ISSN 1822-427X/eISSN 1822-4288
2022 Volume 17 Issue 1: 117–142
https://doi.org/10.7250/bjrbe.2022-17.554

THE BALTIC JOURNAL
OF ROAD
AND BRIDGE
ENGINEERING
2022/17(1)

# UTILISATION OF RECYCLED CONCRETE AGGREGATES FOR SUSTAINABLE POROUS ASPHALT PAVEMENTS

CHIDOZIE MADUABUCHUKWU NWAKAIRE,
SOON POH YAP*, CHIU CHUEN ONN, CHOON WAH YUEN,
SEYED MOHAMMAD HOSSEIN MOOSAVI

*Department of Civil Engineering, Faculty of Engineering, Universiti Malaya, Kuala Lumpur, Malaysia*

*Centre for Transportation Research, Faculty of Engineering, Universiti Malaya, Kuala Lumpur, Malaysia*

Received 18 February 2021; accepted 10 June 2021

**Abstract.** The use of recycled concrete aggregates (RCA) for porous asphalts is a viable attempt towards waste management and sustainable conservation of natural resources. Installation of a porous asphalt wearing course is justified in highway pavements because it offers higher skid resistance, glare reduction, lesser traffic noise, reduction of hydroplaning, and mitigation of urban heat island phenomenon. The performance of porous asphalt mixtures containing 0%, 20%, 40%, 60%, 80% and 100% of coarse RCA as replacement for granite was studied and reported in this paper. The mixture containing 0% RCA was used as the control. The skid properties, permeability, water susceptibility and mechanical behaviour of the mixtures under various loading conditions were investigated. Blending granite and RCA in the porous asphalt mixture gave

* Corresponding author. E-mail: spyap@um.edu.my

Soon Poh YAP (ORCID ID 0000-0002-2036-9740)
Chiu Chuen ONN (ORCID ID 0000-0002-5093-5651)
Choon Wah YUEN (ORCID ID 0000-0001-7751-7292)
Seyed Mohammad Hossein MOOSAVI (ORCID ID 0000-0002-3617-9896)

better Indirect Tensile Strength (ITS), rutting resistance, and impact strength indicators. The mixture with 60% RCA achieved desirable results in all tests. It exhibited the best performance based on its ITS and impact strength of 431 kPa and 380 J, respectively. These values were higher than the control by 3% and 30%, respectively. Utilisation of RCA in porous asphalt pavements is recommended based on the results of this study.

**Keywords:** circular economy, impact strength, permeability, rutting resistance, recycling, sustainability.

## Introduction

Highway pavements are essential infrastructures that require the use of high amounts of natural resources. The associated intensive utilization of natural materials contributes heavily to the carbon footprint of the construction industry through the linear process of extraction, processing, and disposal of materials (Morseletto, 2020; Riekstins, 2020). Construction industry consumes about 30% of the extracted natural resources and is responsible for 25% of the generated solid waste across the globe (Benachio et al., 2020). Despite offering an immediate solution to the societal problems, this continual dependence on the natural materials for construction and maintenance of new pavements neglects imminent sustainability-related problems. The need to achieve sustainable development goals requires meeting the present infrastructural needs without compromising the ability of the future generation to meet their own needs (Brundtland, 1987). This necessitates a shift from the linear economic process to the circular economy model that can ensure environmental friendliness and economic viability of pavement infrastructures both at present and in future (Morseletto, 2020). The circular economy model requires that the materials are kept in a closed loop that maximises the utility of construction materials by reducing raw material extraction and disposal. It has been achieved through recycling, reformation, and reuse of waste construction materials (Hayat et al., 2020; Sanchez-Alonso, 2011). Many solid waste materials have been found suitable as aggregates for different forms of construction. Some agricultural and aquaculture by-products like palm kernel shells, date seed, rubber shell, periwinkle shell, oyster shells among others have demonstrated satisfactory performance as concrete aggregates (Eziefula, 2017; Osei, 2013). Many construction and demolitions wastes are recycled as partial replacement for natural aggregates both in building and pavement structures. The use of waste bricks, tiles, pebbles, railway sleepers, asphalts, and concretes either as partial or complete replacement for natural aggregates in pavement structures has been reported in the existing literature (Hayat et al., 2020; Nwakaire et al., 2020a; Sangiorgi et al., 2014). Utilisation of waste concrete aggregates in porous asphalt mixtures is the focus of this study.

Recycling of concrete aggregates is a sustainable solution as it complies with the principles of the circular economy and ensures reduction in solid waste generation (Zhang et al., 2020). The estimate made by the World Energy Council (WEC) shows that over 6 million tonnes of wastes would be generated daily across the globe by the year 2025 (WEC, 2016; Khan & Kabir, 2020). This is an impressive amount, which would result in an annual waste generation of more than 2 billion tonnes by the year 2025. Aggregates make up about 85% of concrete wastes (Tam et al., 2018). When these aggregates are recaptured, they can be reused or recycled. Such aggregates are referred to as Recycled Concrete Aggregates (RCA). Application of RCA pavement constructions can lead to preservation of natural materials as well as help meet the challenges of solid waste disposal (Haritonovs & Tihonovs, 2014; Plati, 2019). This issue becomes particularly topical as more and more roads are continually being constructed and reconstructed across the world. These frequent construction and maintenance activities demand high volumes of materials sourced from natural resource bases (Haritonovs et al., 2013). These resources are being depleted and their consistent and exhaustive utilisation threatens their future availability.

