THE BALTIC JOURNAL
OF ROAD
AND BRIDGE
ENGINEERING
2023/18(1)

ISSN 1822-427X/eISSN 1822-4288
2023 Volume 18 Issue 1: 94–121
https://doi.org/10.7250/bjrbe.2023-18.590

INTERMEDIATE TEMPERATURE FRACTURE RESISTANCE OF STONE MATRIX ASPHALT CONTAINING UNTREATED RECYCLED CONCRETE AGGREGATE

LEE LEON[1*], JOVANCA SMITH[1], ANNABELLA FRANK[2]

[1]*Department of Civil and Environmental Engineering, University of the West Indies, St Augustine, Trinidad & Tobago*

[2]*International Project Initiatives Limited, Port of Spain, Trinidad & Tobago*

Received 1 February 2022; accepted 4 November 2022

Abstract. The sustainable alternative of blending natural limestone aggregates (NAs) with recycled concrete aggregate (RCA) was investigated in this research in order to encourage the utilization of recycled concrete in heavy traffic paving applications. The Marshall Mix design method was used to optimize mix designs containing 0%, 10%, 35% and 50% RCA. Single-edge notched beam (SENB) and semi-circular bending (SCB) tests were then applied and the fracture energy and fracture toughness determined. The tests were conducted at intermediate temperatures (5 °C, 15 °C, 25 °C) and varying notch depths (0.2H, 0.3H and 0.4H). Fracture energy and toughness did not consistently follow the behaviour of mixes with only NA; however, it was determined in this study that a RCA content between 10% and 35% would achieve peak loads, fracture energies and fracture toughness values comparative to a virgin mix.

Keywords: fracture resistance, recycled concrete aggregate, stone matrix asphalt, sustainability.

* Corresponding author. E-mail: lee.leon@sta.uwi.edu

Lee LEON (ORCID ID 0000-0003-4153-0318)

Introduction

Construction and demolition (C&D) waste have been determined to be one of the largest contributors to global waste levels. In 2014, the United States produced approximately 505 million tons of demolition waste, 70% of which was concrete waste (USEPA, 2016). Further to this, the largest producer of construction waste in the world, China, produces approximately 2 billion tons of construction waste per year, two million of which is concrete (Gross, 2019). Local studies (Smith et al., 2019; Narcis et al., 2019; Rampit et al., 2020) examined the local construction and demolition waste management industry and concluded that further research would be required into C&D waste management locally. Numerous studies (Moazami et al., 2021; Zhang et al., 2021; Choudhary et al., 2021; Motter et al., 2015; Arabani et al., 2013) have investigated avenues including composite pavement (the combination of flexible asphalt pavements and Portland cement pavements), recycling pavements, and most popularly the substitution of waste materials as aggregate in asphalt mixes. Common material substitutions for construction of a sustainable pavement included recycled asphalt pavement (RAP), polymers, rubber, steel slag and recycled concrete aggregate (RCA). Recycled asphalt pavement is reprocessed pavement containing asphalt and aggregates. This material is created when asphalt pavements are removed for various activities, including reconstruction, resurfacing and gaining access to buried utilities (Chesner et al., 2002). Recycled concrete aggregate is defined as aggregate produced from concrete construction and demolition waste, which either partially or completely replaces conventional natural aggregates (NAs) (Bamigboye et al., 2022).

A sustainable pavement as defined by Muench and Van Dam (2014) is one that achieves its specific engineering goals, while, on a broader scale, meets basic human needs, uses resources effectively, and preserves/restores surrounding ecosystems. Considerations of sustainability are not new to the engineering industry, including the design of pavements. Worldwide, governments and private research ventures are encouraging because they are investigating the ways in which asphalt mixes can be made more sustainably while maintaining its performance characteristics. In addition to the environmental aspect surrounding volumes of waste and the use of sustainable approaches taken to design and manufacture asphalt mixes, the overall economic impact is equally vitally important. It is commonly theorized that the lifecycle costs of the pavement can be reduced by having a reduced capital cost compared to traditional aggregates as long as the performance of the pavement is comparative to traditional pavement design, thus maintaining low or equivalent maintenance and operating costs. In a study by Praticò et al. (2020) regarding the lifecycle cost of pavements, an energy analysis was undertaken with consideration from material production to end of life. The study determined that approximately 60% of the lifecycle cost of the pavement was contributed by production of its materials. As such, incorporating recycled or waste materials can assist in reducing the lifecycle cost of the pavement.

With respect to aggregate replacement in the area of asphalt concrete, there have been numerous studies involving the partial or complete replacement of traditional natural aggregates with materials such as recycled concrete, brick, glass, ceramic, rubber, recycled asphalt and steel slag (Ge et al., 2014; Medina et al., 2015; Ameli et al., 2020; Kim and Na, 2021; Pourtahmasb and Karim, 2014). Continuous research into the use of construction waste as recycled aggregates in various types of projects, including bituminous applications, should be conducted (Silva et al., 2019). While there has been research into the acceptability and limitations of recycled concrete aggregate (RCA) as a replacement in hot mix asphalts, Pourtahmasb (2014) notes that there has been little research into its application in gap graded mixes like stone matrix asphalt (SMA). They explored the use of RCA in stone matrix asphalt based on characteristics, such as physical properties, volumetric properties, resilient modulus, rutting resistance, and concluded that in specific amounts, the use of RCA in both SMA and dense graded mixtures – hot mix asphalt (HMA) – could satisfy standard specifications. Paranavithana and Mohajerani (2006) similarly observed the aforementioned properties as influenced by varying percentages of RCA substituted for coarse aggregate. Investigation into the use of RCA as a substitute aggregate based on flakiness, density, crushing resistance, water absorption and compressive strength was deemed successful (Tahmoorian and Samali, 2018).

The suitability of recycled concrete has also been investigated through concrete testing to determine values such as Aggregate Crushing Value (ACV) and Aggregate Impact Value (AIV). These values were noted to mostly be investigated for RCA incorporated into concrete mixtures. Other studies (Sarraz and Hossain, 2017; Al-Bayati et al., 2018) also examined the utilization of RCA effect on the strength and volumetric properties of dense graded asphalt concrete. The strength of SMA is commonly defined to be derived from the stone-on-stone contact of the skeleton structure. Brown et al. (1977) have shown that the percent passing the 4.75 mm sieve is critical in this stone-on-stone contact. Due to the importance of load resistance via direct stone-to-stone contact in SMA, it is a key that the aggregate used in mix design is sufficiently able to withstand degradation (Gatchalian et al., 2006). From another perspective, the high aggregate-to-binder ratio directly links to the performance of asphalt concrete (Sarraz and Hossain, 2017).

Whether using traditional natural aggregate or a blend of recycled aggregate, hot mix asphaltic concrete can become subjected to pavement distress as a result of poor design or inadequate durability over its useful life. Common pavement distresses include bleeding, cracking, potholes, ravelling and rutting. Each form of distress develops as a result of different physical and environmental factors such as design, loading, weather and poor construction to name a few. Multiple forms of pavement distress are manifested through cracking and of key interest are the properties surrounding crack initiation and propagation through the asphalt. The Marshall Stability test is commonly used for asphalt mixture design, but it does not provide the detailed information on material characteristics required for pavement design. Properties like rutting resistance of asphalt mixtures should be combined with fracture energy and fracture toughness to investigate cracking resistance. Fracture energy of asphalt gives the energy required to form a new crack surface, while fracture toughness is a measure of energy absorption to failure (Bazant and Planas, 1998). Understanding the cracking process of initiation and propagation is critical because ultimate failure results from exceeding available fracture energy. Moreover, the effect of temperature fluctuations can also result in brittle and ductile material failure.

RILEM has outlined various test methods to measure fracture energy of concrete. The work-of-fracture method was adopted in this research to determine the fracture energy of asphalt concrete due to its history and ease of testing. The introduction of single-edge notch beam (SENB), semi-circular bending tests (SCB), disc-shaped compact tension (DCT) and indirect tension tests (IDT) have been identified to study fracture properties of asphalt mixtures. Selection of an appropriate test setup depends on the advantages and disadvantages of various tests, as well as the equipment and specimen availability. The SCB, DCT and ITS tests are all suitable for field cores, but SCB tests maintain a smaller fracture surface depth than other tests. Moreover, the IDT test setup naturally results in a higher deformation and coefficient of variance of results compared to other tests, while an additional constraint exists at the top surface of both SENB and SCB tests (Radeef et al., 2021). It is also important to note that complex stress states arise as a result of the arch effects of the SCB tests (Wagoner et al., 2005). Artamendi and Khalid (2006) compared and concluded that the semi-circular bend and single-edge notched beam tests were suitable and comparable test methods for asphalt studies. They observed very minor differences in the stress intensity factors calculated. In fracture mechanics, mode I is defined where stress is orthogonal to the local plane of the crack surface (Zehnder, 2013). For mode I fracture, the fracture energies calculated for SCB tests were more than double the fracture energies from SENB tests. Researchers (You et al., 2015; Ferdowsi and Arabani, 2009) have noted that the SCB test is efficient, repeatable, advantageous and a practical way to characterise tensile and fracture resistance of asphalt concrete. Similarly, Link et al. (2005) have also shown the SENB test procedure, as an advantageous method for determining the fracture mechanics, is notably used for testing fracture mechanics under low and intermediate temperatures.

The re-use of construction and demolition waste as an alternative to traditional aggregates is a reasonable method of boosting sustainability. Therefore, an objective of the study is to investigate the effects of addition of RCA on the fracture behaviour of SMA. Fracture mechanics and behaviour evaluation is noteworthy in the comparison of stone matrix asphalt with RCA, versus stone matrix asphalt with only traditional natural aggregates in certain climatic conditions, for example, tropical climates, where temperatures are above an average of 15°C all year round. Subsequently, since many published works have focused on the cracking and fatigue performance of the commonly used dense graded mixtures at low to extremely low temperatures, the second objective of the study is to consider the effects of intermediate temperatures on the performance of SMA – RCA blended mixtures.

