Engineering Solid Mechanics 14 (2026) 137-150

Contents lists available at GrowingScience

Engineering Solid Mechanics

homepage: www.GrowingScience.com/esm

The influence of different percentages of recycled asphalt pavement (RAP) material on basic modes low temperature fracture toughness (K_{Ic}, K_{IIc} and K_{IIIc}) of asphalt mixtures using ENDB test

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ARTICLE INFO

Article history:
Received 22 December 2025
Accepted 3 March 2026
Available online
4 March 2026

Keywords:
Modified and control HMA mixtures
RAP content
Pure modes I, II, III fracture toughness values
Low temperature conditions
ENDB test
Fracture toughness ratios
Effective total fracture toughness

ABSTRACT

Several waste materials are often used in the mixt-design of asphalt concrete materials to manufacture green construction materials and among them recycled asphalt pavement (RAP) is a favorite material that can be utilized as partial replacement of natural stone aggregates. Addition of such waste and recycled materials may have a negative influence on the mechanical properties and strength or performance of asphalt pavements. In particular, resistance of asphaltic overlays made by some amounts of RAP material against cracking and crack propagation can be reduced and it is necessary to investigate possible effects of RAP addition on cracking resistance of asphalt mixtures. Passage of traffic loads from the cracked overlays and asphaltic pavements can activate all basic tensile and shear mode crack deformations (i.e., pure mode I, pure mode II and pure mode III). In addition, due to the visco-elastic nature of bitumen used in the asphalt mixture, the risk of crack propagation and failure at low temperature conditions is higher than the intermediate and high temperatures. Therefore, in this research, the influence of adding RAP material on the fracture toughness of all three basic fracture modes (namely, K_{Ic}, K_{IIc} and K_{IIIc}) is investigated using edge-notched disc bend (ENDB) specimens. Fracture toughness tests are conducted on hot mix asphalt (HMA) mixtures containing 0, 20 and 40 % RAP material (as replacement of natural aggregates) at five low temperatures of 0, -6, -12, -18, -24 °C. Based on the results, all fracture toughness data were decreased by increasing the temperature from -24°C to zero and increasing the RAP content from 0 to 40%. Depending on the test temperature and mixture type (HMA with or without RAP content) the K_{Ic} and K_{IIc} values were varied from 0.5 to 1.1 MPa.m$^{0.5}$. This range for K_{IIIc} value was in the lower limit of 0.35 MPa.m$^{0.5}$ and 0.75 MPa.m$^{0.5}$. Some fracture indexes such as fracture toughness ratios (K_{IIc}/K_{Ic}, K_{IIIc}/K_{Ic}, K_{IIc}/K_{IIIc}, and $K_{opening}/K_{shearing\text{-}eff}$) and effective fracture toughness were determined and discussed for the investigated HMA mixtures at different temperatures.

1. Introduction

The top layer of roads and highways is constructed by asphalt mixtures and materials and annually millions of tons of asphalt mixture (stone aggregates mixed by bitumen or binder and some filler or reinforcing additives) is utilized for paving the overlays and surface of the roads. Some major issues such as huge amount of raw materials for the asphalt manufacturing, limitations in natural resources, high cost of binder or bitumen, high energy required for warming and mixing the asphalt mixture, environmental issues (such as air pollution, carbon footprints, green gases and etc.) force the designers, maintenance departments and construction sectors of pavement systems to use optimum mixtures for these materials with durable and suitable life cycle period. In this regard, as a possible solution for solving a part of the aforementioned problems and issues, there is an increasing demand for replacing the natural aggregates used in the mixture of asphalt concrete with other materials. The use of industrial wastes or bi-product of heavy industries as partial replacement of stone aggregates seems a suitable solution for manufacturing low cost, cleaner and greener asphaltic overlays and pavement systems (Rahman et al., 2020; Yasanthi et al., 2016: Tuncan et al., 2003; Toghroli et al., 2018). Indeed, the use of such materials not only reduces the volume and amounts of environmental pollution but also can reduce energy consumptions for manufacturing the concrete products.

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ISSN 2291-8752 (Online) - ISSN 2291-8744 (Print)

doi: 10.5267/j.esm.2026.3.003

Accordingly different types of natural and industrial waste materials including waste fibers (Abtahi et al., 210; Xiong et al., 2015; Kim et al., 2018), natural and synthetic fibers (Pirmohammad and Mengharpey, 2010; Pirmohammad et al., 2020; Aliha et al., 2017; Daneshfar et al., 2022; 2023; Narule and Visapure, 2022; Rooholamini et al., 2018; Musa et al., 2019) plastic and rubbers (Hassani et al., 2005; Ahmadinia et al., 2012; Aliha, 2019; Karimi et al., 2023a,b), steel wire (García et al., 2013; Hoseini et al., 2022), glass and wood fibers and particles (Aliha et al. 2022; Karamzadeh et al., 2022), fillers (Das and Singh, 2017) and slags (Falchetto et al., 2017a,b, Rooholamini et al., 2019; Zhao et al., 2022; Arabani & Azargoosh, 2012; Fakhri and Ahmadi, 2017) have been examined in the past in the mix design of asphalt and concrete mixtures. In particular, recycled asphalt pavement (RAP) material is a good candidate for replacement of new and raw aggregates because RAP (that is composed of aggregates and bitumen) is more compatible with the basic ingredient materials of hot or warm mix asphalt (HMA and WMA) mixtures and can be mixed well with the new raw materials. Hence, a large number of papers in the past years have focused on feasibility and reliability of using RAP materials in different contents from low to high weight or volume percentages in the mixture of asphalt concrete or cement concrete materials (Baradaran and Ameri, 2025; Baradaran et al., 2024b; Haghighatpour and Aliha, 2022a2024; Saed et al., 2022; Bazoobandi et al., 2023).