The use of porous asphalts for highway pavement surfacing has gained much attention in recent decades. Malaysia similar to many other countries in the world has adopted the use of porous asphalts for pavement surfacing in low trafficked roads. This solution offers some sustainability benefits due to its unique features (Huurman et al., 2010). High skid resistance of porous pavements makes them safer for driving under wet conditions (Elizondo-Martínez et al., 2020; Yu et al., 2020). Porous pavement retains water in its cavities for a longer time as compared to conventional wearing courses, thus producing a cooling effect that can help control the urban heat island phenomenon in hot areas (Zhu et al., 2019). It has also been found to be effective for reduction of traffic noise, wet pavement glare, water splashing, and hydroplaning (Yu et al., 2020). These are very important benefits for Malaysia with its high volume of rainfall and relatively high temperatures. Inclusion of RCA in porous asphalt mixtures would offer a solution to address some drawbacks of porous pavement constructions. Some previous studies have concluded that inclusion of RCA in asphalt mixtures would lead to higher Optimum Binder Contents (OBC) (Arabani et al., 2013; Ossa et al., 2016). Hence, it may be implied that the absorptive nature of RCA would allow for better performance in terms of binder drain down at higher OBC when utilised for asphalt mixtures (Rafi et al., 2011), which in its turn would enable the design of porous mixtures with higher binder content, resulting in better coating and bonding with the aggregates without excessive drain downs (Huurman et al., 2010). A similar observation was reported by Hu et al. (2019) who used activated carbon in place of mineral filler in porous asphalt mixtures. Inclusion of the activated carbon resulted in increase in OBC due to its higher absorptivity. However, porous asphalts, like porous concrete, exhibit a characteristic low strength, which may lead to an undesirable frequent maintenance (Hu et al., 2019). Inclusion of any innovative material for such a pavement needs to be investigated to ascertain its structural reliability. The study by Qiu et al. (2018) reported higher quality of porous asphalt containing up to 93% of the reclaimed asphalt, using bitumen modified by foaming technology. There is an urgent need for an extensive experimental investigation on the behaviour of porous asphalt mixtures containing different proportions of RCA (Ma et al., 2020; Zhang et al., 2018) to ensure that the presumed performance of the RCA based porous asphalts is ascertained based on the established laboratory studies.

The laboratory tests conducted in this study revealed some important properties of porous asphalt mixtures containing RCA, which can be replicated for other types of dense graded asphalt mixtures. Generally, there is a range of elaborate research on the rutting resistance and impact strength of RCA based porous asphalt mixtures. Within the permeability tests, a unique behaviour was observed – inclusion of higher proportions of RCA resulted in the increase in air voids content and the decrease in the coefficient of permeability. This was explained by the clogging effect of higher OBCs in the RCA mixture, which was observed under the handheld microscopic images. Higher OBCs reduced the interconnection of air voids, yet leaving the entire specimen with higher void content. The results of study will contribute remarkably to the design and application of porous asphalt pavements that are both effective and sustainable by improving the engineering performance of the asphalt, reducing exhaustive use of natural aggregates, and mitigating solid waste disposal challenges.

## 1. Materials and methods

### 1.1. Materials

The materials used for this study include the aggregates, the binder and the filler, or the constituents of the porous asphalt mixture. Before the mixtures were prepared, the coarse (granite and RCA) and fine aggregates, as well as the bituminous binder, were characterised. Ordinary Portland Cement (OPC) was used as the filler in all mixes in compliance with the Standard Specification for Road Works of the Malaysian Department of Transportation (JKR/SPJ/2008-S4).

#### 1.1.1. Aggregates

For the needs of this study, granite and RCA were blended at different proportions. Granite is a conventionally used natural aggregate for pavement construction in Malaysia. The RCA was obtained from waste reinforced concrete beams. The process of breaking the beam into smaller boulders was performed using mallets. The steel reinforcements were separated before the boulders were crushed with the laboratory scale mechanical crusher. The original concrete beams had a compressive strength of 60 MPa. The crushed concrete was sieved through the 20 mm aperture sieve and the fraction retained in the 4.75 mm sieve was used in this experiment as a replacement of the coarse aggregate.

The replacement levels adopted in this study are 0%, 20%, 40%, 60%, 80%, and 100% (by weight) of the coarse aggregate. These proportions of coarse RCA were used as replacements for coarse granite in the porous asphalt mixtures. The mixtures were designated as R0, R20, R40, R60, R80, and R100, respectively. The control mixture R0 contained 100% granite without RCA. Table 1 presents the testing methods used for characterising the properties of materials and test results for both granite and RCA.

