, scatter more electrons and appear light and elements with low atomic numbers such as carbon that is present in bitumen or plastics, scatter less electrons and appear dark.

### 3.8. Surface texture characterization

The reason for the use of SDA in Switzerland is to minimize the noise generated due to tire/road interaction. An important parameter affecting the noise reduction properties of SDA is the surface texture [29]. The Ames Engineering 9400HD 3D laser scanner as shown in Fig. 8, was used to measure the surface texture of asphalt mixture specimens. The specimens were placed under the scanner horizontally and the scan measurements were conducted on a  $50 \times 50 \text{ mm}^2$  area. The resolutions along the length of the scan, width and depth were 0.006, 0.025 and 0.005 mm, respectively. The area of each scan consists of 200 scan lines and was used to calculate the average Mean Profile Depth (MPD) and texture level with the Ames software. According to the method prescribed by ISO 1373-1, the MPD was calculated by removing wavelengths below 2.5 mm, which represents the texture amplitude in a single value. However, due to the limitation of specimen size, the maximum scan line was limited to 50 mm, less than the 100 mm minimum prescribed [29].

The texture level ( $L_{TX,\lambda}$ ) relative to the texture wavelengths,  $\lambda$ , was calculated by taking the 1/3rd octave band power spectral density graphs for each scanline (scan consists of 200 scan lines) by using Eq. (2) derived from ISO 13473-4.

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

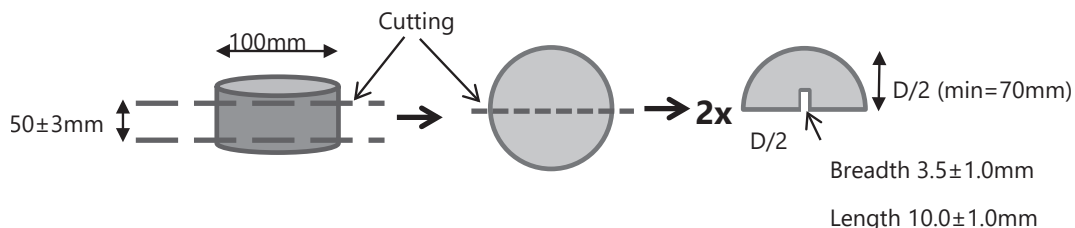


Fig. 7. Schematics of Semi-circular Bending Test.



Fig. 8. Scanning Asphalt Texture with Ames Engineering 9400HD 3D Laser Scanner [29].

Where,

$Z_{p,\lambda}$  = the 1/3rd octave band power spectral density (PSD) amplitude for a certain texture bandwidth  $\lambda$ ,  $0.232f$  = the bandwidth of the 1/3rd octave band (with spatial center frequency  $f = 1/\lambda$ ,

$a_{ref}$  = the reference value of the surface profile amplitude ( $10^{-6}$ m given by ISO 13473-4).

## 4. Results and discussion

### 4.1. Compactability analysis

The results of compactability in terms of compaction energy index are shown in Fig. 9. It can be clearly seen that the mixtures prepared with PmB require higher amounts of energy and therefore, required higher number of gyrations to reach the desired compaction level that is the target air voids (16 %). However, the mixtures prepared with PE blended binders required comparatively less energy and smaller number of cycles for compaction. It is also interesting to observe that the mixtures with PE blended binder content of 6.5 % and 6.1 % required less energy compared with mixtures using 70/100 binder without PE modification. These findings can be attributed to the fact that the

stiffening effect of PmB modified binder is higher compared to the mixtures prepared with PE blended binder and also the PE content facilitates the compactability when compared with mixtures prepared without PE content.