As a strength or performance criterion, it is necessary to investigate the effect of adding waste or additive materials (such as RAP) on the mechanical properties and strength indexes of the final asphalt concrete materials and products. For asphaltic mixtures that are composed of visco-elastic bitumen, low temperature conditions provide critical and risky situations for their safe and reliable performance or long-term service life and durability. This is because at such situations the bitumen acts mostly as brittle material and therefore catastrophic cracking of pavements at low temperature is a common mode of failure in cold regions (Marasteanu et al., 2002; Yousefi et al., 2021; Zarei et al., 2022a,b,c; Dave et al., 2011; Shahryari et al., 2021; Haghighatpour and Aliha, 2022a; He et al. 2022a, Fakhri et al., 2020). Cracking phenomenon in the surface of roads is accelerated by passing the vehicles from the asphaltic overlays. According to previous studies and published papers every passage of a vehicle from a top-down crack initiated at the surface of overlay or edges of roads and pavements may activate all basic failure modes including (i) tensile mode (crack opening deformation), (ii) in-plane shear mode (crack sliding deformation) and (iii) out-of-plane shear mode (crack face tearing deformation) as stated in different works (Aliha et al., 2021; Ziari et al. 2022; Ameri et al., 2011). These modes are known as pure mode I, pure mode II and pure mode III, respectively in the terminology of fracture mechanics. In order to evaluate the performance of asphaltic overlays against cracking failure mode and estimate the life cycle and rehabilitation time of the roads, it is necessary to know the fracture toughness value of asphalt mixtures. The fracture toughness that shows the resistance of any cracked material against cracking is known as material characteristic parameter at the onset of failure and crack propagation and is considered as mechanical property. The fracture toughness of asphaltic materials under any of the mentioned loading modes (denoted by K_{Ic}, K_{IIc} and K_{IIIc}) may depend on the mix design, type of ingredients, environmental conditions, loading mode, etc. Accordingly, several researchers have experimentally determined the fracture toughness of asphaltic mixtures with different mix-designs (Aliha et al., 2015; Behbahani et al., 2013; Eghbali et al., 2019), under different temperatures (Molayem et al., 2021; Fakhri et al., 2018; Aliha et al., 2018; Hamedi et al., 2020: He et al., 2021, 2022a; Karimi et al., 2021), different loading modes (Badeli et al., 2018; Haghighatpour and Aliha 2022b; Najjar et al., 2019; Xiongzhou et al., 2021) or environmental conditions (Amirdehi et al., 2019, Yang et al., 2021;Wen et al., 2022; Saed et al., 2022; He et al., 2022b).

In order to determine the fracture toughness for any engineering materials, suitable test samples and configurations and loading and testing devices and fixtures should be employed. Selection of the test sample depends significantly on the nature and condition of the material to be characterized. In the fracture toughness studies of asphaltic mixtures some test specimens (often in the shape of disc or circular configuration) including: disc compact tension (DCT) specimen (Mandal et al., 2019; Stewart et al., 2018; Ashani et al., 2022; Dave et al., 2011, Gu et al., 2023), edge notched disc bend (ENDB) specimen (Fuan et al., 2021; Haghighatpour et al., 2018; Motamedi et al., 2020; Hoseini et al., 2025; Raeisi et al., 2024; Aalinejadian et al., 2023; Afshar et al., 2025; Bidadi et al., 2020; Bahmani et al., 2026), edge notched diametral compression disc (ENDC) specimen (Mousavi et al., 2025a,b, Mohammadaliha et al., 2021; Bahmani and Nemati, 2021), indirect diametral compression (Falchetto et al., 2017,2018), center cracked Brazilian disc (He et al., 2022b, Mubaraki et al., 2013) and semi-circular bend (SCB) specimen (Mubaraki and Sallam, 2020; Falchetto et al., 2018; He et al., 2021, 2022b; Al-Qudsi et al., 2020; Aliha et al., 2020, Baradaran et al., 2024, Biligiri et al., 2012; Bui and Saleh 2021; Ameri et al., 2016; Fattahi Amirdehi et al., 2024; Aliha 2019; Xiongzhou et al., 2021; Mohammad et al., 2012; Erarslan and Aliha, 2025; Aliha et al., 2025; Saesaei et al., 2024) have been frequently employed by the asphalt fracture researchers. Among the mentioned samples, the SCB specimen is a simple and most common one that has been proposed by AASHTO and ASTM standards for fracture toughness testing of asphalt concrete (AC) materials. In addition, short and long length beam type configurations with edge crack and subjected to three-point bend loading have also been employed by a few researchers (Yang et al., 2021; Saed et al., 2022; Aliha et al., 2024; 2026; Reis et al., 2003,2004, 2011a,b) for conducting fracture toughness experiments on asphalt and concrete samples. The ENDB specimen has also received much attention in recent years for conducting fracture toughness experiments on asphalt and concrete mixtures. This is mainly because of ability of this specimen in introducing all three basic modes (I, II and III) fracture deformations (Liu and Ma, 2024; Cao et al., 2024; Gan et al., 2024; Aliha et al. 2023b; Zhao et al., 2024; Zheng, et al., 2024; Mousavi et al., 2024;; Tabasi et al., 2023; Bakhshizadeh et al. 2024; Najjar et al. 2023; Zheng et al., 2023; Hoseini et al., 2023; Zarei et al., 2022a) as well as ease of sample manufacturing and testing process for the mentioned construction materials. However, there is still a need for completing the knowledge of cracking resistance performance of modified HMA mixtures containing waste materials (like RAP) under different loading conditions. Hence, the aim of this research is to investigate the effect of adding RAP material in the mixture of hot mix asphalt (HMA) concretes on the fracture toughness and cracking resistance values. To do that, using several ENDB test samples made of HMA mixtures containing different percentages of RAP, the corresponding values of K_{Ic}, K_{IIc} and K_{IIIc} are determined at low temperature conditions.