**Table 1. Characteristic properties of granite and RCA aggregates**

| Properties | Granite | RCA | Specification | Testing method |
|---|---|---|---|---|
| Flakiness index, % | 8.70 | 3.60 | <20% | BS812: Part 3 |
| Elongation index, % | 15.80 | 22.00 | <20% | BS812: Part 3 |
| Los Angeles Abrasion, % | 15.00 | 18.70 | <30% | ASTM C131 |
| Angularity number | 6.40 | 8.60 | 6 – 9 | BS812: Part 3 |
| Coarse aggregate specific gravity | 2.52 | 2.41 | – | ASTM C127-07 |
| Fine aggregate specific gravity | 2.60 | – | – | ASTM C128-07 |
| Coarse aggregate apparent specific gravity | 2.56 | 2.48 | – | ASTM C127-07 |
| Fine aggregate apparent specific gravity | 2.61 | – | – | ASTM C128-07 |
| Coarse aggregate bulk specific gravity | 2.55 | 2.53 | – | ASTM C127-07 |
| Fine aggregate bulk specific gravity | 2.66 | – | – | ASTM C128-07 |
| Coarse aggregate water absorption, % | 0.70 | 4.82 | – | ASTM C127-07 |
| Fine aggregate water absorption, % | 0.90 | – | – | ASTM C128-07 |

In general, the granite aggregate exhibited better properties than RCA. The observed water absorption of RCA was 4.82%, this value is seven times the value for granite. The Malaysian Standard (MS 30) requires that the water absorption for aggregates should be less than 2%. RCA does not meet this requirement. The flakiness index of RCA is better than that of granite, but granite had a better elongation index than RCA. The presence of adhered mortar in RCA is the reason for the higher content of flaky particles and water absorption of RCA. The values for RCA specific gravities are lower than the values for granite. Nevertheless, it can be seen that the values are comparable as a result of the adhered mortar quality from the original concrete with high compressive strength. Therefore, it may be stated that the quality of RCA depends on the strength properties of the parent concrete (Kou & Poon, 2015).

The air void content is an important factor considered during mix design of porous asphalts. Estimation of the volume of aggregates in the mix is vital for computation of air void contents. This in its turn depends on the specific gravity of the aggregates. To eliminate errors from adoption of a uniform specific gravity, the combined coarse granite and RCA were subjected to specific gravity tests at the adopted replacement levels. Specific gravities decrease linearly within the range from 2.52 to 2.41 as the amount of coarse RCA was increased from 0% to 100%.

#### 1.1.2. Bitumen

Considering the fact that the main focus of this study is to observe and analyse the behaviour of RCA based porous asphalt mixtures, bitumen grade 80/100, which is also used for some pavement constructions in Malaysia, was adopted for this study. The JKR specification requires that a polymer modified bitumen be used for porous asphalt pavement constructions in Malaysia. Notwithstanding, the use of 80/100 bitumen was considered adequate at it would better buttress the influence of RCA on the porous mixtures without any other contributing factor, such as polymer modification of the binder. The bitumen exhibited a penetration value of 8.6 mm confirming it was of grade 80/100. The specific gravity of the bitumen was 1.02. The softening point, the flash point, and the fire point of the bitumen were 47.65 °C, 286 °C, and 305 °C, respectively. These fall within the required limits for binder efficiency and safe construction.

## 1.2. Preparation of the samples and mix design

### 1.2.1. Mix type

Porous asphalts are special mixtures designed for air voids of 15–25% and coarse aggregate content of 90–95% by weight. JKR specifies two types of aggregate gradation for porous asphalt mixtures. Grading B mixture with the maximum aggregate size of 20 mm was selected in this study, because RCA contains aggregate with a similar maximum size.

### 1.2.2. Gradation of the aggregates

The aggregate Grading B for porous asphalt as specified by JKR was used in this study. The limits are set to ensure that about 92.5% of the aggregates will be retained in the 5 mm aperture sieve. The gradation depicts an open-graded aggregate combination with 2% minimum mineral filler aimed at achieving higher air voids to enable water drainage. For this reason, JKR specified that it can only be used as a wearing course over the existing impermeable surfaces. In accordance with JKR specifications for porous asphalt materials, Portland cement was used as the mineral filler for all mixtures analysed in this study. The midpoint of the specified limits was selected and used for the control mix as well as for the mixes containing RCA in this study. Figure 1 shows