### 4.2. Cyclic compression test analysis

The results shown in Fig. 10 represent the cumulative axial permanent strain  $\epsilon_n$ , from the creep curve expressed in %, as a function of the number of load applications. Furthermore, Fig. 11 shows the cumulative axial permanent strain  $\epsilon_n$  at 2500 cycles for the purpose of comparison as well as the turning point indicating the number of cycles where the samples experience catastrophic failure. As can be seen from Fig. 11, the highest turning point was reached by the PmB (6.2) mixture followed by plastic (6.1), plastic (6.5) and 70/100 (6.2). The results show that the highest number of cycles to turning point was attained by the two PmB (6.2) mixtures (2340 and 2269). Whereas, the two mixtures produced with 6.1 % and 6.5 % PE modified binder content, reached 782 with standard deviation of 27 and 701 cycles with standard deviation of 107, respectively. However, the mixtures produced using base binder 70/100 only reached 413 cycles with standard deviation of 40 before at the turning point. This corresponds to the compactability results of the mixtures, where the mixtures produced using 70/100 base binder were easier to compact compared to the PmB mixtures. Therefore, these results affirms that the PmB modified binder is stiffer compared to 70/100 and hence requires more compaction energy compared to mixtures

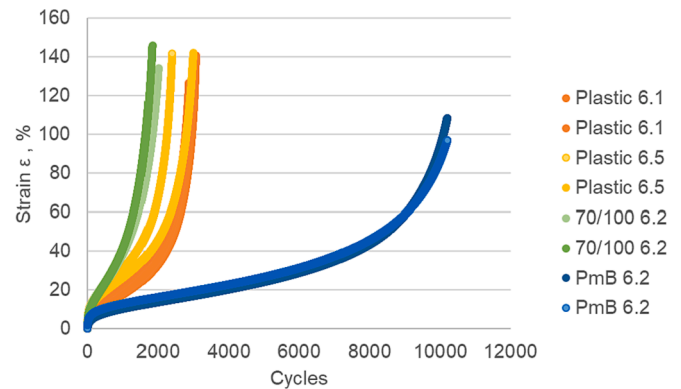


Fig. 10. Cumulative axial permanent strain  $\epsilon_n$  vs Number of Cycles at 50 °C.

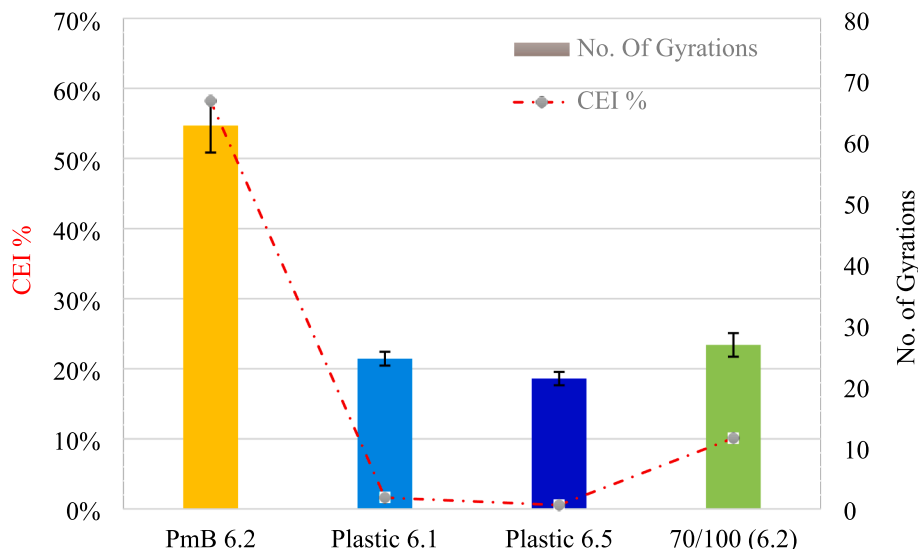


Fig. 9. Compaction Energy Index (CEI) and No. of Gyrations.