2. Test specimen for fracture toughness study of HMA mixtures

In 2011, Tutluoglu and Keles (2011) introduced a novel method called the cracked disc bend configuration to study the mode I fracture toughness of rocks. Afterwards this specimen was named as "ENDB" (edge notched disc bend) by Aliha and colleagues (Aliha et al., 2015) and extended its utilization to address mixed mode fracture problems including a combination of modes I and III. In 2020, Bahmani et al. (2020) introduced the asymmetric three-point bend loaded version of the ENDB specimen to investigate mixed mode I/II fracture problem as well. Afterwards, Aliha and his coworkers (Aliha et al.,2023a) introduced an updated and modified version of the ENDB specimen for studying fracture problems including all combinations of modes I, II and III. So far, the ENDB specimen has been utilized by many researchers to investigate the mixed mode tensile-shear cracking resistance behavior of different geomaterials (Bakhshizadeh et al. 2024; Liu and Ma, 2024; Cao et al., 2024; Gan et al., 2024; Zhao et al., 2024; Zheng, et al., 2024; Mousavi et al., 2024; Aliha et al. 2023b; Tabasi et al., 2023; Najjar et al. 2023; Zheng et al., 2023; Hoseini et al., 2023; Zarei et al., 2022a,b; Yang et al., 2022). **Fig. 1** illustrates an overall schematic of the ENDB specimen that is a disc with the radius R and height H. The disc has an edge crack of length a and be subjected to a three-point bend loading. Through adjusting the angle α between the crack plane and the triple parallel upper and bottom load/support rollers, the ENDB specimen can introduce any desired combination of modes I and III at the mid-point of the crack front. The existence of unequal positioning of support rollers relative to the crack edge will result in the occurrence of mode II deformation, which includes in-plane shear, at the mid-section. In the ENDB test, the geometry and shape of specimen for conducting all three modes are the same but the locations of bottom loading supports (S_1 and S_2 distances) or the crack angle relative to the rollers can alter the type of loading mode or crack deformation state. For $\alpha = 0^\circ$, when S_1 and S_2 are equal, the mode I case occurs and when S_2 is significantly smaller than S_1 pure mode II or pure shear deformation can be obtained. Pure mode III also obtains for symmetric spans but rotated disc (α angle) relative to the roller directions. **Fig. 2**, shows schematically the situations in which pure modes I, II, III cases are achieved by the ENDB specimen.

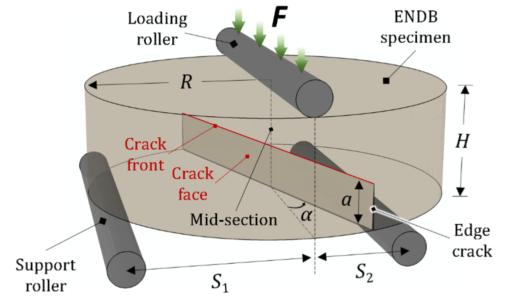


Fig. 1. Geometry and loading conditions for the Edge-Notched Disc Bend (ENDB) specimen for conducting fracture toughness experiments on asphaltic mixtures.

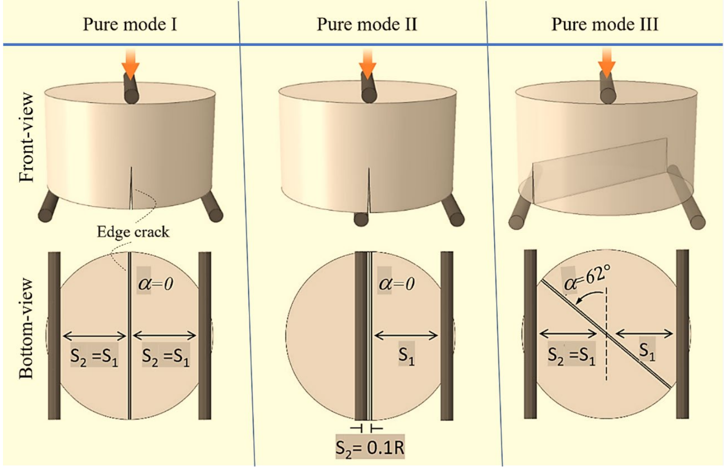


Fig. 2. Corresponding situations of the loading rollers to produce pure modes I, II and III conditions in the ENDB specimen.