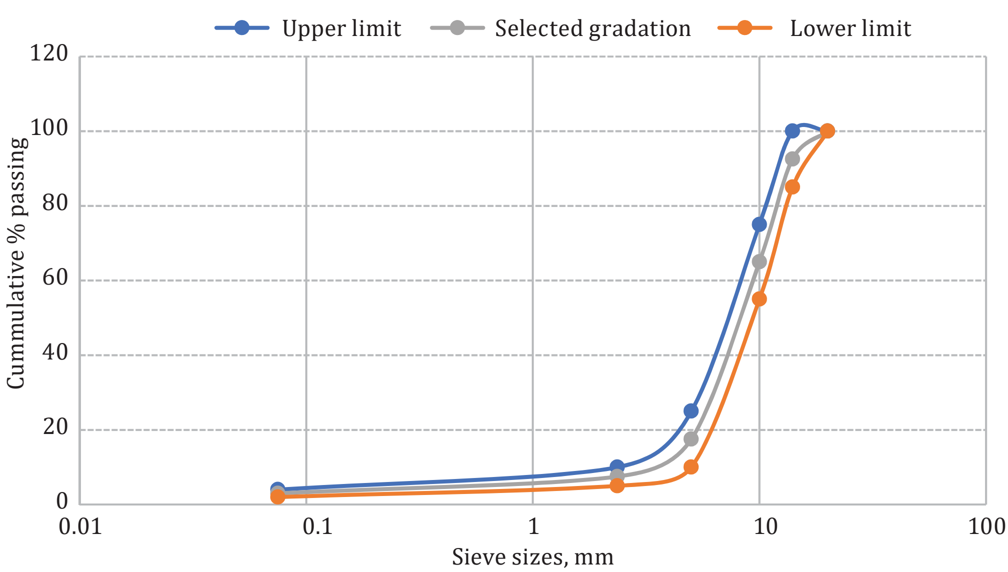


**Figure 1.** Specified limiting curves for the porous asphalt

the particle size distribution limiting curves for the porous asphalt Grading B. The selected gradation is also shown in the curve. This was adopted for both granite and RCA used in this study.

#### 1.2.3. Optimum binder contents

The Optimum Binder Content (OBC) for the porous asphalt mixes containing different proportions of RCA was determined in accordance with JKR guidelines. Considering the open graded nature of the aggregates, higher binder content would be required for optimum performance. However, increasing the binder content would result in a high amount of binder drain down from the mixture during transportation and placing, as well as a possible reduction in the air voids content below the desirable limits. The code, therefore, establishes a trade-off between these three important factors: the bond strength (measured by Cantabro abrasion resistance), the binder drain-down, and percentage air voids in the mix. Apart from being recommended by JKR, this method has been seen as a more efficient design method for porous pavement mixtures than the overlay and the Hamburg wheel tracking methods (Alvarez et al., 2010). With regard to the OBCs, JKR requires that the porous asphalt should exhibit binder drain-down of not more than 3%, abrasion loss – not more than 15%, and air voids within the range of 18–25%.

Nine Marshall specimens were prepared at each binder content for each replacement level in accordance with ASTM D1559. Three samples were used for each of the three tests at each replacement level. Compaction was done with the automated compactor exerting 50 blows

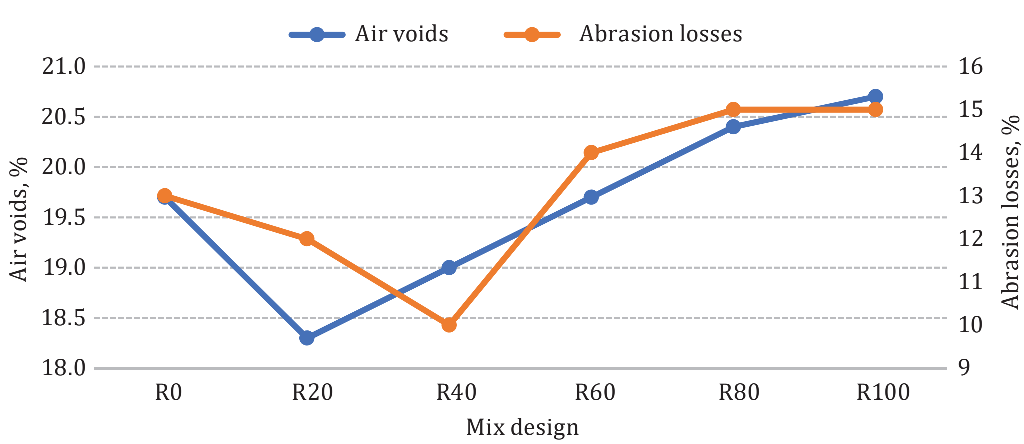


**Figure 2.** Design air voids and abrasion losses

on each face of the specimens. The binder contents were varied at a common difference of 0.5. The OBCs obtained for different replacement levels were 4.7%, 5.2%, 5.6%, 5.7%, 5.8%, and 6% for R0, R20, R40, R60, R80, and R100, respectively. These binder contents satisfied the design criteria stipulated by JKR. Though there is an increase in binder contents with higher amounts of RCA, all OBCs still fall within the range of 4–6% recommended by JKR. The reason for the rise in the OBCs is the presence of the adhered mortar on RCA. The binder is imbibed by the mortar resulting in a reduced binder drain-down. At the same time, the design binder drain-down for the control was 0.13%, the drain-down for the RCA mixtures ranged from 0.008% to 0.005% from R20 to R100. Moreover, RCA is more prone to abrasion losses than granite, as shown in Table 1. This in turn makes the mixes with higher RCA content more prone to abrasion losses, as shown in Figure 2. These factors contributed to the increase in OBCs with increase in RCA contents. The air voids contents were also found to be adequate at these design OBCs. Figure 2 shows the air voids and abrasion loses at the OBCs of the different mix designs.