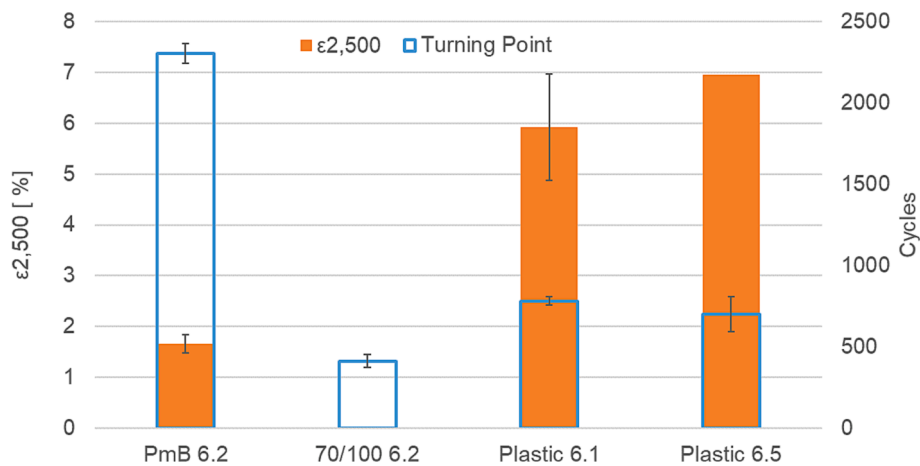


Fig. 11. Average values and standard deviation for Turning point and  $\epsilon_{2,500}$  at 50 °C. One sample of Plastic 6.5 did not reach the required 2500 cycles.

prepared with and without PE blended binders. Another parameter of interest is the cumulative strain at 2500 cycles  $\epsilon_{2500}$  shown in Fig. 11. Three of the mixtures tested did not reach 2500 cycles (two 70/100 and one plastic 6.5). The  $\epsilon_{2500}$  values for the other mixtures were as follows: 1.75 %/1.54 % for the two PmB mixtures, 6.66 %/ 5.18 % for the plastic 6.1 mixture and 6.96 % for the plastic 6.5 mixture. Consequently, the strain experienced by the PmB mixtures is much lower compared to PE modified and unmodified 70/100 mixtures. However, the effect of PE modification on the permanent deformation in terms of cyclic compression test is positive compared to mixtures prepared with base binder 70/100 only. Naturally, the binder content has an influence also. The mixture prepared with higher amount of PE modified binder content (6.5 %) reached comparatively a smaller number of cycles compared to mixtures prepared with 6.1 % PE modified binder. It is also worth mentioning here that the PmB reference with 6.2 % binder, reached 2340 and 2260 cycles to the turning point and also reached 10,000 cycles. This infers that the different nature of PmB modification in the mixture has a dominating influence on the high temperature performance and the mixture prepared with and without PE blended binder does not attain PmB performance. Since the control mixtures (70/100)

are prepared with the same binder and similar aging conditions, it can be concluded that PE modification adds a slight improvement in terms of high temperature performance in comparison to the 70/100 bitumen.

#### 4.3. Semi circular bending test analysis

Fig. 12 shows the results of fracture toughness of PmB and PE modified mixtures at 0 °C as an indication of the low temperature performance of the mixtures. The results show that the highest fracture toughness (FT) was attained by the reference PmB mixtures followed by PE mixtures with 6.5 % and 6.1 % binder content. Furthermore, the PE mixture containing 6.1 % binder had on average comparatively lower fracture toughness values of nearly 93 N/mm<sup>1.5</sup>. Fig. 13 presents the fracture energy calculated from the area under the vertical force vs displacement curve. It was interesting to see that mixtures prepared with 6.5 % PE modified binder had on average the highest fracture energy (FE) compared to PE modified mixtures with 6.1 % binder content and PmB modified mixtures. This infers that the 6.5 % PE modified binder mixtures had comparatively higher potential for low temperature cracking resistance, but it should be noted that fracture energy results