The critical stress intensity factors (SIFs) at the onset of fracture or crack initiation that corresponds to the fracture toughness values can be determined via the below equations for all three basic modes I, II, III:

$$K_{Ic} = \sigma_{cr} \sqrt{\pi a}\, Y_I \left(\frac{a}{H}, \frac{S_1}{R}, \frac{S_2}{R}, \alpha\right) \tag{1}$$

$$K_{\mathrm{IIc}} = \sigma_{cr}\ \sqrt{\pi a}\, Y_{\mathrm{II}}\ \left(\frac{a}{H}, \frac{S_1}{R}, \frac{S_2}{R}, \alpha\right) \tag{2}$$

$$K_{\mathrm{IIIc}} = \sigma_{cr}\ \sqrt{\pi a}\, Y_{\mathrm{III}}\ \left(\frac{a}{H}, \frac{S_1}{R}, \frac{S_2}{R}, \alpha\right) \tag{3}$$

where

$$\sigma_{cr} = \frac{3F_{cr}\, S_1 . S_2}{RH^2(S_1 + S_2)} \tag{4}$$

In the aforementioned equations, F_{cr} is the critical (peak) applied load to the ENDB sample and Y_{I}, Y_{II} and Y_{III} are the geometry factors of mode I, mode II and mode III, respectively. These geometry factors are functions of a/R, S_1/R, S_2/R and α can be determined numerically using commercial software such as ABAQUS.

3. Asphalt mix design and manufacturing process

The asphaltic concrete of this work is hot-mix-asphalt (HMA) made of limestone aggregates (Lime) with nominal-maximum-aggregate-size of 12.5 mm and semi-hard bitumen with penetration gradation of (60-70) and performance gradation of (64-24). Such basic stone and binder materials are commonly used for manufacturing TOPECA layer (upper layer) of asphaltic pavement in most of the roads in Iran. In addition, as partial replacement of natural and virgin ingredients (such as bitumen and aggregates) with recycled asphalt pavement materials, different RAP contents (0, 20 and 40%) were added to the mixture of modified HMA concrete. For preparing control and modified HMA mixtures containing 0, 20 and 40% RAP, the fractions of raw and recycled materials were obtained according to code 234 of Iran Highway Standard. Table 1, illustrates the sieve size gradation and fraction of raw and RAP materials for preparing three HMA mix designs. Using the extraction analysis suggested by ASTM D 2172, the bitumen content of the RAP material was determined. Also, in accordance with the ASTM D5444 standard, the aggregate sieve size of the virgin and natural aggregates and the aggregates of RAP material obtained via the extraction method are illustrated in Table 1. The specific density of RAP material was also determined equal to 2.57 gr/cm^3.

Table 1. Sieve size of natural and RAP extracted aggregates utilized for manufacturing the control and modified HMA mixture of this research.

Natural stone aggregates		Recycled asphalt pavement (RAP) aggregates	
Sieve size	% of Passing	Sieve size	% of Passing
19	100	19	100
12.5	90-100	12.5	99
-	-	9.5	95
4.75	44-74	4.75	60
2.36	28-58	2.36	40
0.3	5-21	0.3	16
0.075	2-10	0.075	10

For the samples containing RAP material, an oil-based rejuvenator material with 5% (w.t) was used in the mix design of HMA. By determining some indexes such as the specific density of mixture, and the Marshall strength values, the optimum percentages of bitumen content for the HMA mixtures containing 0, 20 and 40% RAP were obtained. All ingredients were mixed together and then compacted inside the gyratory compactor cylinder with diameter of 100 mm according to ASTM D6926 mixing procedure. The compaction temperature of the samples made of 20 and 40% RAP was 140ºC and 135ºC, respectively. Accordingly, several controls (without RAP content) and modified HMA mixtures (with 20 and 40% RAP) were manufactured. The average value of air void content in the manufactured asphaltic cylinders was approximately 4%.

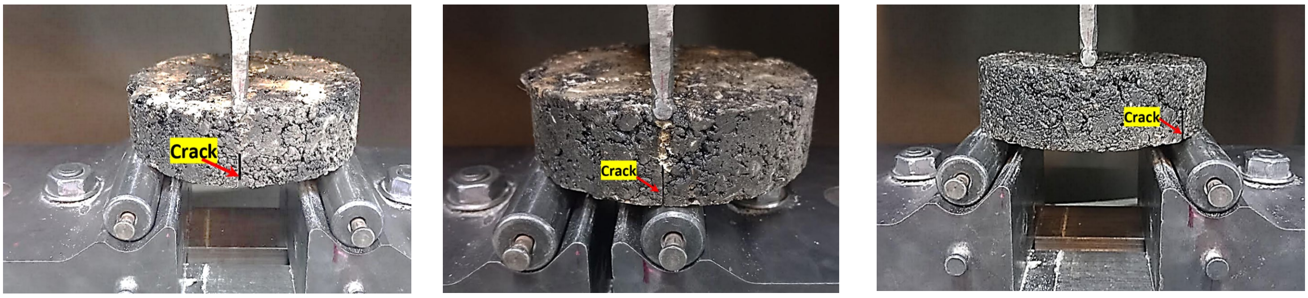
4. Low temperature fracture toughness tests

The cylindrical gyratory samples were then cut and sliced perpendicular and along the cylinder axis to create disc samples (ENDB) with thickness of 30 mm. An edge crack with length of 12 mm was created at the middle of each sample using a rotary diamond saw blade. The crack length ratio (a/H) in all ENDB samples of this research was therefore a fixed value of 0.4. In order to investigate low temperature cracking resistance of the control HMA and modified with RAP, the ENDB samples were tested at five low temperatures of 0, -6, -12, -18 and -24 ºC. Accordingly, before testing, the manufactured samples were stored at the mentioned temperatures for 12 hours. A large number of ENDB specimens (with radius of 50 mm and thickness of 30 mm and the crack length of 12 mm) made of HMA mixture with different RAP contents were prepared for mode I, mode II and mode III fracture toughness testing using the ENDB samples. The loading conditions and span lengths for different modes are illustrated in **Table 2**. The corresponding values of geometry factors (Y_{I}, Y_{II} and Y_{III}) are also given in this Table that have been extracted from previous works (Aliha et al., 2015, Bahmani et al., 2020).