1. Materials and methods

1.2. Materials and mix design

Limestone aggregates, 60/75 penetration grade bitumen, and recycled concrete aggregates were used in this study. The crushed limestone aggregates were supplied from the National Quarries Company Ltd located in Trinidad and Tobago. The RCA was made using scrap concrete cubes that were collected from construction sites and measured to have a minimum design strength of 30 MPa. The cubes were crushed using a sledgehammer and subsequently processed in a jaw crusher to achieve the aggregate gradation required. Bitumen was obtained from Trinidad Lake Asphalt (TLA). The physical properties of limestone aggregates, RCA and 60/75 binder are outlined in Table 1. The particle distribution of the 1/2” limestone, 3/8” limestone, limestone dust, filler and RCA aggregate used in this study are shown in Figure 1. The coarse materials such as RCA, 1/2” and 3/8” limestone are all uniformly graded.

According to the blends shown in Figure 2 and Table 2, SMA mixes were created with four different RCA contents (0%, 10%, 35%, and 50%), crushed limestone, limestone dust, and mineral filler aggregates. The SMA design was conducted utilizing a local modified Marshall Mix design procedure to obtain the optimum binder content (OBC) for the four SMA mix types of varying RCA contents. The mix types were identified by asphalt concrete type (SMA) and percent RCA content (SMA-0, SMA-10, SMA-35, SMA-50). The acceptance of the ideal bituminous mix is based on the specified volumetric properties at the

Table 1. Physical properties of aggregates and binder

Aggregate test	Value		Binder test	Value
	Limestone	RCA		
LA abrasion, %	33	43	Penetration	72
Aggregate impact value	26.7	36.0	Softening point	52
Aggregate crushing value	28.4	32.7	Flash point	283
Specific gravity (coarse)	2.629	2.266	Viscosity at 135 °C, Pa·s	0.414
pH	7.95	10.88	Specific gravity	1.012
Water absorption rate	1.2	7.7		

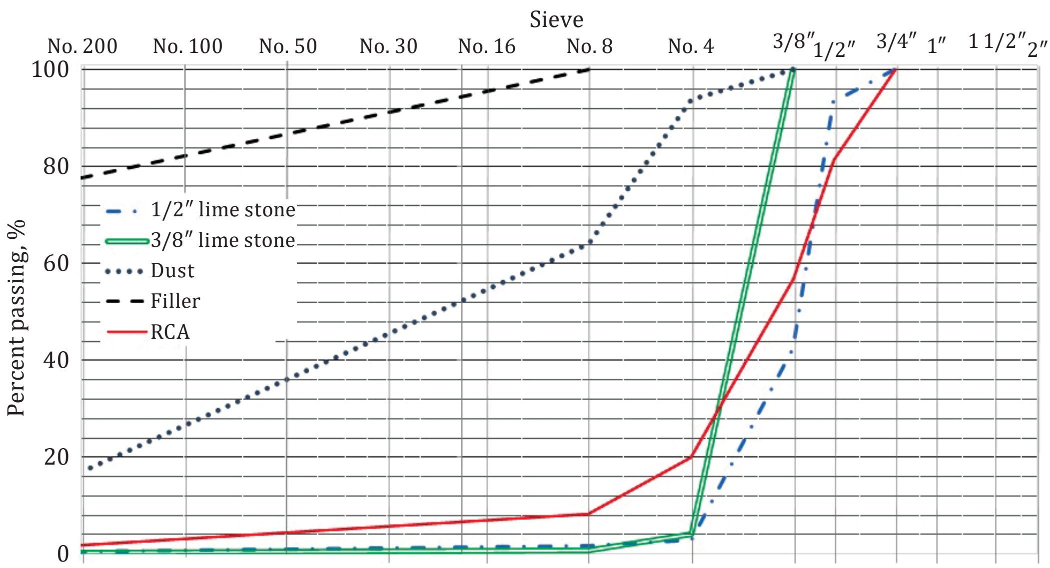

Figure 1. Gradation of the study materials

optimum binder content. Table 2 also highlights volumetric properties based on the OBC and gradation. As the percentage of RCA increases so does the OBC. This can be attributed to the RCA high absorption value, thus requiring more asphalt binder to coat the aggregate. Samples were compacted after the chosen mix design was finished in order to get them ready for the three-point bending tests and semi-circular bend tests.

Table 2. Summary of blended mix designs and volumetric properties

Mix type	SMA-0	SMA-10	SMA-35	SMA-50
1/2 Limestone, %	27	21	4	0
3/8 Limestone, %	49	49	43	34
3/8 Limestone dust, %	15	10	9	5
Filler, %	9	10	9	11
RCA, %	0	10	35	50
Optimum binder content – OBC, %	5.1	5.4	5.8	6.4
Density, kg/m^3	2390	2358	2280	2204
Stability, kN	8.5	8.2	10.5	7.5
Flow, mm	2.7	3.2	3.3	4.4
ITSM @ 25 °C, MPa	1628	1641	1735	1551

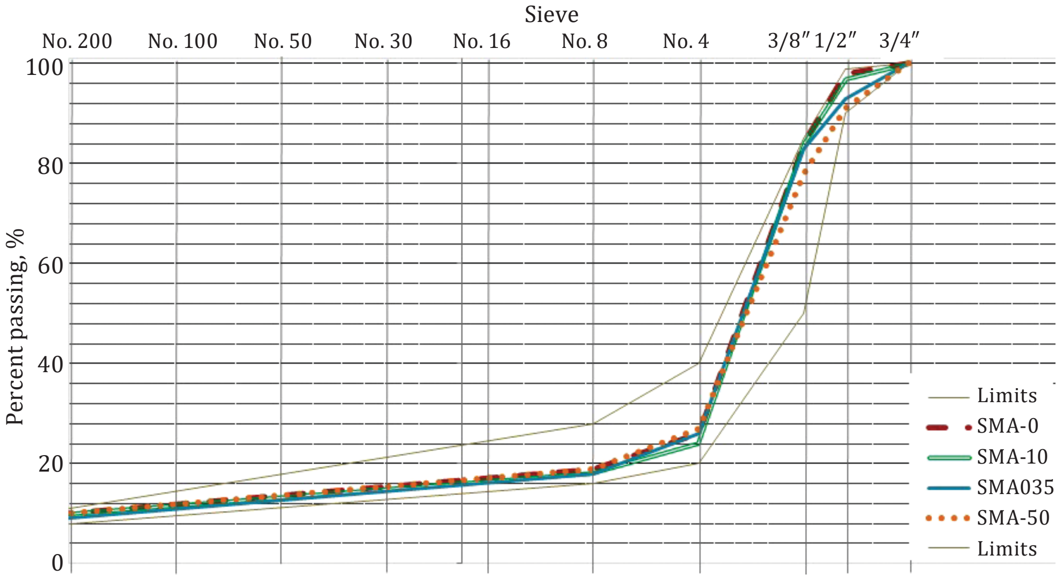

Figure 2. Mix gradation

1.2. Sample preparation and test procedure

Detailed and property-specific tests, like Indirect Tensile Strength and Fracture Energy tests, have grown in popularity and are thus being explored heavily to determine relationships between physical properties or environmental conditions and performance. The introduction of beam and semi-circular bending tests have increasingly been used to study fracture properties of SMA. Artamendi and Khalid (2006) compared and concluded that the semi-circular bend (SCB) and single-edge notched beam (SENB) tests were suitable and comparable test methods for asphalt studies. Evaluation of published studies as indicated in Table 3 was examined to determine the specimen dimensions and notch depths to use in the SENB method of fracture evaluation. Since there was no discernible pattern of dimensions, this study chose sample dimensions based on the available mold and the viability of the specimen preparation. To fabricate the SENB samples, each mix type was compacted using a roller compactor to create slab samples. The mold was modified to create slabs of size 300 mm × 300 mm × 50 mm. A wet masonry saw was then used to create small beams from the slab of approximately 25 mm width; the two end beams were discarded. Notches were cut into the beam samples of depth ratios 0.2H (10 mm), 0.3H (15 mm) and 0.4H (20 mm). This was repeated for each mix design until sufficient samples were gathered to ensure three replicas for each test temperature (5 °C, 15 °C, 25 °C) and notch length. A typical beam specimen is shown in Figure 3. The volumetric properties, dimensions and weights of each sample were measured and recorded for subsequent analysis.

The SENB specimen is loaded under a simply supported, three-point bending configuration. The testing device has a span length and width of 300 mm and 100 mm, respectively. The device rollers are 25.4 mm in diameter and are free to rotate to reduce friction. The centre loading

Table 3. Comparison of SENB dimensions

Reference	Length (L)	Width (W)	Depth (H)
Ding et al. (2018)	250	30	35
Birgisson et al. (2011)	300	100	75
Link et al. (2005)	305	25	25
Kim and El Hussein (1997)	300	70	50
Bhurke et al. (1997)	203.2	50.8	50.8
Current study	*300*	*25*	*50*

point has a radius of 12.7 mm and can swivel in the transverse direction to promote more uniform loading conditions across the width. The loading rate used is in accordance with AASHTO TP 124 for SCB testing. This constant displacement rate of 50 mm/min was directly applied at the mid-point right above the notch on the upper surface. The mid-span displacement was recorded during the loading process. The applied load was monitored using a 10 kN load cell with the load-line displacement being measured by the actuator. The samples were kept in a refrigerated environmental chamber capable of maintaining air temperature within ±0.2 °C for at least 6 hours before being tested. Each SENB test contained three replica samples that were averaged to determine results.

A 150 mm diameter mold was used to fabricate the Semi-Circular Beam (SCB) test samples. Each batched sample was prepared in accordance with the relevant mix design. The mixture was then placed into the mold and compacted using a gyratory compactor. The extruded and cooled sample was then cut into circular slices of 25 mm thickness. Each cylindrical sample was then further cut into a semi-circle as shown in Figure 4 with the ends being discarded. Notch ratios similar to the SENB were cut into the cut side of the semi-circle samples (15 mm,

Figure 3. SENB sample preparation

Figure 4. SCB sample preparation

25.4 mm and 31.8 mm). A total number of 108 notched specimens were placed into the environmental chamber for at least 6 hours to ensure homogenous conditioning of the sample to the testing temperature (5 °C, 15 °C, 25 °C). Each semi-circular asphalt mixture specimen was positioned in the testing device with the flat side on two rollers that were covered with a friction reducing material. The samples were then tested using similar conditions as used in the SENB testing procedure. For each test condition, three replicates were employed as in earlier studies (Saed et al., 2021; Mansourian et al., 2016), and the average value was used to calculate the results.