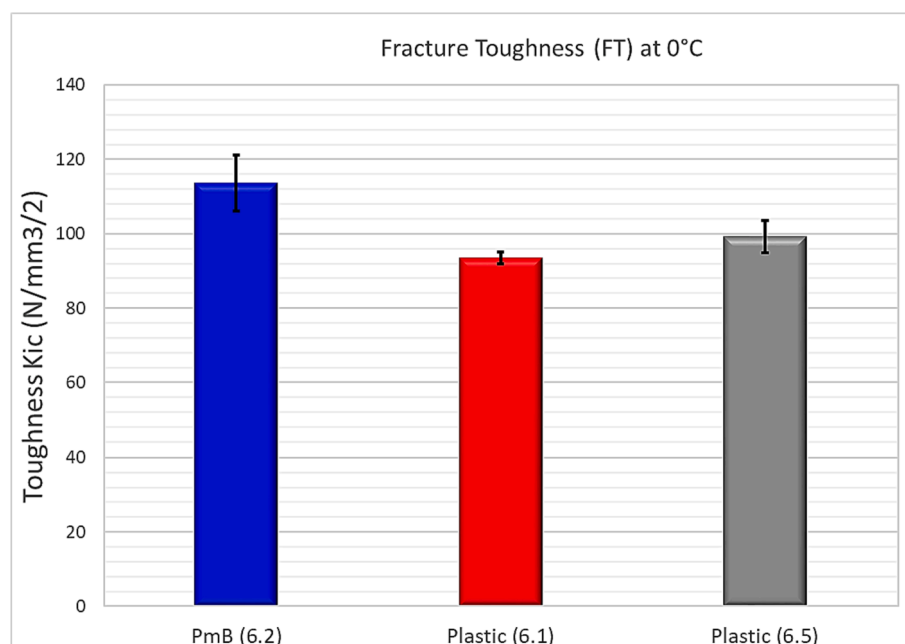


Fig. 12. Fracture Toughness (SCB) Test Results at 0 °C.

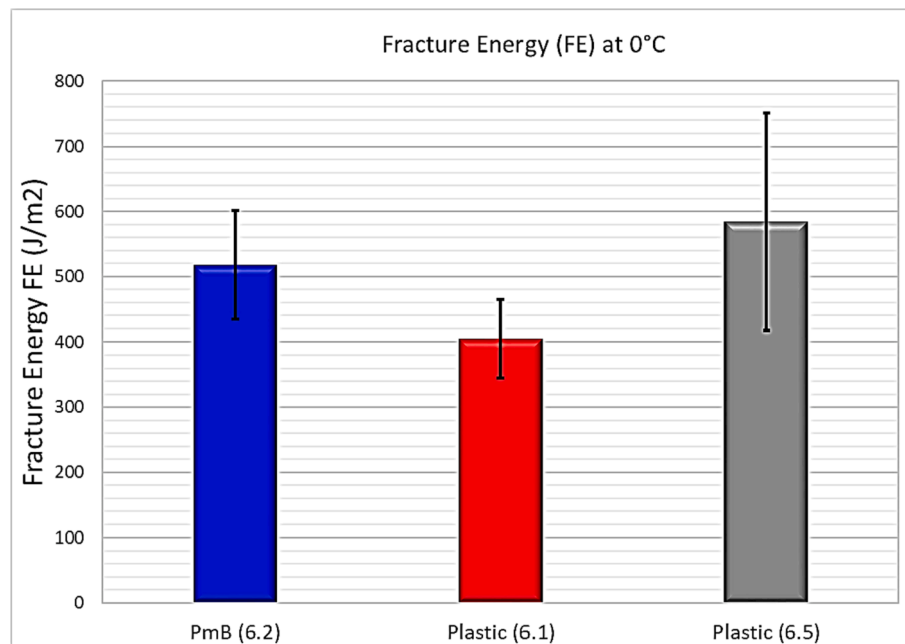


Fig. 13. Fracture Energy (SCB) Test Results at 0 °C.

had much higher variability as reported previously by Mikhailenko et al. (2021) [30], indicating that FE and FT should both be taken into account. Based on the results of 6.5 % PE, Semi-circular bending test at low temperature, showed that the PE modified mixtures had no significant effects compared to the PmB mixtures.