Table 2. Loading conditions and geometry factors for introducing pure mode I, pure mode II and pure mode III fracture cases using the ENDB test.

	R (mm)	H (mm)	a/H	S_1/R	S_2/R	α (degree)	Y_{I}	Y_{II}	Y_{III}
Pure mode I	50	30	0.4	0.8	0.8	0	1.248	-	-
Pure mode II	50	30	0.4	0.8	0.09	0	-	2.114	-
Pure mode III	50	30	0.4	0.8	0.8	62	-	-	0.302

The experimental test set up for mode I, mode II and mode III fracture tests of the ENDB specimen are shown in Fig. 3. All manufactured asphaltic test samples (control and RAPed ones) were loaded monotonically with loading rate of 3 mm/min. The fracture curves of all tested samples showed dominantly linear behavior up to the onset of fracture and peak load at the tested temperatures. This behavior reveals that the framework of linear elastic fracture mechanics (LEFM) is valid with good accuracy for the investigated asphaltic mixtures at low temperature conditions. Consequently, the fracture toughness values of asphaltic mixtures tested with the ENDB specimen were obtained by replacing the fracture load (F_{cr}) of each sample into Eqs. (1) to (3) and utilizing the corresponding geometry factors given in Table 2 for the test conditions of this research.



(a) (b) (c)

Fig. 3. Loading setup for conducting (a) pure mode I, (b) pure mode II and (c) pure mode III fracture experiments on the asphaltic mixtures using the ENDB specimen.

4. Results and discussion

Fig. 4 presents the variations of mode I fracture toughness (K_{Ic}) for the tested HMA mixtures at different temperatures. It is seen that generally by increasing the RAP content, the fracture toughness reduces typically about 15 % relative to the control mixture (i.e. 0% RAP case). Also, the value of K_{Ic} is increased by decreasing the test temperature from zero to -24°C for both control and RAPed HMA mixtures (with 20% and 40% RAP content). This could be due to increasing the stiffness of bitumen and mastic part of the HMA by reducing the test temperature. The impact of input parameters studied in this research (i.e. RAP content and temperature) on the cracking resistance of HMA material is not the same and according to the results, it is seen that the test temperature has much more significant influence on the variation of K_{Ic} compared to the RAP percentage parameter.

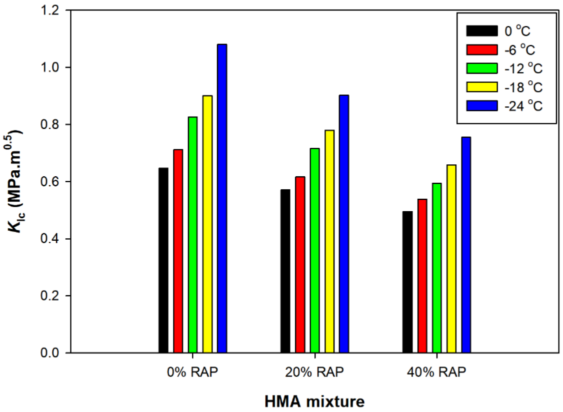


Fig. 4. Variations of mode I fracture toughness (K_{Ic}) results obtained from ENDB testing under different low temperatures and for control and RAPed HMA mixtures.

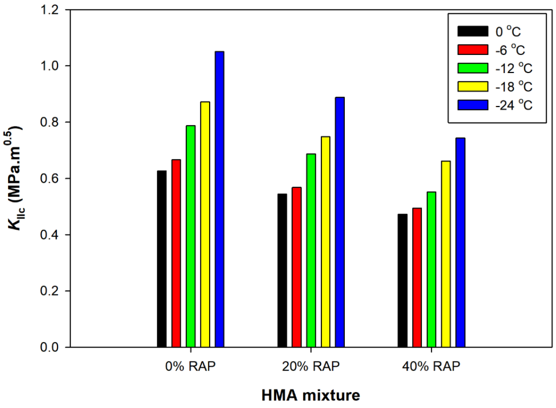


Fig. 5. Variations of mode II fracture toughness (K_{IIc}) data obtained from ENDB testing method under different low temperatures (from zero to -24°C) and for control and RAPed HMA mixtures.

Similar trends and results were also obtained for the variations of shear mode fracture toughness values (i.e., K_{IIc} and K_{IIIc}) with the RAP percentage and temperature for the tested ENDB samples as shown in **Fig. 5** and **Fig. 6**. These results confirm that the low temperature failure mechanism of the tested HMA mixtures under tensile and shear deformations are the same and similar. **Fig. 7** depicts the fracture pattern and path of fracture observed for the tested ENDB samples under different basic fracture modes. Based on this Figure, straight and self-similar fracture path was observed for modes I and II (i.e., in-plane deformations of crack) but twisted and kink fracture trajectory was seen for mode III (i. e., out-of-plane fracture) case. In addition, for all tested modes the fracture was propagated through both mastic (soft part) and aggregate such that in all fracture surfaces some broken fine and coarse stone materials are observed.