1.3. Fracture test properties

Fracture occurs when the available energy is greater than the material resistance, which may include forms such as surface energy or plastic work (Anderson, 2017). From the various test methods available for determining the fracture energy of a material, the primary output is a load-displacement curve which can subsequently be used to determine the fracture properties based on the work done as determined from the area below the curve as seen in Figure 5 (Abu et al., 2014).

The Fracture Energy (G_f) of the specimen was calculated based on the area below the load-displacement curve using Equation (1). Fracture toughness (K_{IC}) describes the resistance of brittle materials to the propagation of flaws under an applied stress, and it assumes that the longer the flaw, the lower is the stress needed to cause fracture. The ability of a flaw to cause fracture depends on the fracture toughness of the material (Vaidya and Pathak, 2019). The Fracture Toughness of each SCB specimen was calculated based on the peak load and the specimen dimensions using Equation (2) and Equation (3) (AASHTO, 2013). However, for SENB specimen it was calculated using Equations (4)–(6).

$$G_f = \frac{W_f}{A_{lig}} \tag{1}$$

$$K_{IC} = Y_1 \frac{P}{2rt}\sqrt{\pi a} \tag{2}$$

$$Y_1 = 4.782 + 1.219\left(\frac{a}{r}\right) + 0.063e^{7.045\left(\frac{a}{r}\right)} \tag{3}$$

$$K_{IC} = \sigma_0 Y_1 \sqrt{\pi a} \tag{4}$$

$$\sigma_0 = \frac{3PL}{2h^2 W} \tag{5}$$

$$Y_1 = \frac{1.99 - \left(\frac{a}{W}\right)\left(1 - \frac{a}{W}\right)\left(2.15 - \left(3.93\frac{a}{W}\right) + \left(2.7\frac{a^2}{W^2}\right)\right)}{\sqrt{\pi}\left(1 + \frac{2a}{W}\right)\left(1 - \left(\frac{a}{W}\right)^{3/2}\right)} \quad (6)$$

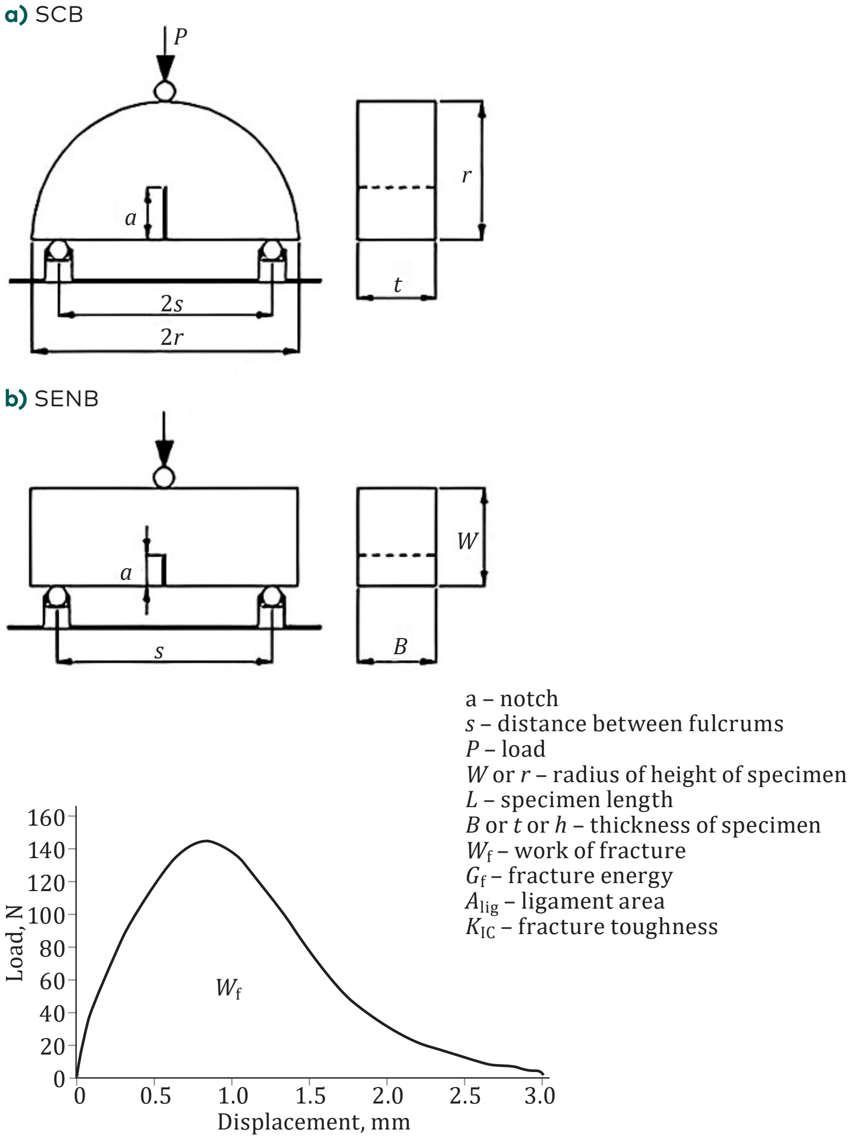

Figure 5. Test setup and typical Load-Displacement curve (a) SCB (b) SENB (Abu Abdo et al., 2014)

2. Results and discussions

2.1. Mix properties

The Marshall stability and flow parameters of SMA mixtures with varying RCA content percentages are shown in Figure 6(a). The specimens' Marshall flow values increased nonlinearly from 2.7 to 4.4 as the RCA content increased. The flow rate was higher during the initial 10% and final 15% increases in RCA, and there was only a slight rise from 10% to 15%. The increase in the optimum binder concentration of the mix types from 5.1% to 6.4% is what causes the overall increase in flow. According to test results, there is a maximum stability of 10.5 kN and a reduction to 7.5 kN at about 35% RCA content. This drop at 50% RCA was less than the 8.5 kN readings at 0% RCA content. Since the minimum SMA stability required by local regulations is 6 KN, the 50% RCA contains stability that is within the permissible range.

The percentages of voids in mineral aggregates (VMA) and voids filled with asphalt (VFA) for SMA specimens with 100% virgin aggregate

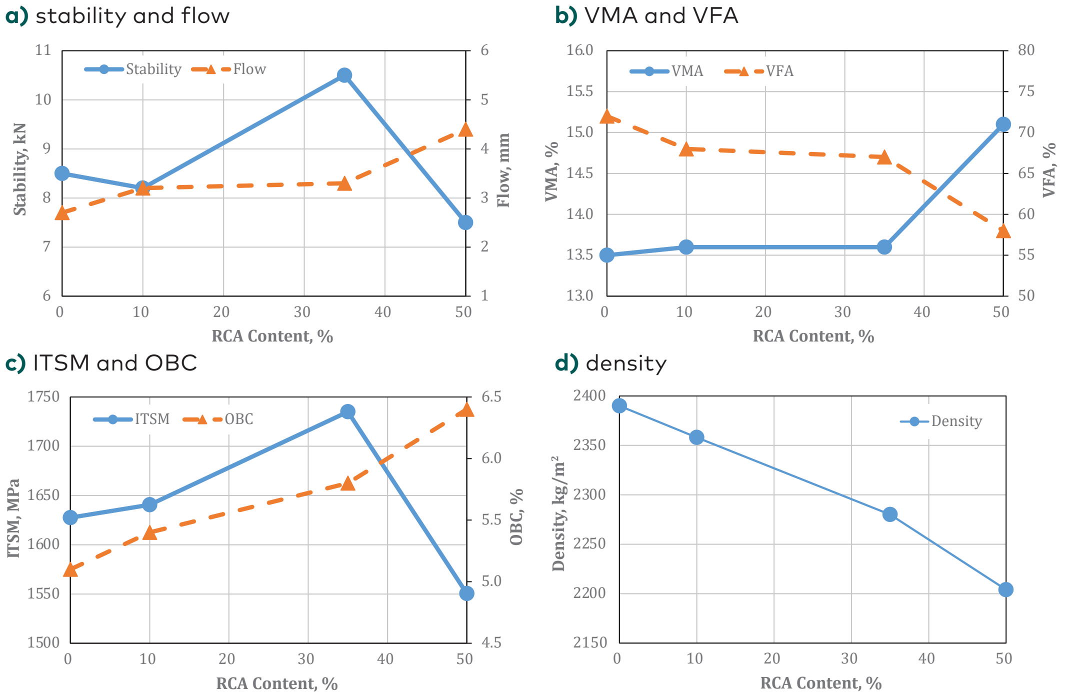

Figure 6. RCA-SMA properties (a) stability and flow; (b) VMA and VFA; (c) ITSM and OBC; (d) density

were 13.5% and 72%, respectively (see Figure 6(b)). According to test results, at 4% air void content, the VMA values increased by a factor of 12% after 35% RCA while remaining nearly constant up to that point. In contrast, the VFA values showed a downward trend. VFA decreased by a factor of 6% with an increase in RCA from 0% to 10%, plateaued between 10% and 35% RCA, and then decreased by a further factor of 15% with an increase in the final 50% SMA-RCA mixture. Higher optimum asphalt binder content is caused by the RCA greater porosity and absorption as compared to natural aggregates, which also induced the behaviours in the asphalt mixtures mentioned above. VMA is not a requirement for the approval of SMA combinations locally.

Figure 6(c) presents the Indirect Tensile Stiffness Modulus (ITSM) of the SMA mixtures containing RCA. The initial 10% addition of RCA resulted in a small increase of less than 1% in ITSM. At 35% RCA, the ITSM values were comparable to the NA mix (0 RCA). However, a 5% decrease in ITSM values was observed for an increase in RCA content from 35% to 50%. It is thought that increasing the coarse RCA content above an equilibrium value, which is regulated by mix gradation and OBC, is responsible for the significant decrease in ITSM values. The comparison of the impact of RCA on the density values of SMA is shown in Figure 4(d). SMA mixes with 100% virgin limestone aggregates had recorded densities of 2390 kg/m^3. Because RCA has a lower specific gravity and density than natural limestone, test findings showed that density decreased practically linearly as RCA concentration increased.