These results demonstrate that mixtures with higher void contents exhibit lower resistance to abrasion. R20 and R40 mixtures exhibited more resistance to abrasion than the control. In contrast, the mixtures from R60 to R100 experienced higher losses, despite their higher OBC. Increasing the binder contents will definitely improve their abrasion resistance, but this will not be necessary as it would lead to the violation of other design criteria as well as would increase the cost of the mixture. Besides, all mixes complied with JKR specifications for air voids and abrasion losses. The air voids are closer to the specified lower limit of 18%.

## 1.3. Test procedures

In this study, a laboratory evaluation of the behaviour of porous asphalt mixtures has been made. Currently, there are only a few studies on the use of RCA in porous pavements. Laboratory tests were conducted on the mixtures to investigate their performance under different testing and loading conditions. Various tests were conducted on the porous mixtures, including conventional asphalt tests like determination of the stability and flow, analysis of the volumetric properties, evaluation of the resilient modulus, indirect tensile strength testing, assessment of moisture susceptibility, fatigue and skid resistance. The resistance of the mixtures to rutting was evaluated using wheel track experiment, their impact strengths were evaluated using the falling weight hammer method, and their permeability was evaluated using the hydraulic falling head test. These tests were conducted on all mixtures with different proportions of RCA. Employing all these tests in this study helped make a holistic assessment and evaluation of the behaviour of different mixtures under various loading conditions and porous pavement parameters.

Most of the tests evaluated the mechanical properties of the asphalt mixtures. The Marshall stability and flow test was performed in accordance with ASTM D1559 after conditioning the samples in a water bath at 60°C for a minimum duration of 2 h. The resilient modulus and fatigue tests were conducted in accordance with ASTM D4123 and EN 12697, respectively. The samples for both tests were conditioned to the test temperature of 25°C in the Universal Materials Testing Apparatus (UMATTA). The indirect tensile strength and moisture susceptibility tests were done in accordance with ASTM D6931 and ASTM D4867, respectively. The loaded wheel track experiment was performed in accordance with BS598-110 on the compacted slabs of 400×300×50 mm at 45°C test temperature. A modified impact test was also conducted on the asphalt mixtures. The impact test was done in accordance with the guidelines of American Concrete Institute (ACI 544). The only exception was that Marshall specimens were used instead of the samples with 150 mm diameter. In addition to the mechanical properties of the asphalt mixtures, their skid resistance was also evaluated in accordance with ASTM E303. The permeability of the asphalt mixtures, which is a very important hydraulic property of porous pavements, was also assessed.

It is important to note that the moisture susceptibility test was done using three specimens conditioned in water and three unconditioned specimens for each replacement level. The specimens for the moisture susceptibility tests were compacted to their specific design air void content ranging from 18.3% to 20.7%. The loaded wheel tracking test was conducted on two slabs for each mix design. The skid resistance test was conducted on the same slabs that were used for wheel tracking test, but the rubber slider was aligned to pass at the untracked portions of the slabs. These tests were performed at the design OBCs of the mixtures. Three samples were tested for each of the replacement levels in most of the tests. The permeability test was carried out using the fallen head apparatus as described by Alvarez et al. (2006). A water tight elastic membrane was used to cover the circumference of the samples to avoid leakages through the sides of the specimens. A uniform flow of water way allowed after saturation of the test specimens before the time taken for 1571 $cm^3$ of water to discharge through the specimen cross-section was recorded. Hence, for a glass tube of 10 cm diameter used in this experiment, the time taken for the water head to drop from 30 cm to 10 cm was recorded. The permeability of the porous asphalt was then estimated based on the coefficient of permeability ($K$) in cm/sec computed using Equation (1). Coefficient of permeability

$$K = 2.3\left(\frac{aL}{At}\right)\log\left(\frac{h_1}{h_2}\right), \tag{1}$$

where $a$ is the tube cross-sectional area in cm$^2$, $A$ is the specimen cross-sectional area in cm$^2$, $L$ is the thickness of the specimen in cm, $t$ is the time taken in seconds for the water to flow from initial head ($h_1$) to the final head ($h_2$).

## 2. Results and discussion

The result of the laboratory tests conducted to evaluate the performance of the RCA based porous asphalt designs are presented and discussed in this section. Table 2 presents the result of the most fundamental performance tests generally used in quality control of asphalt mixtures. These results are discussed in the subsequent subsections. Result of other performance tests are plotted in relevant figures to provide for more comprehensive analysis.