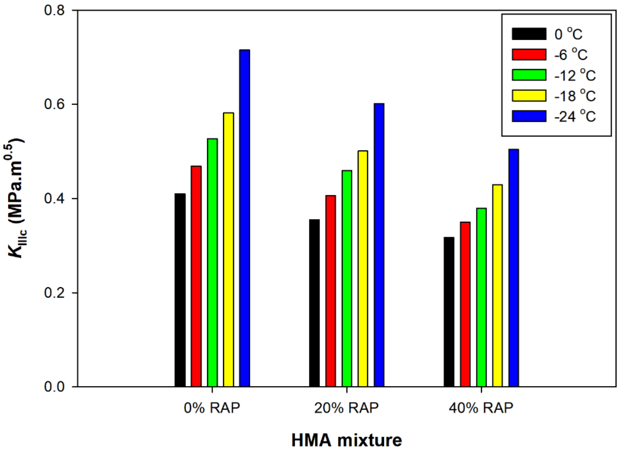
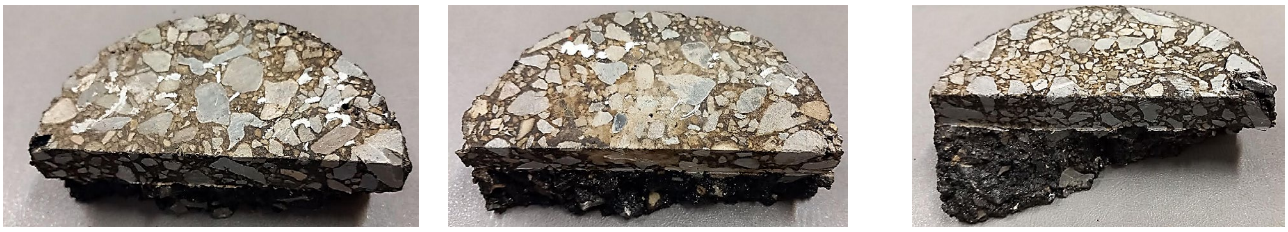


Fig. 6. Trends of mode III fracture toughness (K_{IIIc}) test results obtained from the ENDB samples under different low temperatures (from zero to -24°C) and for both control and modified mixtures (containing RAP).



(a) (b) (c)

Fig. 7. Fracture pattern of the ENDB samples tested under (a) pure mode I, (b) pure mode II and (c) pure mode III at low temperature conditions.

In order to compare the influence of loading mode on the cracking resistance of the tested HMA mixtures, **Fig. 8** to **Fig. 10** present the fracture toughness ratios (K_{IIc}/K_{Ic}, K_{IIIc}/K_{Ic} and K_{IIc}/K_{IIIc}) for different temperatures and RAP contents. Based on these results, the resistance of asphaltic mixtures against modes I and II fracture deformations is nearly the same and identical such that the K_{IIc}/K_{Ic} ratio varies in the range of 0.92 and 1 for different HMA mixtures and testing temperatures (Fig. 8). However, mode III fracture toughness value (K_{IIIc}) is noticeably lower than the corresponding values of K_{Ic} and K_{IIc} as can be observed from **Fig. 9** and **Fig. 10**; demonstrating the weakness of HMA mixtures and concretes against out-of-plane deformations.

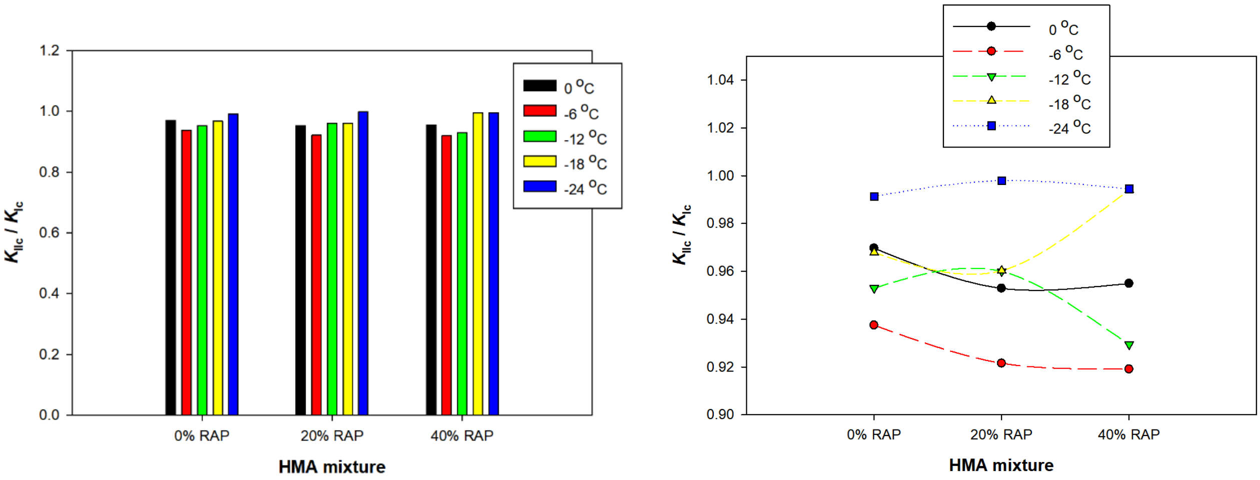


Fig. 8. Variations of K_{IIc}/K_{Ic} ratio for the tested HMA mixtures at different temperatures and RAP contents.