2.2. Crack patterns and load-displacement curves

The pattern of cracks in the failed SCB and SENB specimens with RCA concentrations of 0, 10, 35, and 50% is depicted in Figure 7. No matter the sample geometry, the crack travels in a consistent upward direction from the top of the notch to the location where the load is directly applied. The test results show that, regardless of RCA concentration, temperature, or geometry, all test samples fracture symmetrically into two halves. Typically, for a quasi-brittle test, the crack forms around the coarse aggregates as less energy is required for the crack path. A minimal quantity of coarse aggregate cracking was observed in the results along the vertical crack trajectory. In comparison with a sample where there was no coarse material immediately in the loading route, this condition led to a larger failure load. In samples tested at lower temperatures, which result in a more brittle failure, this aggregation failure pattern occurs more frequently. The greater ductility and viscosity allow for crack propagation around the coarse particles in tests conducted at higher temperatures. Regardless of whether coarse

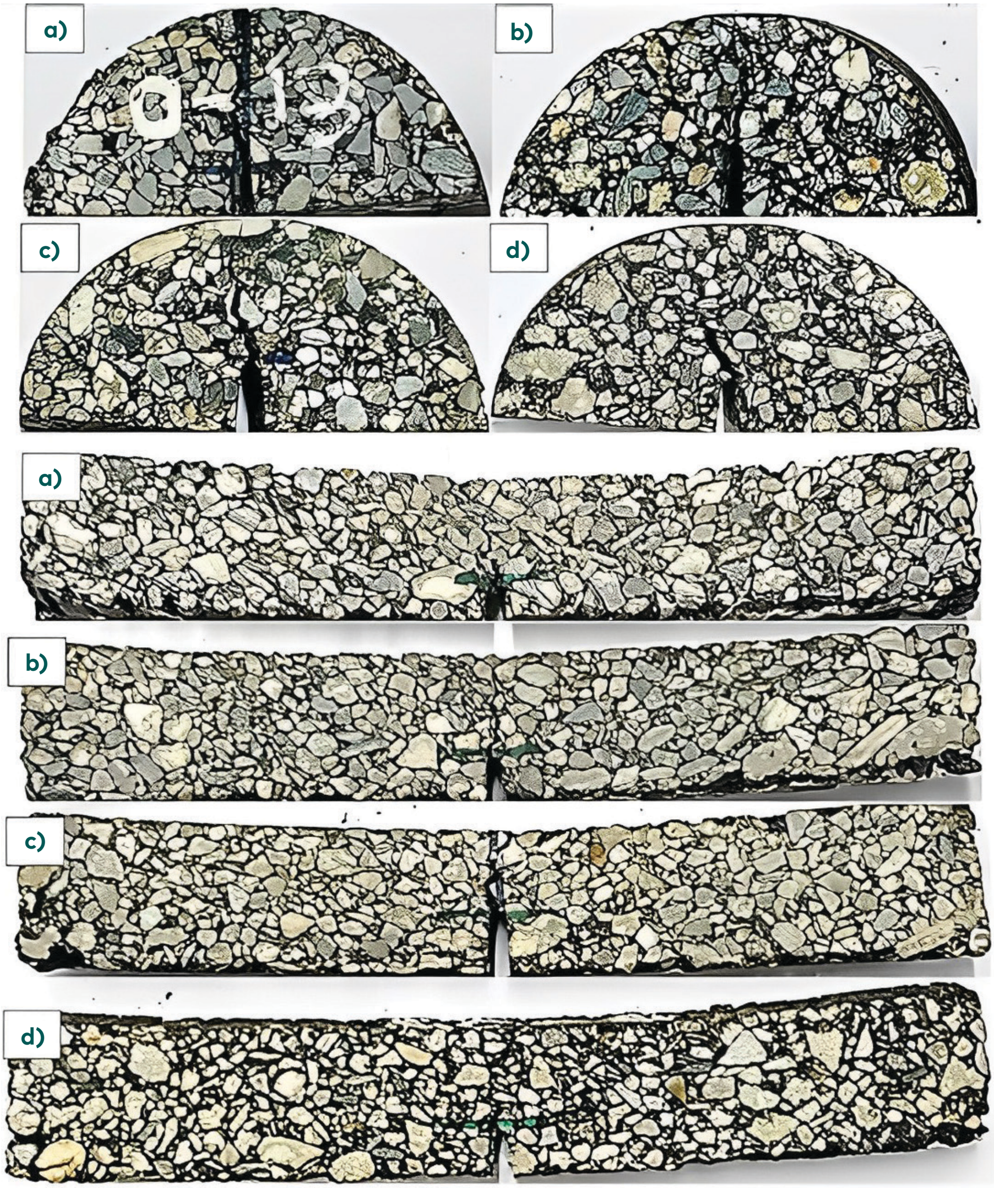

Figure 7. Cracks in SCB and SENB samples (a) SMA-0; (b) SMA-10; (c) SMA-35; (d) SMA-50

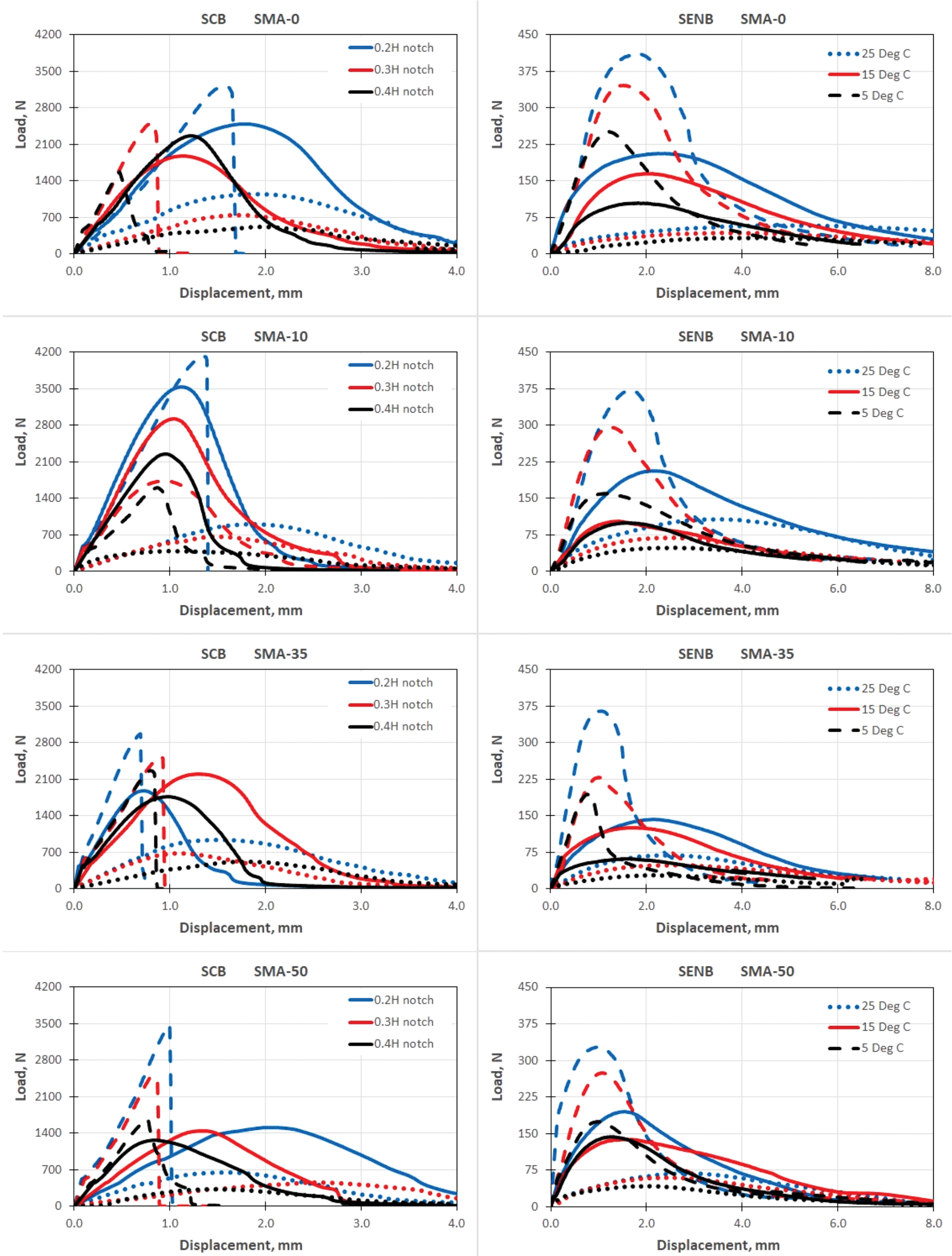

Figure 8. Load–displacement curves of SCB and SENB tests at varying notch depths and temperatures

aggregates are present in the loading path, the fracture path often follows the fine mastic or binder area for samples tested at 25 °C.

The typical load-deformation charts from the SCB and SENB tests are shown in Figure 8. Peak load generally decreases with increasing temperature and notch depth. Furthermore, a drop in temperature clearly results in an increase in pre-peak stiffness and post-peak brittleness. For specimens with three distinct notch depths and varied RCA content percentages, the areas beneath the load-deformation curves at pre-peak regions are determined to reflect the strain energy values to failure. The load-displacement patterns among blends are more evident at high temperatures. The variation in temperature and notch depths affects displacement range, peak load, and post-peak slope. Both the SCB and SENB tests experience two different types of failure, both of which are influenced by temperature. The asphalt mix exhibits a quasi-brittle behaviour at low temperatures like 15 °C and 5 °C. High temperatures cause the sample to behave more ductile, lengthening the time to fracture and lowering the final strength of the mixes. Due to the binder transition from a solid-plastic state (low temperature) to an elastic-vicious state (high temperature), failure happens significantly later at high temperatures than it does at low temperatures.