#### 4.4. Scanning electron microscopy analysis

In order to investigate the presence of PE waste plastic in asphalt mixture matrix, the environmental scanning electron microscopy (ESEM) experiments were performed on the cut and polished specimen. Fig. 14 shows the ESEM image of the surface of the test specimen. It can be seen that the PE particles are clearly distinguishable from the asphalt mastic and aggregates. The light gray large particles show the mineral aggregates surrounded by the mastic that contains small gray particles that are the filler in the lighter black binder part. The plastic particles are still intact within the mastic with dimensions of ca 30  $\mu\text{m}$ . The smaller dimension of the plastic particles indicates that they partially melted during the mixing process as mixing temperature of 160 °C is greater

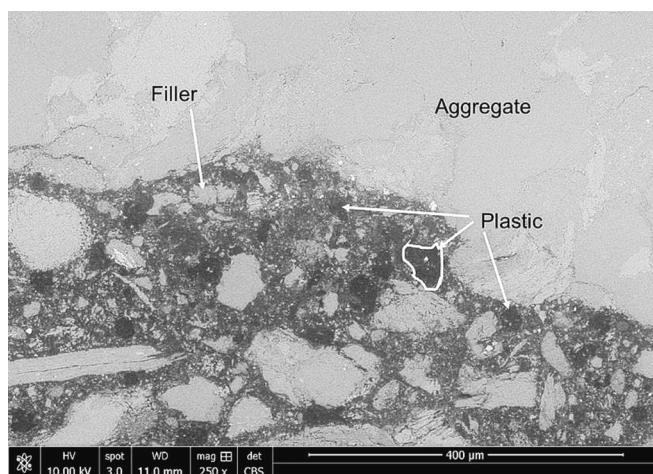


Fig. 14. Environmental scanning electron microscopy (ESEM) image of a PE Modified mixture at 250x.

than the melting temperature of PE at around 120 °C [4]. However, they clearly do not melt completely. This has direct connotations for the composite material as the binder has a softening point of 52 °C; that is at higher experimental temperatures the binder starts to soften and acts as a viscoelastic material whereas the plastic still remains elastic at these temperatures. The CCT results of the PE samples compared to the base binder show this clearly (Fig. 10). At colder temperatures however both materials are elastic, and the addition of the plastics would not affect the performance as seen in the SCB tests.

#### 4.5. Surface texture

Fig. 15 presents the surface texture measurements taken using the laser scanner. The surface texture level ( $L_{tx}$ ) of the pavements in the wavelength range from 0.01 to 100 mm is shown in Fig. 16. Based on the results, it can be observed that the surface texture level of the mixture with PE waste plastic shows no significant difference over all the texture level range. Unlike the case of crumb rubber in SDA [30], the PE material does not have a significant effect on the texture. A lower texture amplitude at wavelengths 2–8 mm is correlated to higher noise generation at higher frequencies (200–5000 Hz), while lower amplitude at 16–160 mm has been correlated to lower noise at lower frequencies below 800 Hz and there might be a reduction in low frequency noise but an increase for higher frequencies. The PE modified mixtures have registered slightly lower texture levels at lower wavelengths below 1 mm, which could indicate lower skid resistance [31].

## 5. Conclusion

The use of waste polyethylene in low noise asphalt mixtures can potentially improve the sustainability of low noise pavements in the urban environment. The low (0 °C) and high (50 °C) temperature performance of polyethylene (PE) modified asphalt mixtures was evaluated using semicircular bending and cyclic compression test, respectively, and was compared to reference mixtures with PmB and straight run bitumen 70/100. The results show a strong correlation of performance of the PE modified mixtures with test temperature. This is a consequence of the difference in the composite material with bitumen only and bitumen plus PE and the resulting elastic and viscous response. The overall results are summarized as follows:



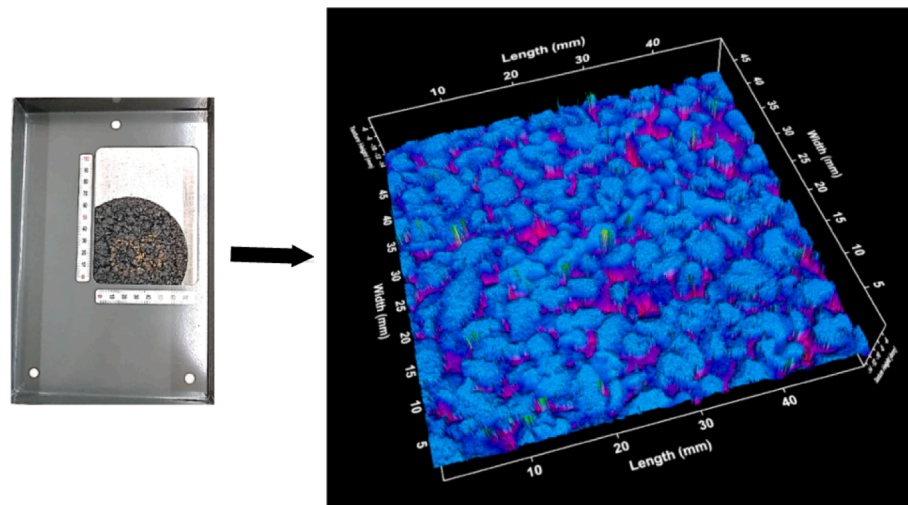


Fig. 15. Specimen (left) and Surface Texture of PE Modified Asphalt Mixture (right).

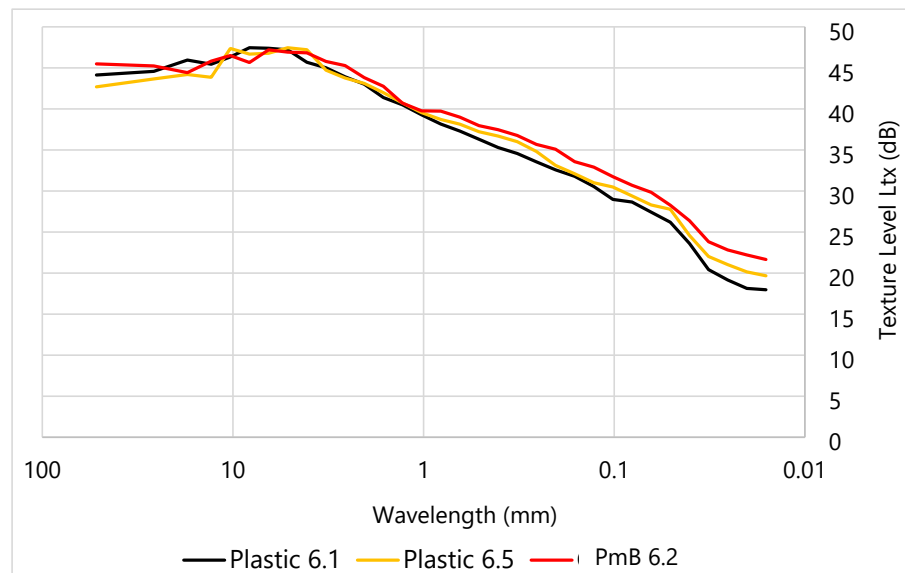


Fig. 16. Texture Profile Level (ISO 13473-4).

- The compactability results revealed that waste PE modified mixtures were significantly easier to compact in comparison to the asphalt mixtures with polymer modified bitumen (PmB).
- Based on the cyclic compression test results, mixtures prepared with PE showed improved resistance against cyclic loading compared to mixtures without PE modification. However, as evidenced in the compactability results, PmB mixtures have shown significantly higher resistance against cyclic loading and creep compared to mixtures with and without PE modification. This is a result of different PmB modification mechanism in the binder compared to mixtures prepared with and without PE blended binder.
- Moreover, semi-circular bending test results demonstrated that the low temperature performance of mixtures prepared with PE waste plastic blended binders had relatively similar or slightly lower performance.
- The fracture toughness energy of PE mixture containing 6.5 % binder was improved slightly showing an improvement in low temperature cracking resistance.
- Electron microscopy images show that the PE is still visible in the mastic, imparting an elastic response when the binder becomes more viscous at higher temperatures.

- Use of PE in mixtures did not change the surface texture in comparison to standard mixtures which is an important parameter in the low noise property of SDA mixtures.
- The use of PE waste as additive can be a viable option for asphalt mixtures, but not as a replacement for PmB, rather, in mixtures where unmodified binder is employed. Special attention should be paid to type of base binder and appropriate testing incorporating performance at different test temperatures.