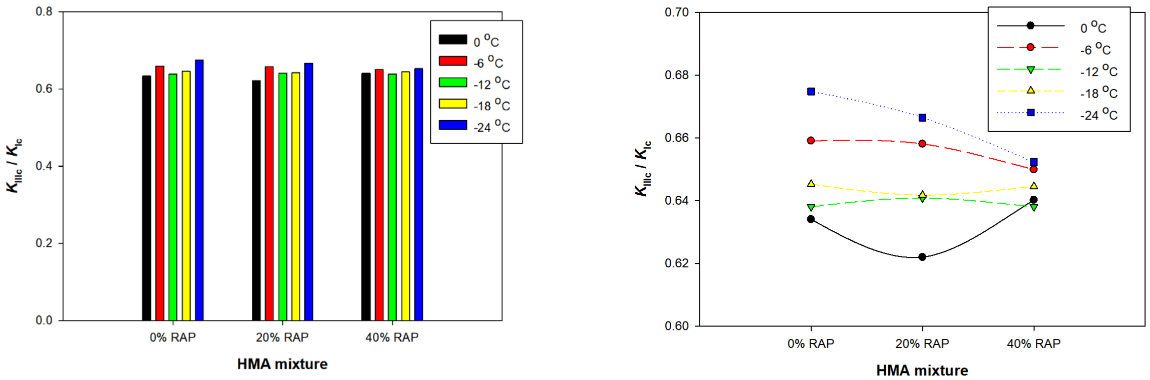


Fig. 9. Variations of $K_{\text{IIIc}}/K_{\text{Ic}}$ ratio for the tested HMA mixtures at different temperatures and RAP contents.

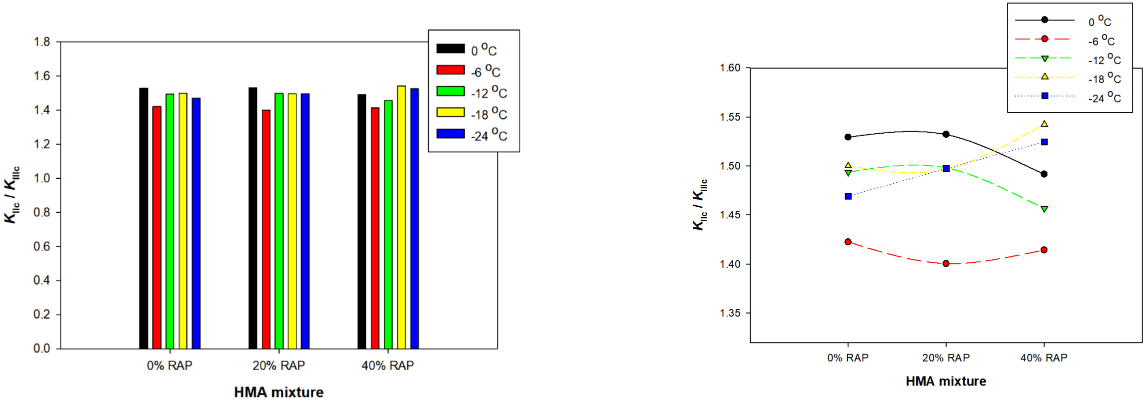


Fig. 10. Variations of $K_{\text{IIIc}}/K_{\text{IIc}}$ ratio for the tested HMA mixtures at different temperatures and RAP contents.

Based on the previous works every passage of a vehicle from a cracked pavement containing a top-down crack can activate different times opening and shearing mode deformations (Ziari et al., 2022; Ameri et al., 2011, Aliha et al., 2021). Therefore, it is interesting to investigate the role and impact of tensile and shear modes on the cracking resistance behavior of asphaltic concrete materials that are used as the top layer of the overlay. Two fracture characteristic indexes called tensile to shear resistance ratio ($K_{\text{opening}}/K_{\text{shearing-eff}}$) and effective fracture toughness (K_{eff}) defined as below relations are used for examining the importance of different fracture modes.

$$K_{\text{Opening}}/K_{\text{Shearing-eff.}} = \frac{K_{\text{Ic}}}{\sqrt{K_{\text{IIc}}^2 + K_{\text{IIIc}}^2}} \tag{5}$$

$$K_{\text{eff-total}} = \sqrt{K_{\text{Ic}}^2 + K_{\text{IIc}}^2 + K_{\text{IIIc}}^2} \tag{6}$$

Variations of these two fracture indexes for the investigated HMA mixtures of this research under different temperatures are shown and compared in **Fig. 11** and **Fig. 12**.