2.3. Peak load

The pre-notched specimen in these tests are commonly used to study the influence of pavement cracks and crack propagation. The Notch-to-Depth ratio (a/D), rather than the actual notch depth, was employed as the specimen parameter to enable a comparable analysis for both the SCB and SENB tests. Since varied notch depths may be achieved using the ratios of 0.2H, 0.3H, and 0.4H, it also enables comparison between the two tests (SCB and SENB). The average Peak Load of each test group was therefore plotted against the notch-to-depth ratio as seen in Figure 9. All testing conditions showed a distinctly declining pattern, with the Peak Load declining as the notch-to-depth ratio rose. Larger notches may be used to simulate pre-existing pavement cracks; as a result, the pavement can withstand lesser weights before failing.

As seen by a steeper trend, the low temperature specimens produced the greatest variation in peak load with increasing notch depth. This indicates that, while specimens with greater faults fail at a higher rate, the more brittle specimen offers a higher peak failure force for smaller flaws. As the specimen temperatures increased, the observed trend of peak load with pre-existing crack tended toward a plateau. The trend and slope of the relationship between peak load and notch depth are similar regardless of mix type and sample geometry. The average Peak

Load of each test group was plotted against its testing temperature as shown in Figure 10 to further examine and evaluate the effects of testing temperature on the experiment. The reduced peak loads reported in the 50% RCA blend may have been a result of the optimum binder content

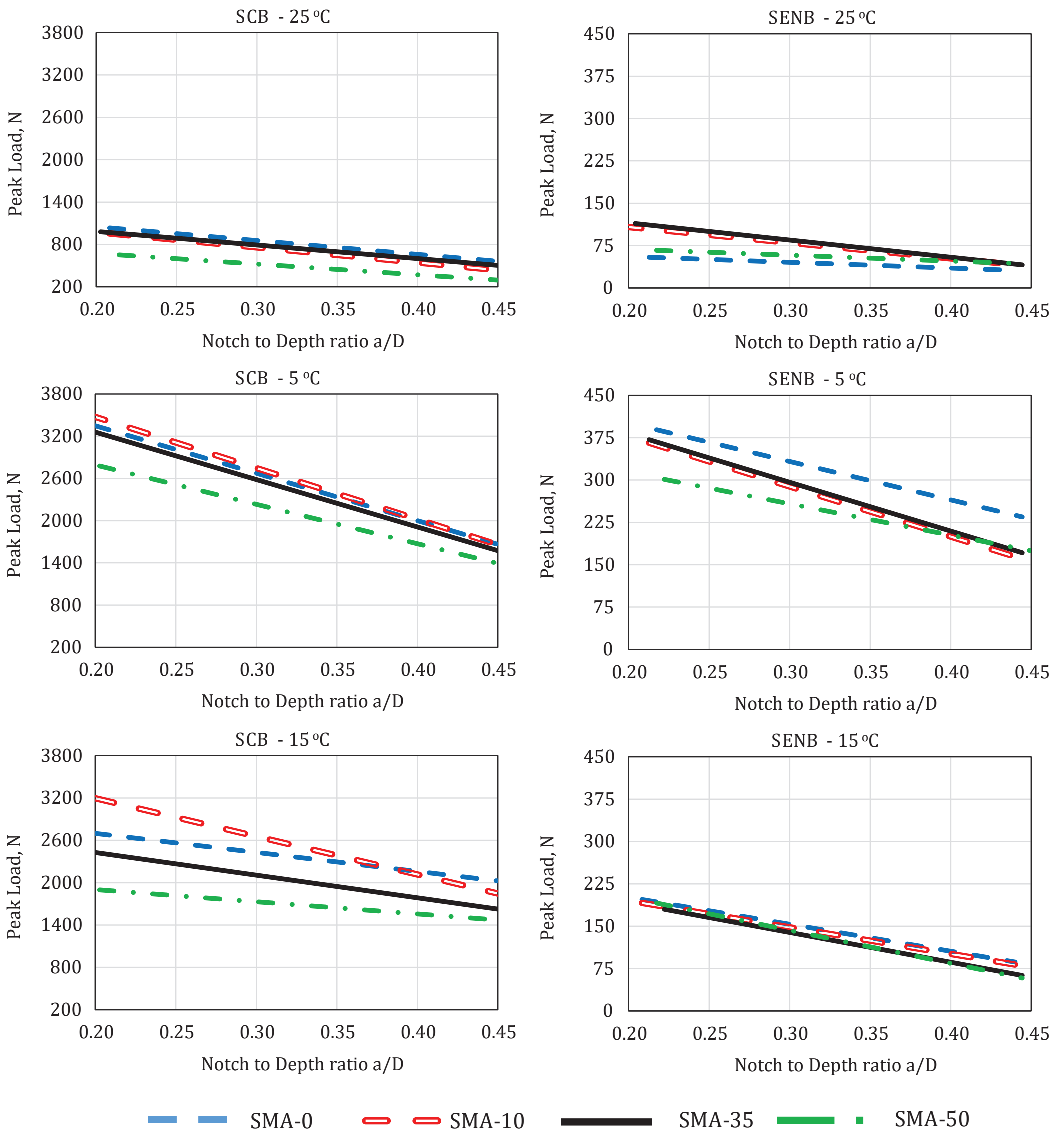

Figure 9. Peak load vs. notch depths at varying temperatures

and effective asphalt content increasing for the increasing amount of blended RCA. The peak loads at 25 °C were similar (< 100 N) regardless of notch depths and RCA content. This implies that RCA content has no significant effects on peak load for cracking at temperatures greater than 25 °C.

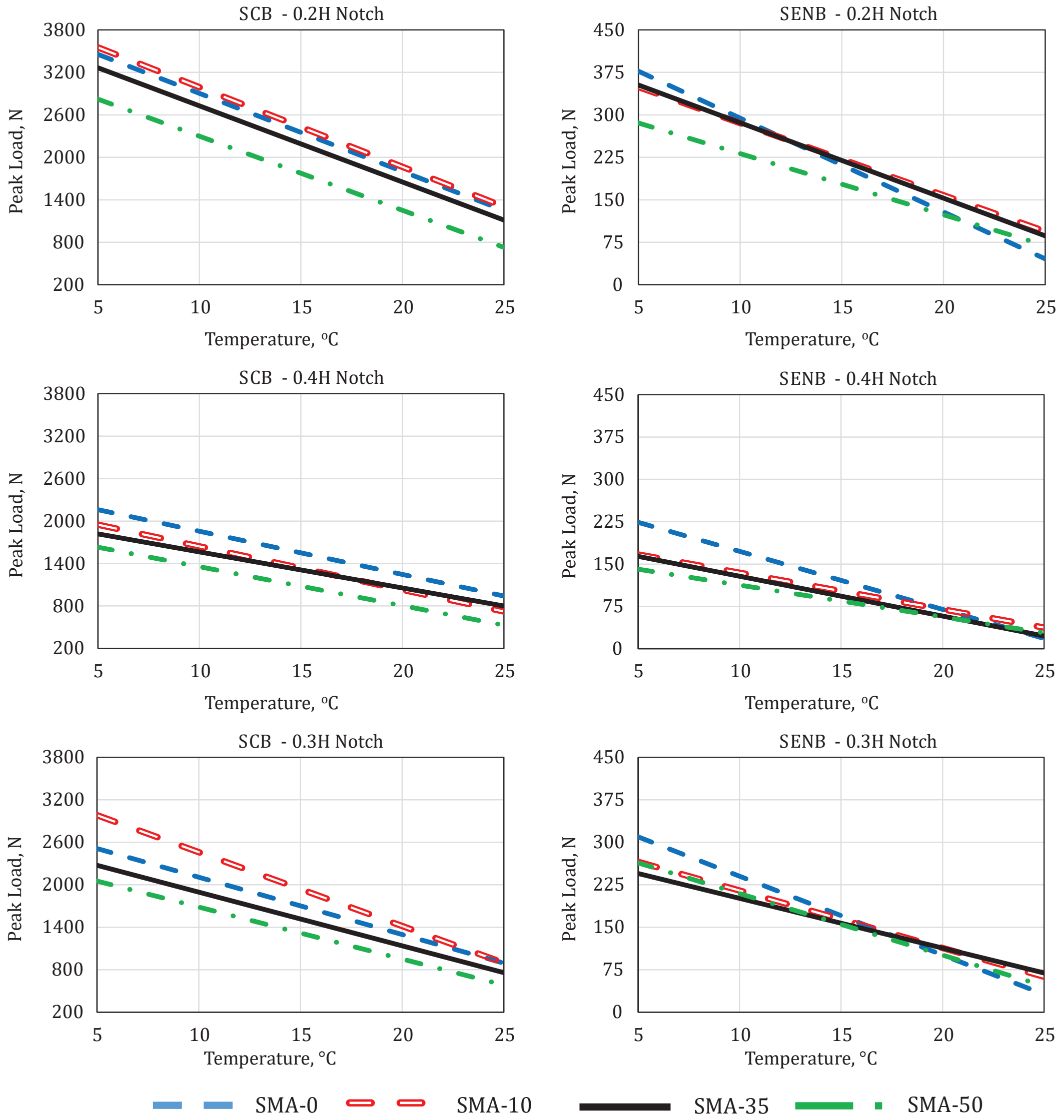

Figure 10. Peak load vs. temperature for varying notch depths

2.4. Fracture energy

There is a decreasing trend presented for all testing conditions where the Fracture Energy (G_f) decreased as the notch-to-depth ratio increased (see Figure 11). For both the SCB and SENB studies, the slopes are basically comparable at various blends and temperatures. For all mixes, the variation in fracture energy is significant. Pavement failure