Table 2. Results of tests on fundamental mechanical properties

| Mix Design | Mechanical Properties | | | | |
|---|---|---|---|---|---|
| | Marshall stability, N | Flow, mm | Resilient Modulus, MPa | Indirect Tensile Strength (ITS), kPa | Tensile Strength Ratio (TSR), % |
| R0 | 5283 | 3.9 | 7419 | 419 | 89 |
| R20 | 6490 | 3.1 | 7065 | 419 | 95 |
| R40 | 6433 | 2.9 | 7198 | 424 | 96 |
| R60 | 6524 | 2.8 | 7165 | 431 | 89 |
| R80 | 6803 | 3.2 | 6930 | 429 | 89 |
| R100 | 7276 | 3.7 | 6035 | 417 | 89 |

### 2.1. Marshal stability and flow

The Marshall stability of conventional asphalt mixtures is used for mixture design and performance assessments in order to ensure that the mixtures are strong enough to withstand traffic wheel loads. For porous asphalt pavements, the case is different. JKR refers to it as a specialty mix adopted as a non-structural layer applicable in low trafficked roads with low density and relatively high design speed. For this reason, the design interest in case of porous asphalt is in its resistance to abrasion and permeability. Nevertheless, this study proposes that utilisation of RCA for porous asphalts will be justified when the porous pavement mixtures achieve comparable or better stability values than the control. In other words, inclusion of RCA in porous asphalt mixtures should not result in significant loss of stability, because this would make the pavement perform much poorer than expected, it may even fail unduly at low traffic levels. When this happens, the riding quality deteriorates and the benefits of porous pavement surfacing depreciate. The results of Marshall stability tests on different porous mix designs are reported in Table 2.

The stability result for R0, which serves as the control, is 5283 N. This is below 6200 N recommended for conventional hot mix asphalts and stone mastic asphalts, confirming that the porous pavement is not to be used as a structural layer of the pavement but rather as an overlay on a more stably impermeable binder course. The stability of the asphalt mixtures was improved by inclusion of RCA. R20, R40, and R60 achieved comparable stability result with approximately 23%, 22%, and 23% increase in stability values, respectively. Mixtures with higher replacement levels of granite by RCA achieved even higher stability values. R80 achieved 6803 N and R100 achieved 7276 N, these represent

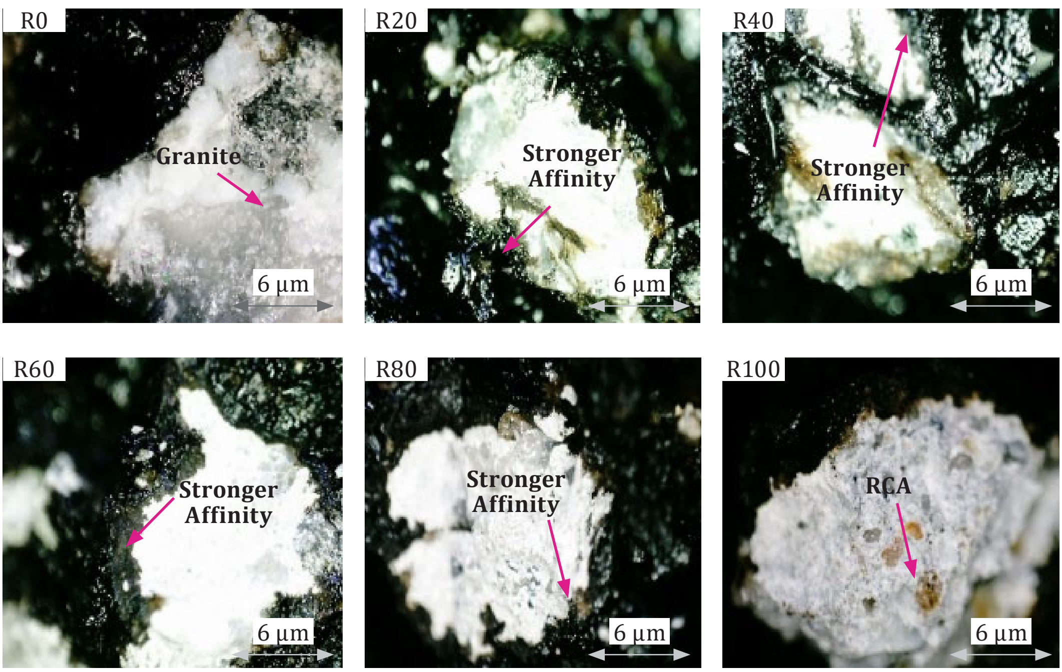


**Figure 3.** The bonding of aggregates with bitumen in the porous mixture

29% and 38% increase in stability values, respectively. All mixes with RCA achieved beyond 6200 N stability, which reveals the ability of porous pavement surfaces with RCA to withstand higher traffic loads with an acceptable axle load distribution efficiency. The flow values are also within the recommended limits of 2–4 mm for well graded asphalt mixtures. Most studies on porous asphalts do not adopt the Marshall stability as a performance test due to the lower stability values recorded, as it can be seen in the case of R0 in this study. Besides, limited work has been done on the use of RCA in porous asphalts. Notwithstanding, the study by Kareem et al. (2019) reported improvement in the stability of hot mix asphalt mixtures with RCA inclusion. Their results show a 6% increase in Marshall stability for 60% inclusion of RCA. The improvement in Marshall stability was not a result of increase in density, because the mixtures with higher RCA contents had lesser bulk specific gravities. The increase in binder content could not significantly influence these weight properties because the specific gravity of bitumen is 1.02, which is more than 50% less than this of the aggregates. This is also the reason why the specific gravities of all the porous asphalt mixtures are below the specific gravities of the aggregates but higher than the specific gravity of bitumen. The improved bonding between the aggregate and the binder was responsible for the increase in stability of the mixtures. Figure 3 shows how RCA partially absorbed the bitumen leading to stronger affinity. This improved the compressive strength of the asphalt, leading to higher stability values.