#### CRediT authorship contribution statement

**Muhammad Rafiq Kakar:** Conceptualization, Investigation, Methodology, Writing – original draft. **Peter Mikhailenko:** Investigation, Writing – review & editing. **Zhengyin Piao:** Writing – review & editing. **Lily D. Poulidakos:** Writing – review & editing.

#### 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.

## Data availability

Data will be made available on request.

## Acknowledgements

The authors would like to acknowledge the Swiss National Science Foundation (SNSF) for the financial support of the project titled “Urban Mining for Low Noise Urban Roads and Optimized Design of Street Canyons” number 205121\_178991 and Dr. Moises Bueno for his technical advice, Dr. Martin Arraigada for his support with the SCB test setup and measurements, along with the technical staff of the Empa Laboratory for Concrete and Asphalt. The authors also would like to thank the support of InnoPlastics AG for providing the PE waste materials.

## References

- [1] Z. Du, C. Jiang, J. Yuan, F. Xiao, J. Wang, Low temperature performance characteristics of polyethylene modified asphalts—A review, *Constr. Build. Mater.* 264 (2020) 120704.
- [2] Z. Piao, P. Mikhailenko, M.R. Kakar, M. Bueno, S. Hellweg, L.D. Poulikakos, Urban mining for asphalt pavements: A review, *J. Cleaner Prod.* 124916 (2020).
- [3] D. Movilla-Quesada, A.C. Raposeiras, L.T. Silva-Klein, P. Lastra-González, D. Castro-Fresno, Use of plastic scrap in asphalt mixtures added by dry method as a partial substitute for bitumen, *Waste Manage.* 87 (2019) 751–760.
- [4] M.R. Kakar, P. Mikhailenko, Z. Piao, M. Bueno, L. Poulikakos, Analysis of waste polyethylene (PE) and its by-products in asphalt binder, *Constr. Build. Mater.* 280 (2021) 122492.
- [5] D. Landi, S. Gigli, M. Germani, M. Marconi, Investigating the feasibility of a reuse scenario for textile fibres recovered from end-of-life tyres, *Waste Manage.* 75 (2018) 187–204.
- [6] S. Haider, I. Hafeez, Jamal, R. Ullah, Sustainable use of waste plastic modifiers to strengthen the adhesion properties of asphalt mixtures, *Constr. Build. Mater.* 235 (2020) 117496.
- [7] A.I. Al-Hadidy, T. Yi-qiu, Effect of polyethylene on life of flexible pavements, *Constr. Build. Mater.* 23 (3) (2009) 1456–1464.
- [8] P. Jew, J.A. Shimizu, M. Svazic, R.T. Woodhams, Polyethylene-modified bitumen for paving applications, *J. Appl. Polym. Sci.* 31 (8) (1986) 2685–2704.
- [9] V.S. Punith, A. Veeraragavan, Behavior of asphalt concrete mixtures with reclaimed polyethylene as additive, *J. Mater. Civ. Eng.* 19 (6) (2007) 500–507.
- [10] M. Attaelmanan, C.P. Feng, A.I. Al-Hadidy, Laboratory evaluation of HMA with high density polyethylene as a modifier, *Constr. Build. Mater.* 25 (5) (2011) 2764–2770.
- [11] S. Hınısloğlu, E. Ağar, Use of waste high density polyethylene as bitumen modifier in asphalt concrete mix, *Mater. Lett.* 58 (3–4) (2004) 267–271.
- [12] L. Jun, Z. Yuxia, Z. Yuzhen, The research of GMA-g-LDPE modified Qinhuangdao bitumen, *Constr. Build. Mater.* 22 (6) (2008) 1067–1073.
- [13] F. Zhang, C. Hu, The research for crumb rubber/waste plastic compound modified asphalt, *J. Therm. Anal. Calorim.* 124 (2) (2016) 729–741.