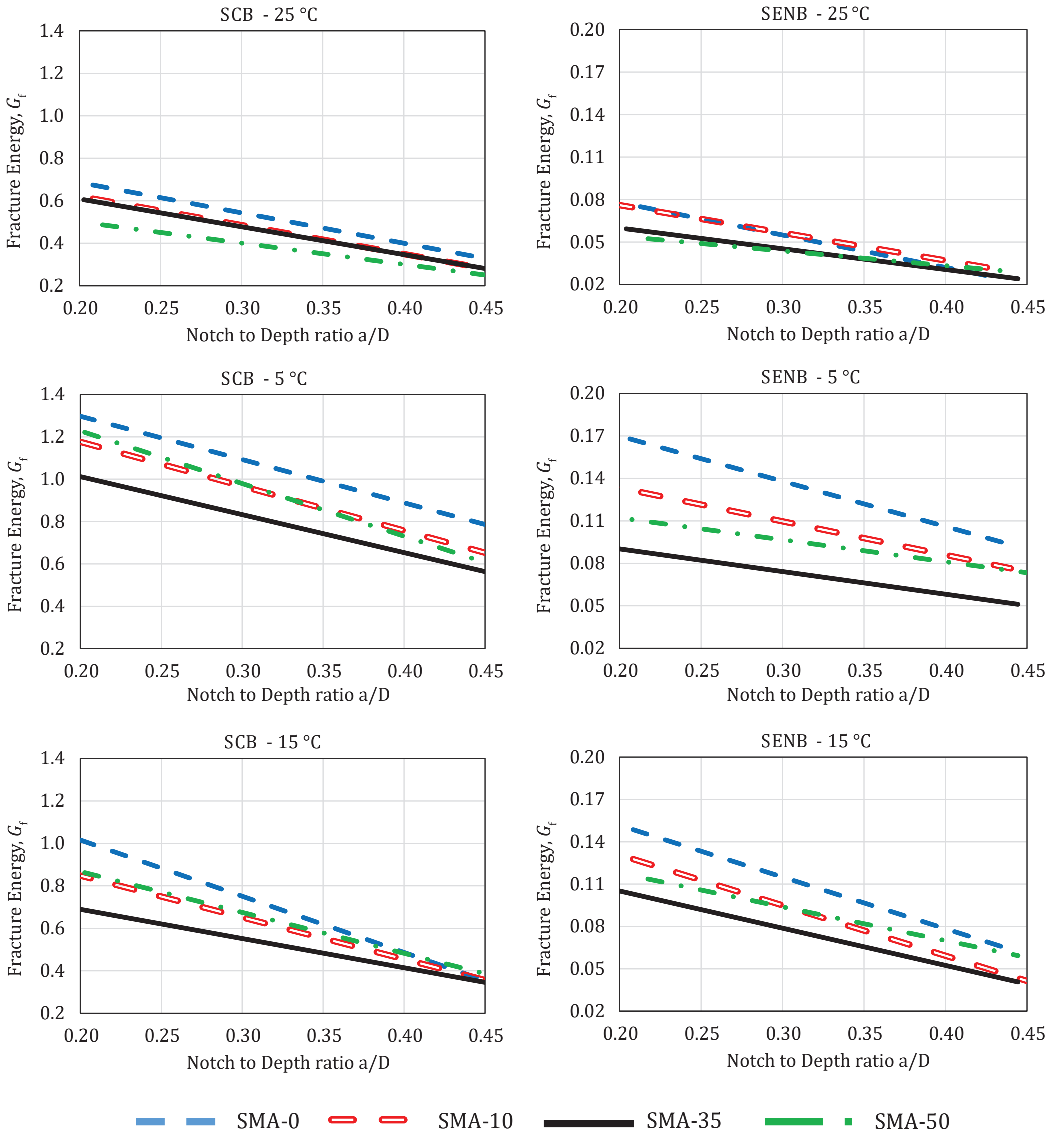

Figure 11. Fracture energy vs. notch depths for varying temperatures

can occur with less energy input in larger notches (cracks). The data also demonstrated that there were significant differences in fracture energy for changes in fracture ligament lengths, notch depth as well as sample geometry. The fracture energy of the SMA-RCA blends is calculated from the entire load-displacement curves highlighted in Figure 8. The calculated values are similar to results of an investigation done by Bui and Saleh (2021).

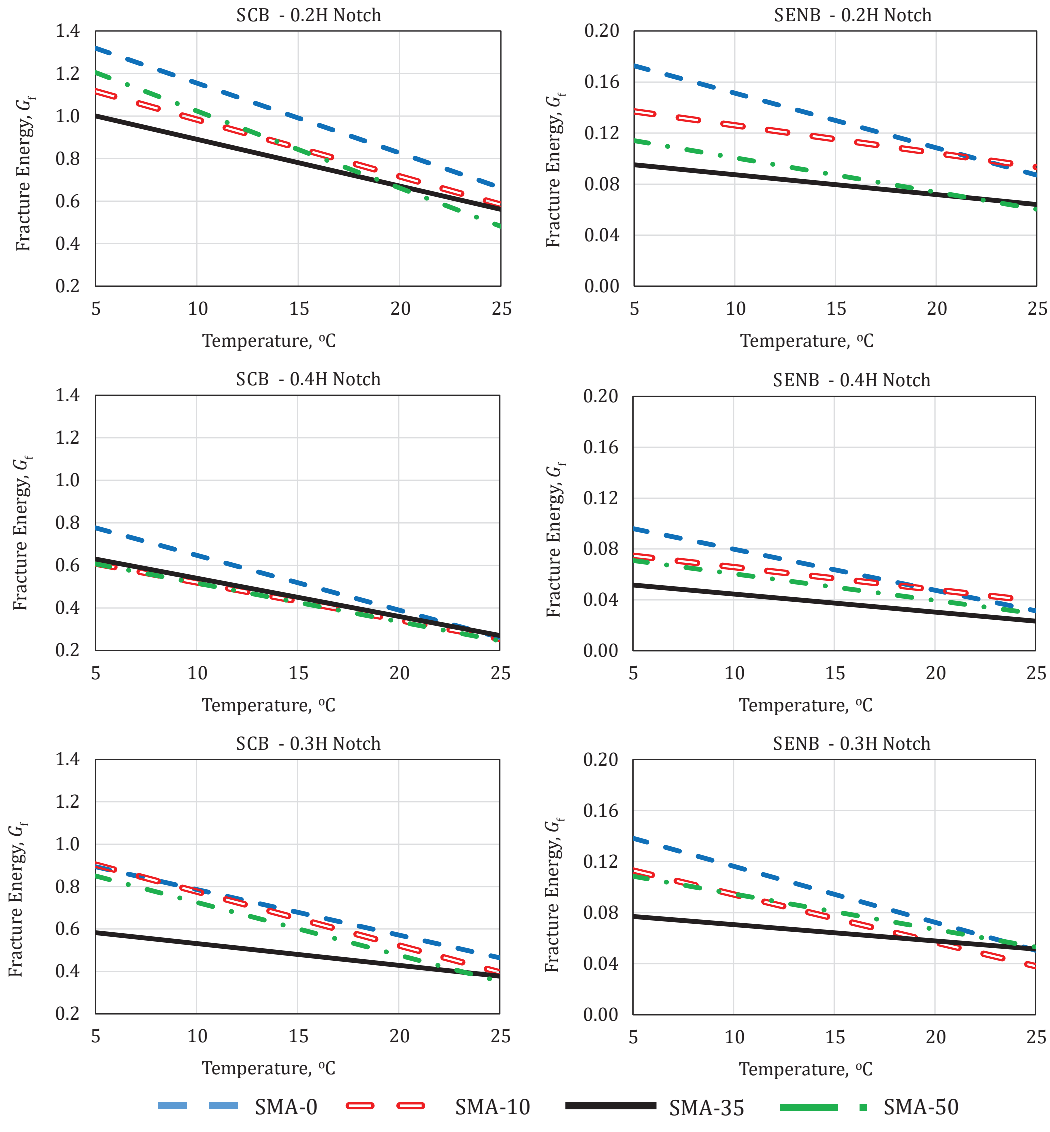

Figure 12. Fracture energy vs. temperature for varying notch depths

The fracture energy decreased as temperature increased to 25 °C, as indicated in Figure 12, which was consistent with comparable findings of the Ding et al. (2018) study. The lower the material temperature, the greater the material stiffness, thus requiring a higher loading and energy to fracture to asphalt mixture regardless of notch height and RCA blends. The more brittle specimen also demonstrates a higher variability in