The better bonding was brought about by presence of cement in the adhered mortar. This added to the filler proportion of the RCA mixtures resulting in lesser compressibility. This is consistent also to the findings of Wang et al. (2018) as well as Guha & Assaf (2020) who recommended that use of cement or crushed concrete dust fillers can increase the stability of asphalt mixtures than the use of crushed granite fillers. For this reason, JKR specified only cement and hydrated lime as fillers for porous pavements in order to ensure a reasonable level of stability. The stability results obtained from this study show that inclusion of RCA into the porous asphalt mixtures would achieve this aim even more effectively.

## 2.2. Resilient modulus

The resilient modulus of asphalt mixtures measures how stiff the mixture is to absorb repeated loading and unloading without undergoing plastic deformation. It is a measure of the elastic strength of the asphalt mixture and is used to evaluate the ability of asphalt mixtures to withstand traffic loadings and vehicular movement vibrations without severe permanent deformations. The results of resilient moduli of the porous asphalt samples at the various replacement levels of granite by RCA are given in Table 2.

The maximum resilient modulus of 7419 MPa was observed for R0 which was used as the control. The resilient modulus of the mixtures reduced sequentially with higher proportions of RCA, apart from R20 with a slightly lesser resilient modulus than R40. This sequential reduction in resilient modulus is traceable to the air void contents of the mixtures, as mixtures with higher air voids generally achieved lower resilient moduli. The values of the resilient modulus for R20, R40, and R60 are very comparable to the control with less than 5% reductions in the control resilient modulus. More significant reductions in the resilient modulus were recorded for R80 and R100. 6930 MPa for R80 and 6035 MPa for R100 represent 7% and 19% reductions in control resilient modulus, respectively. This allows concluding that porous asphalt mixtures with RCA inclusion beyond 60% may not be able to withstand shock waves as successfully as the control. They would require a higher thickness to perform as satisfactory as the control. Asphalt mixtures with RCA inclusion of 60% or less can perform as efficiently as the control in resisting repeated loading at the same design thickness. Besides, previous studies have reported resilient modulus ranging from 2000 MPa to 10 000 MPa for dense graded asphalts (Ar-Rabti & Judycki, 2000; Radhakrishnan et al., 2019). This suggests that the drop in resilient modulus beyond R60 may not pose a threat of undue failure because all values are considerably higher than 6000 MPa. Moreover, JKR has recommended a minimum thickness of 50 mm for efficient drainage of porous wearing courses in addition to the fact that the porous asphalts should be placed on an existing impermeable and stiff binder course. These factors justify the use of RCA in porous asphalts mixtures even at a slightly lower resilient modulus than the control, as observed in this study.

## 2.3. Indirect tensile strength and moisture susceptibility

The compressive forces exerted by vehicular wheel loads on the highway pavement causes tensile stresses within the pavement surfaces (Ossa et al., 2016). For the pavement to remain serviceable and durable, it should withstand such induced tensile stresses. This ability to withstand higher tensile stresses is the measure of the pavement's tensile strength. The indirect tensile strength (ITS) test is a laboratory experiment used to estimate the tensile strength of a particular asphalt mixture. The test was conducted on various mixes with different proportions of RCA; the results are reported in Table 2. The resistance of the asphalt mixes to moisture damage was also investigated based on this test. The air void contents for the mixtures were not uniform. This variation in air void content was necessary because it represents the actual air voids of different mix designs. Three samples were vacuum soaked and conditioned in a water bath maintained at 60°C for 48 h. The ratio of the tensile strength of the conditioned to the unconditioned samples was used as a measure of moisture susceptibility of the porous asphalt mixtures. The results of the moisture susceptibility test are also reported in Table 2.

The ITS results for all mixes are very comparable. R40, R60, and R80 achieved higher values than the control, R20 achieved the same value as the control, whereas R100 achieved almost the same value as the control. This shows that porous asphalt mixtures with RCA can perform similar as the granite mixtures in terms of resistance to the tensile stress. The increase in affinity between RCA particles and the bitumen resulted in a significant increase in the bond strengths. This was why the RCA mixtures were able to withstand higher indirect tensile loading before failure. The tensile strength ratio (TSR) also ranged from 89% to 96%. R60, R80, and R100 achieved the same TSR as R0, whereas R20 and R40 achieved higher values. All mixes are considered satisfactory in terms of their resistance to moisture damage because all observed TSRs are above 80% (Qasrawi & Asi, 2016). This also agrees with the recommendations of ASTM D4867/D4867M–04. Therefore, the use of RCA would not make the porous pavement surface susceptible to moisture damage. The good quality of RCA used in this study is the major factor that contributed to this satisfactory performance of porous asphalt mixtures containing different proportions of RCA.