- [14] P. Lin, W. Huang, Y. Li, N. Tang, F. Xiao, Investigation of influence factors on low temperature properties of SBS modified asphalt, *Constr. Build. Mater.* 154 (2017) 609–622.
- [15] A.M. Othman, Effect of low-density polyethylene on fracture toughness of asphalt concrete mixtures, *J. Mater. Civ. Eng.* 22 (10) (2010) 1019–1024.
- [16] C. Fang, Y. Zhang, Q. Yu, X. Zhou, D. Guo, R. Yu, M. Zhang, Preparation, characterization and hot storage stability of asphalt modified by waste polyethylene packaging, *J. Mater. Sci. Technol.* 29 (5) (2013) 434–438.
- [17] D. Ge, K. Yan, Z. You, H. Xu, Modification mechanism of asphalt binder with waste tire rubber and recycled polyethylene, *Constr. Build. Mater.* 126 (2016) 66–76.
- [18] S. Standard, Swiss Standard SN 640 436 Semidichtes Mischgut und Deckschichten Festlegungen, Anforderungen, Konzeption und Ausführung, 2013.
- [19] S.W. Goh, Z. You, Mechanical properties of porous asphalt pavement materials with warm mix asphalt and RAP, *J. Transp. Eng.* 138 (1) (2012) 90–97.
- [20] H.U. Bahia, T.P. Friemel, P.A. Peterson, J.S. Russell, B. Poehnel, Optimization of constructibility and resistance to traffic: a new design approach for HMA using the superpave compactor, *J. Assoc. Asphalt Paving Technol.* 67 (1998).
- [21] EN 12697-25, (2016). Bituminous mixtures – test methods for hot mix asphalt – Part 25: Cyclic compression test.
- [22] L.D. Poulikakos, S. dos Santos, M. Bueno, S. Kuentzel, M. Hugener, M.N. Partl, Influence of short and long term aging on chemical, microstructural and macro-mechanical properties of recycled asphalt mixtures, *Constr. Build. Mater.* 51 (2014) 414–423.
- [23] I.M. Lancaster, H.A. Khalid, I.A. Kouglioumtzoglou, Extended FEM modelling of crack propagation using the semi-circular bending test, *Constr. Build. Mater.* 48 (2013) 270–277.
- [24] I.L. Lim, I.W. Johnston, S.K. Choi, Stress intensity factors for semi-circular specimens under three-point bending, *Eng. Fract. Mech.* 44 (3) (1993) 363–382.
- [25] A.A.A. Molenaar, A. Scarpas, X. Liu, S.M.J.G. Erkens, Semi-circular bending test; simple but useful? *J. Assoc. Asphalt Paving Technol.* 71 (2002).
- [26] H.H. Bui, M. Saleh, Effects of specimen size and loading conditions on the fracture behaviour of asphalt concretes in the SCB test, *Eng. Fract. Mech.* 242 (2021), 107452.
- [27] EN 12697-44, Bituminous Mixtures - Test Methods for Hot Mix Asphalt - Part 44: Crack Propagation by Semi-circular Bending Test, 2019.
- [28] L.D. Poulikakos, M.N. Partl, Investigation of porous asphalt microstructure using optical and electron microscopy, *J. Microsc.* 240 (2) (2010) 145–154.
- [29] P. Mikhailenko, Z. Piao, M.R. Kakar, S. Athari, M. Bueno, L.D. Poulikakos, Effect of waste PET and CR as sand replacement on the durability and acoustical properties of semi dense asphalt (SDA) mixtures, *Sustain. Mater. Technol.* 29 (2021) e00295.
- [30] P. Mikhailenko, Z. Piao, M.R. Kakar, M. Bueno, L.D. Poulikakos, Durability and surface properties of low-noise pavements with recycled concrete aggregates, *J. Cleaner Prod.* 319 (2021) 128788.
- [31] P. Mikhailenko, Z. Piao, M.R. Kakar, M. Bueno, S. Athari, R. Pieren, K. Heutschi, L. Poulikakos, Low-Noise pavement technologies and evaluation techniques: A literature review, *Int. J. Pavement Eng.* (2020) 1–24.