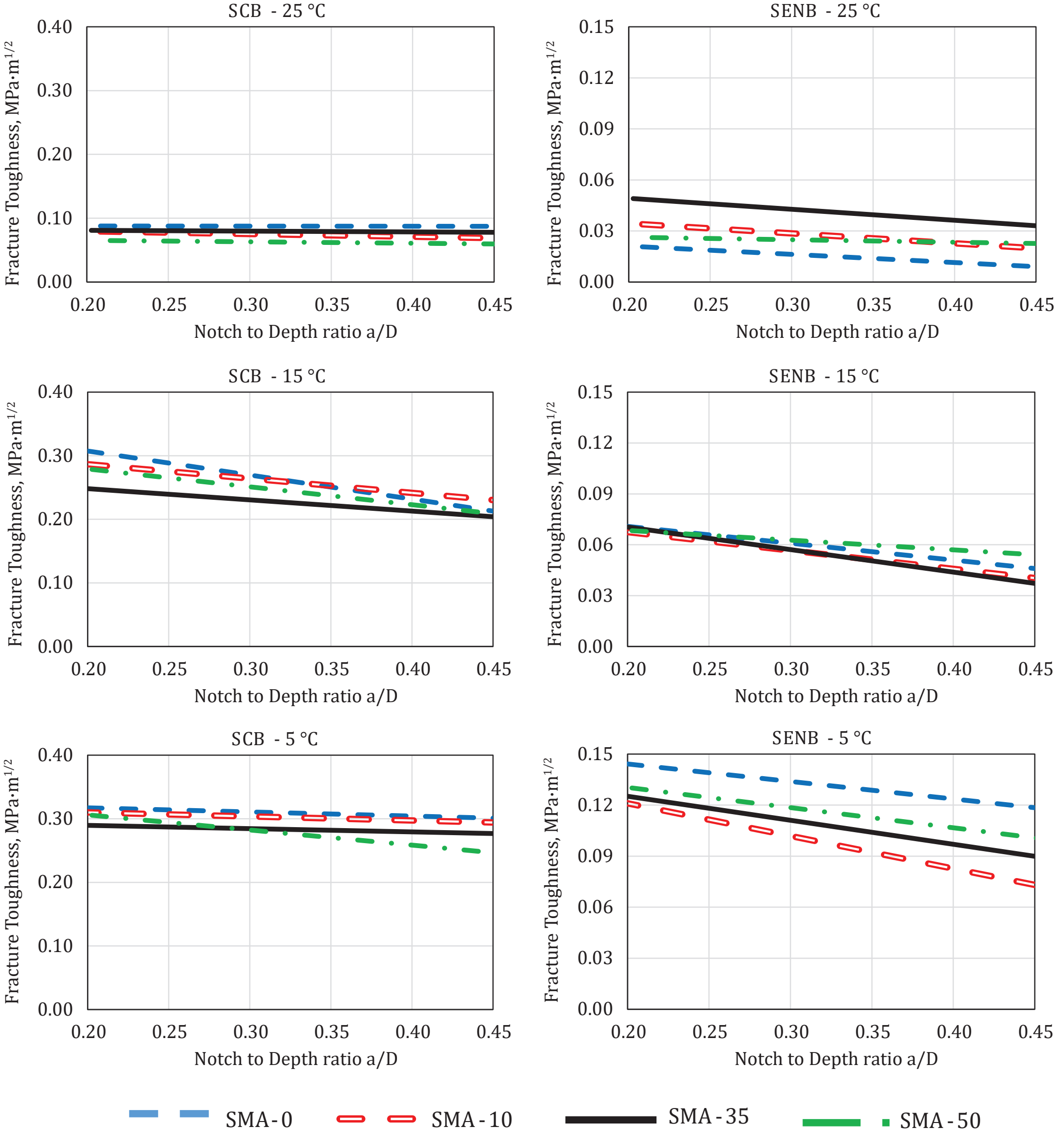

Figure 13. Fracture toughness vs. notch depths (a) 25 °C; (b) 15 °C; (c) 5 °C

fracture energy with change in notch depth. Additionally, the decrease in fracture energy due to temperature may also be attributed to the increase in optimum binder content with the increase in RCA content and the effective asphalt content. As a result, higher RCA contents are expected to present with lower fracture energies; 35% and 50% RCA blends are mostly observed to comply for both the SCB and SENB tests. The G_f ranges observed in this study were similar to those reported by Aliha et al. (2017).

2.5. Fracture toughness

The trend for fracture toughness (K_{IC}) at 25 °C, as shown in Figure 13, demonstrates that there is no significant decrease in fracture toughness as notch size increases. However, at lower temperatures, fracture toughness decreases significantly, which is also related to the previously mentioned decrease in fracture energy. The results show that the K_{IC} values obtained by the SCB and SENB testing methods agree well. The SCB corresponding values are roughly twice that of the SENB.

The fracture toughness decreases as the RCA content increases. This was true for the SCB and SENB tests at lower temperatures. According to the data in Figure 13, the fracture toughness decreased with increasing temperature for both the SCB and SENB tests. This is expected due to the behaviour of the asphalt binder, which is more susceptible to temperature effects than either virgin or recycled concrete aggregates. This observation is supported by the results of the SCB and SENB tests.

Conclusions

This research combined the experimental procedures of SCB and SENB to investigate the fracture properties of SMA mixtures blended with RCA (0%, 10%, 35% and 50%). Although the physical properties of the recycled concrete aggregate were less suitable than the traditional natural limestone aggregates, its use as a sustainable replacement aggregate was a key objective of the study. Based on the previously mentioned study materials, mix design, gradation, analysis, and discussion, the following conclusions can be drawn:

1. SMA with RCA contents up to 10% performed relatively well compared to the conventional SMA mix when investigating the peak load performance regardless of test methods. In the SCB test at 0.2H notch depth, these SMA-35 mixes achieved an average of 2.9% less of the Peak Load of SMA designed with only virgin aggregate, whereas the SMA-50 achieved a decrease of 21%. In the

SENB test, however, the natural mixture achieved the highest peak load, while the blended RCA mixes were all outperformed by the conventional mix, but with very low peak load decreases of 1.3% for the SMA-10 and SMA-35 blends but a decrease of 21% for the SMA-50 blends.

2. For the fracture energy evaluation, most of the RCA blended gap-graded mixture performed relatively well compared to the conventional mixes regardless of SCB or SENB test methods. The study showed that at RCA contents higher than 10% the results of fracture energy are not consistent, which may indicate a limit of RCA in a gap graded mixture based on the gradation and mix design in this study. The peak load has a strong correlation to the fracture energy mechanisms when evaluating asphalt concrete cracking.
3. Fracture toughness, which is significantly influenced by temperature, was found to perform well in mixes with RCA contents ranging from 10% to 35%. When compared to the SMA-0, these mixes performed relatively well in the SCB test, achieving a decrease as low as 2.5% and a decrease as high as 12.5%. In SENB testing at the low temperatures all blends were outperformed by the natural aggregate blend with no RCA with 7% decrease below the SMA-0 Fracture Toughness for SMA-10, SMA-35 and SMA-50, respectively. The fracture toughness evaluation of RCA in mixtures shows that it can provide a level of ability in containing cracks to resist further pavement fracture or failure.

A large driving factor in the exploration of incorporating recycled concrete aggregates as substitutions for traditional aggregates would be environmental preservation of non-renewable resources, namely traditional aggregate materials. Despite the increased global interest in sustainability and environmental responsibility, as well as the technical feasibility, the economic impact remains a major factor in the acceptance of such a venture.

RCA has been shown to not only increase the fracture energy before cracking failure, but also to reduce the rate of crack propagation at an intermediate temperature, implying that asphalt mixtures with RCA have an overall improvement in intermediate-temperature cracking resistance. Overall, adding RCA to SMA mixtures can provide comparable performance to conventional SMA mixtures while also providing a sustainable aggregate replacement option with economic and environmental benefits. However, more caution should be exercised when it comes to the properties of asphalt mixtures as the RCA content increases.

Further research is under way to extend the scope of comparison of laboratory-measured fracture properties of RAP versus RCA blended SMA mixtures. Additionally, examination of the behaviour of the combination of RAP and RCA together in dense graded asphalt mixtures may meet the ultimate objective of providing a cost effective sustainable use of construction waste.

ACKNOWLEDGEMENTS

The authors would like to thank all the technicians of the Highway and Transportation Laboratory at the Department of Civil and Environmental Engineering, UWI St Augustine Campus who assisted in the execution of the tests. The authors would also like to acknowledge the local contractors who provided the recycled concrete aggregate and strength data.

REFERENCES

AASHTO (2013). AASHTO TP 105-13 Standard method of test for determining the fracture energy of asphalt mixtures using the semicircular bend geometry (SCB). Washington, DC.

Abu Abdo, A.M., Eckwright, F., Jung, S. J., Bayomy, F., and Nielsen, R. (2014). Semi-circular notched beam testing procedure for hot mixture asphalt. *Proceedings of the Institution of Civil Engineers-Transport*, *167*(1), 48–58. https://doi.org/10.1680/tran.11.00051

Al-Bayati, H. K. A., Tighe, S. L., and Achebe, J. (2018). Influence of recycled concrete aggregate on volumetric properties of hot mix asphalt. *Resources, Conservation and Recycling, 130*, 200–214. https://doi.org/10.1016/j.resconrec.2017.11.027

Aliha, M. R. M., Fakhri, M., Kharrazi, E. H., and Berto, F. (2017). The effect of loading rate on fracture energy of asphalt mixture at intermediate temperatures and under different loading modes. *Frattura ed Integrità Strutturale*, *12*(43), 113–132. https://doi.org/10.3221/IGF-ESIS.43.09

Ameli, A., Maher, J., Mosavi, A., Nabipour, N., Babagoli, R., and Norouzi, N. (2020). Performance evaluation of binders and stone matrix asphalt (SMA) mixtures modified by ground tire rubber (GTR), waste polyethylene terephthalate (PET) and anti-stripping agents (ASAs). *Construction and Building Materials*, *251*, Article 118932. https://doi.org/10.1016/j.conbuildmat.2020.118932

Anderson, T.L. (2017). *Fracture mechanics fundamentals and applications* (4th ed.). Boca Raton: CRC Press. https://doi.org/10.1201/9781315370293

Arabani, M., Moghadas Nejad, F., and Azarhoosh, A. R. (2013). Laboratory evaluation of recycled waste concrete into asphalt mixtures. *International Journal of Pavement Engineering*, *14*(6), 531–539. https://doi.org/10.1080/10298436.2012.747685

Artamendi, I., and Khalid, H. A. (2006). A comparison between beam and semi-circular bending fracture tests for asphalt. *Road Materials and Pavement Design*, *7*(sup1), 163–180. https://doi.org/10.1080/14680629.2006.9690063

Bamigboye, G. O., Ademola, D., Kareem, M., Orogbade, B., Odetoyan, A., and Adeniyi, A. (2022). Durability assessment of recycled aggregate in concrete production. *The Structural Integrity of Recycled Aggregate Concrete Produced with Fillers and Pozzolans*, *2022*, 445–467. https://doi.org/10.1016/B978-0-12-824105-9.00010-X

Bazant, Z. P., and Planas, J. (1998). *Fracture and size effect in concrete and other quasi-brittle materials* (1st ed.). New York, Routlege. https://doi.org/10.1201/9780203756799

Bhurke, A. S., Shin, E. E., and Lawrence, T. D. (1997). Fracture morphology and fracture toughness measurement of polymer-modified asphalt concrete. *Transportation Research Record*, *1590*(1), 23–33. https://doi.org/10.3141/1590-04

Birgisson, B., Montepara, A., Romeo, E., and Tebaldi, G. (2011). Characterisation of asphalt mixture cracking behaviour using the three-point bending beam test. *International Journal of Pavement Engineering*, *12*(6), 569–78. https://doi.org/10.1080/10298436.2011.565766

Brown, E. R., Haddock, J. E., and Mallick, R. B. (1977). *Development of a mixture design procedure for stone matrix asphalt (SMA)* (NCAT Report No. 97-3). US Department of Transportation. https://rosap.ntl.bts.gov/view/dot/13192