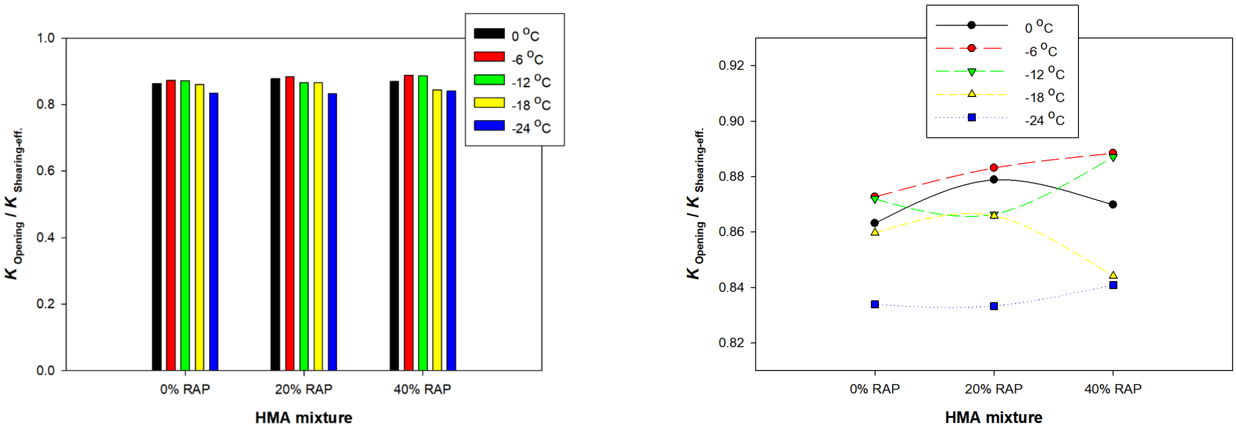


Fig. 11. Variations of $K_{\text{opening}}/K_{\text{shearing-eff}}$ for the investigated HMA mixtures of the current research under different low-temperature conditions.

Based on these results, the effective fracture toughness of all three-basic modes is increased by decreasing the test temperature and reduced by increasing the RAP content. The corresponding value of $K_{\text{eff-total}}$ varies in the range of 0.8 to 1.7 MPa.m$^{0.5}$ depending on the mixture type and testing temperature. Comparison of the tensile mode crack resistance and effective shear crack resistance data shown in **Fig. 11** reveals that shear mode has more important influence on the failure of asphaltic mixtures.

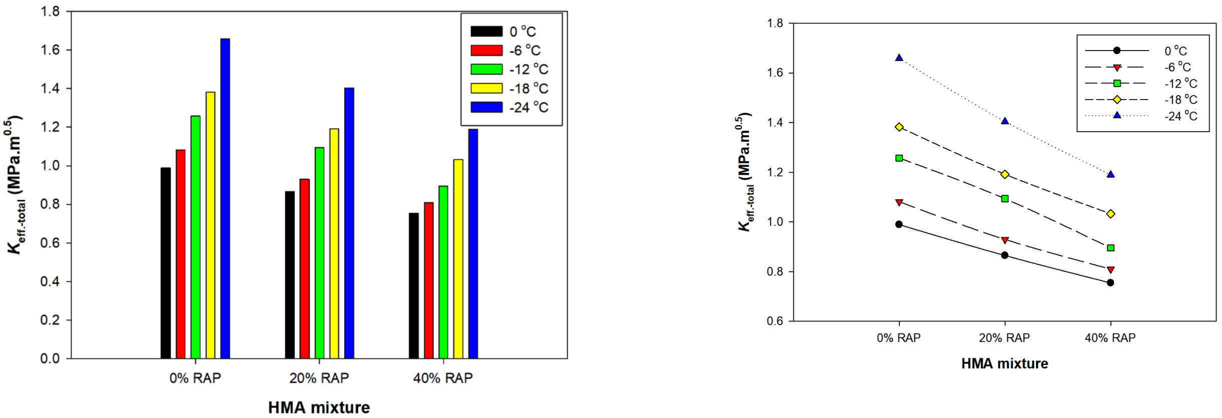


Fig. 12. Variations of total effective fracture toughness for the investigated control and modified HMA mixtures under different low-temperature conditions.

4. Conclusions

- The effect of RAP content on three basic modes fracture toughness (K_{Ic} , K_{IIc} and K_{IIIc}) of hot mix asphalt concrete was studied experimentally at different low temperature conditions (0, -6, -12, -18 and -24ºC) using the ENDB method. The RAP was added as partial replacement of aggregates to the mix design of HMA in weight percentages of 0, 20 and 40%. Symmetric and asymmetric loading supports of the rollers in the ENDB test can introduce all three basic modes with the same geometry.
- Corresponding values of K_{Ic}, K_{IIc} and K_{IIIc} were decreased by increasing the RAP content and decreasing the test temperature from zero to -24 ºC. However, the effect of temperature on the variations of all fracture toughness values was more effective than the RAP content.
- Fracture toughness value was dependent on the loading mode type. Depending on the mixture type and temperature, mode I and mode II fracture toughness (K_{Ic} and K_{IIc}) was varied in the range of 0.5 and 1.1 MPa.m$^{0.5}$. K_{IIIc} value was varied in a lower magnitude from 0.35 to 0.75 MPa.m$^{0.5}$.
- Variations and trends of different fracture indexes such as: $K_{\text{IIc}}/K_{\text{Ic}}$, $K_{\text{IIIc}}/K_{\text{Ic}}$, $K_{\text{IIc}}/K_{\text{IIIc}}$, $K_{\text{eff-total}}$ and $K_{\text{opening}}/K_{\text{shearing-eff}}$ were obtained and investigated for different HMA mixtures with or without RAP contents. These indexes can help the researchers in better understanding the failure mechanism of asphaltic mixtures under different loading modes and testing conditions.

Acknowledgments

This work was supported (T.Sadowski) and funded under the grant “Subvention for Science” by the Ministry of Science and Higher Education of the Republic of Poland - project No. FD-20/IM-5/155. M.R. M. Aliha acknowledges the Polish National Agency for Academic Exchange (Grant No. ULAM NAWA BNI/ULM/2024/1/00180/UO/00001) for visiting scientists on sabbatical leave to visit Lublin University of Technology, Poland. Also, M.R.M. Aliha acknowledges the TÜBİTAK (Grant No. 2221-1059B212200747) program for visiting scientists on sabbatical leave to visit Gebze Technical University, Turkey.

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