Bui, H. H., and Saleh, M. (2021). Effects of specimen size and loading conditions on the fracture behaviour of asphalt concretes in the SCB test. *Engineering Fracture Mechanics*, *242*, Article 107452. https://doi.org/10.1016/j.engfracmech.2020.107452

Chesner, W. H., Collins, R. J., MacKay, M. H., and Emery, J. (2002). *User guidelines for waste and by-product materials in pavement construction* (No. FHWA-RD-97-148, Guideline Manual, Report No. 480017). Recycled Materials Resource Center. https://www.fhwa.dot.gov/publications/research/infrastructure/pavements/97148/index.cfm

Choudhary, J., Kumar, B., and Gupta, A. (2021). Potential utilization of construction wastes in asphalt pavements as fillers using ranking framework. *Construction and Building Materials*, *277*, Article 122262. https://doi.org/10.1016/j.conbuildmat.2021.122262

Ding, B., Zou, X., Peng, Z., and Liu, X. (2018). Evaluation of fracture resistance of asphalt mixtures using the single-edge notched beams. *Advances in Materials Science and Engineering*, 2018, Article 8026798. https://doi.org/10.1155/2018/8026798

Ferdowsi, B., and Arabani, M. (2009). Evaluating the semi-circular bending test for HMA mixtures. *International Journal of Engineering*, *22*(1), 47–58. https://www.ije.ir/article_71758.html

Gatchalian, D., Masad, E., Chowdhury, A., and Little, D. (2006). Characterization of aggregate resistance to degradation in stone matrix asphalt mixtures. *Transportation Research Record*, *1962*(1), 54–63. https://doi.org/10.1177/0361198106196200107

Ge, Z., Huang, M., and Wang, Y. (2014). Fatigue behaviour of asphalt concrete beams reinforced by glass fibre-reinforced plastics. *International Journal of Pavement Engineering*, *15*(1), 36–42. https://doi.org/10.1080/10298436.2013.799281

Gross, A. S. (2019). *Concrete chokes our landfill sites – but where else can it go*? The Guardian. https://www.theguardian.com/cities/2019/feb/26/concrete-chokes-our-landfill-sites-but-where-else-can-it-go

Kazemian, F., Rooholamini, H., and Hassani, A. (2019). Mechanical and fracture properties of concrete containing treated and untreated recycled concrete aggregates. *Construction and Building Materials*, *209*, 690–700. https://doi.org/10.1016/j.conbuildmat.2019.03.179

Kim, H.J., and Na, I.H. (2021). The mechanical properties of SMA concrete mixture using steel slag aggregate. *Journal of the Korean Recycled Construction Resources Institute*, *9*(1), 109–116.

Kim, K. W., and El Hussein, M. (1997). Variation of fracture toughness of asphalt concrete under low temperatures. *Construction and Building Materials*, *11*(7), 403–411. https://doi.org/10.1016/S0950-0618(97)00030-5

Link, R. E., Wagoner, M. P., Buttlar, W., and Paulino, G. H. (2005). Development of a single-edge notched beam test for asphalt concrete mixtures. *Journal of Testing and Evaluation*, 33(6). https://doi.org/10.1520/JTE12579

Mansourian, A., Razmi, A., and Razavi, M. (2016). Evaluation of fracture resistance of warm mix asphalt containing jute fibers. *Construction and Building Materials*, *117*, 37–46. https://doi.org/10.1016/j.conbuildmat.2016.04.128

Medina, C., Zhu, W., Howind, T., Frías, M., and Sánchez de Rojas, M. I. (2015). Effect of the constituents (asphalt, clay materials, floating particles and fines) of construction and demolition waste on the properties of recycled concretes. *Construction and Building Materials*, *79*, 22–33. https://doi.org/10.1016/j.conbuildmat.2014.12.070

Moazami Goodarzi, M., Naderi, K., and Moghadas Nejad, F. (2021). Cracking resistance of hot-mix asphalt mixtures containing terminal blend rubberized asphalt nanocomposite at intermediate temperature. *Journal of Materials in Civil Engineering*, *33*(10), Article 04021255. https://doi.org/10.1061/(ASCE)MT.1943-5533.0003875

Motter, J. S., Miranda, L. F. R., and Bernucci, L. L. B. (2015). Performance of hot mix asphalt concrete produced with coarse recycled concrete aggregate. *Journal of Materials in Civil Engineering*, *27*(11), Article 04015030. https://doi.org/10.1061/(ASCE)MT.1943-5533.0001284

Muench, S., and Van Dam, T. (2014). *Pavement sustainability* (Report No. FHWA-HIF-14-012). Federal Highway Administration. https://www.fhwa.dot.gov/pavement/sustainability/hif14012.pdf

Narcis, N., Ray, I., and Hosein, G. (2019). Construction and demolition waste management actions and potential benefits: A perspective from Trinidad and Tobago. *Buildings*, *9*(6), Article 150. https://doi.org/10.3390/buildings9060150

Paranavithana, S., and Mohajerani, A. (2006). Effects of recycled concrete aggregates on properties of asphalt concrete. *Resources, Conservation and Recycling*, *48*(1), 1–12. https://doi.org/10.1016/j.resconrec.2005.12.009

Pourtahmasb, M. (2014). Performance evaluation of stone mastic asphalt and hot mix asphalt mixtures containing recycled concrete aggregate. *Advances in Materials Science and Engineering*, *2014*, Article 863148. https://doi.org/10.1155/2014/863148

Pourtahmasb, M. S., and Karim M. R. (2014). Utilization of recycled concrete aggregates in stone mastic asphalt mixtures. *Advances in Materials Science and Engineering*, *2014*, Article 902307. https://doi.org/10.1155/2014/902307

Praticò, Filippo G., Giunta, V., Mistretta, M., and Gulotta, T. M. (2020). Energy and environmental life cycle assessment of sustainable pavement materials and technologies for urban roads. *Sustainability*, *12*(2), Article 704. https://doi.org/10.3390/su12020704

Rampit, R., Smith, J., and Ray, I. (2020). A review of recycled concrete aggregates as a sustainable construction material. P*roceedings on the International Conference of Emerging Trends in Engineering and Technology (IConETech 2020)*, 190–200. https://doi.org/10.47412/DNIZ7049

Radeef, H. R., Hassan, N. A., Abidin, A. Z., Mahmud, M. Z. H., Satar, M. M., Warid, M. M., and Al Saffar, Z. H. (2021). Determining fracture energy in asphalt mixture: A review. *IOP Conference Series: Earth and Environmental Science*, *682*(1), Article 012069. https://doi.org/10.1088/1755-1315/682/1/012069

Saed, S. A., Kamboozia, N., Ziari, H., and Hofko, B. (2021). Experimental assessment and modeling of fracture and fatigue resistance of aged stone matrix asphalt (SMA) mixtures containing RAP materials and warm-mix additive using ANFIS method. *Materials and Structure*s, *54*, Article 225. https://doi.org/10.1617/s11527-021-01812-9

Sarraz, A., and Hossain, Md. N. (2017). *Comparative study of recycle concrete aggregate as a construction material*. Project: Advanced Structural Materials: Innovation and Research. https://doi.org/10.13140/RG.2.2.23742.18243

Silva, R. V., de Brito, J., and Dhir, R. K. (2019). Use of recycled aggregates arising from construction and demolition waste in new construction applications. *Journal of Cleaner Production*, *236*, Article 117629. https://doi.org/10.1016/j.jclepro.2019.117629

Smith, J., Rampit, R., and Parey, R. (2019). Characterization of vibration effects on the internal structure and strength of regular and high strength recycled concrete. *Proceedings of the Sixth International Conference on Durability of Concrete Structures*, UK, 703–710. https://docs.lib.purdue.edu/cgi/viewcontent.cgi?article=1247&context=icdcs

Son, S., Said, I. M., and Al-Qadi, I. L. (2019). Fracture properties of asphalt concrete under various displacement conditions and temperatures. *Construction and Building Materials*, *222*, 332–341. https://doi.org/10.1016/j.conbuildmat.2019.06.161

Tahmoorian, F., and Samali, B. (2018). Laboratory investigations on the utilization of RCA in asphalt mixtures. *International Journal of Pavement Research and Technology*, *11*(6), 627–638. https://doi.org/10.1016/j.ijprt.2018.05.002

USEPA. (2016). Assessing trends in material generation, recycling, composting, combustion with energy recovery and landfilling in the United States. United States Environmental Protection Agency.

Vaidya, A., and Pathak, K. (2019). Mechanical stability of dental materials. *Applications of Nanocomposite Materials in Dentistry*, *17*, 285–305. https://doi.org/10.1016/B978-0-12-813742-0.00017-1

Wagoner, M. P., and Buttlar, W. G. (2007). Influence of specimen size on fracture energy of asphalt concrete (with discussion). *Journal of the Association of Asphalt Paving Technologists*, *76*. https://trid.trb.org/view/839487

Wagoner, M. P., Buttlar, W. G., and Paulino, G. H. (2005). Development of a single-edge notched beam test for asphalt concrete mixtures. *Journal of Testing and Evaluation*, *33*(6), 452. https://doi.org/10.1520/JTE12579

You, T., Kim, Y-R., and Nsengiyumva, G. (2015). *Development of a semi-circular bend (SCB) test method for performance testing of Nebraska asphalt mixtures* (Technical report 26-1121-4023–001). https://www.researchgate.net/publication/312330593_Development_of_a_Semicircular_Bend_SCB_Test_Method_for_Performance_Testing_of_Nebraska_Asphalt_Mixtures

Zehnder, A. T. (2013). Modes of fracture. In Q. J. Wang, and Y. W. Chung (Eds.), *Encyclopedia of Tribology*. Springer, Boston, MA. https://doi.org/10.1007/978-0-387-92897-5_258

Zhang, Z., Han, S., Guo, H., Han, X., and Wu, C. (2021). Fatigue performance evaluation of recycled asphalt fine aggregate matrix based on dynamic shear rheometer test. *Construction and Building Materials*, *300*, Article 124025. https://doi.org/10.1016/j.conbuildmat.2021.124025