## 2.4. Resistance to fatigue damage

Indirect Tensile Fatigue Test (ITFT) has been used to evaluate the resistance of the porous asphalt mixes to fatigue damage. It was presumed that porous asphalt mixtures would be more susceptible to fatigue damage than conventional well graded asphalt mixtures. This is because of the presence of higher air voids content and water percolation through the air voids. The voids content tends to expose the mixture to a wider area prone to adverse climatic conditions and water movements exert some pressure on the internal structure of the specimen. Figure 4 presents the result of the fatigue test conducted on various porous asphalt mixes.

The fatigue loading was increased sequentially till the maximum failure deformation of 9 mm was reached. The number of loading cycles before the specimens failed was taken as indicator to mixture's resistance to fatigue damage. In other words, the mixtures with the higher loading cycles to failure would be expected to exhibit longer fatigue life when adopted for the porous pavement surfacing. Therefore, it can be concluded that the porous mixtures with RCA exhibited better performance in fatigue resistance than the control. All RCA samples sustained lesser strains at each loading cycle and as a result they withstood more strains before failure. This performance improved with incorporation of higher proportions of RCA. The higher binder contents in the mixtures with higher RCA proportions is considered the main reason for this improved fatigue resistance (Nwakaire et al., 2020b). The higher bitumen contents made the mixtures less brittle under the fatigue loading.

## 2.5. The rutting resistance of the mixtures

The dynamic stability of pavements is evaluated based on their resistance to rutting.  Increase in temperature and traffic loading are two factors that contribute to rutting of the pavements. Due to the high air voids, porous pavements can compress at higher traffic loadings, it can also be severe at higher temperatures. For this reason, JKR specified that roads surfaced with porous asphalts should experience not more

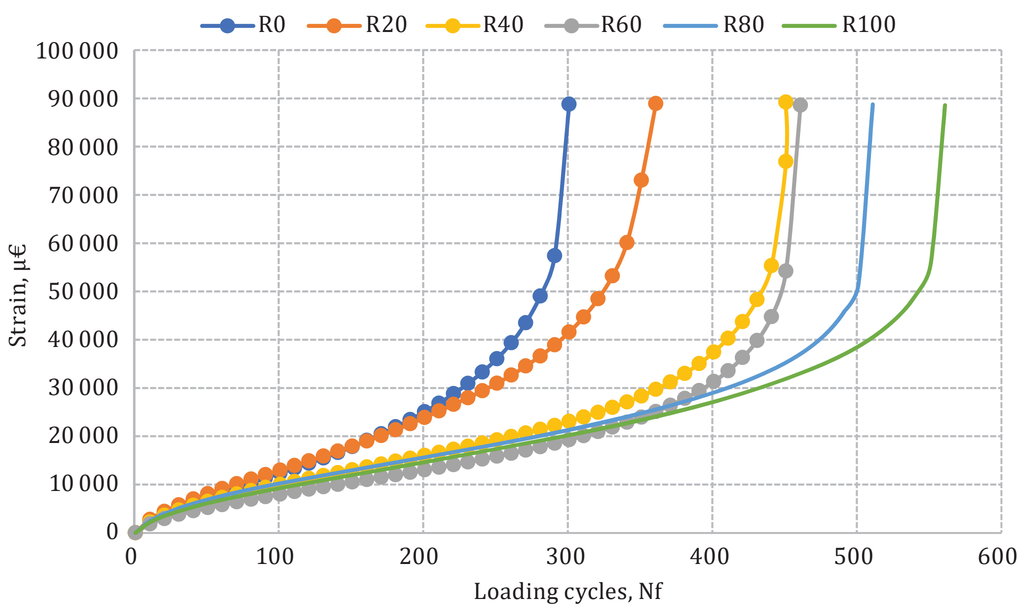


**Figure 4.** Fatigue loadings and strains to failure

than 4000 commercial vehicles per lane per day at opening. But the fact is that once the road is open to traffic, the rate of vehicular increase may be very high to such an extent that this limit is exceeded. Moreso, Malaysia, experiences high temperatures around the first quarter of the year. This temperature may rise until as much as 40 °C in some parts of the country. For these reasons, it is pertinent to investigate the behaviour of porous asphalts under repeated wheel tracking at high temperatures. Asphalt materials used for flexible pavement surfacing were subjected to wheel track experiment in order to evaluate their resistance to rutting. In this study, the porous asphalt slabs were compacted using mechanical compactors to the respective design air void contents of the different mixes. The results of this wheel tracking test are presented in Figure 5.

Addition of RCA to the porous asphalt mixes improved the resistance of the porous asphalt slabs to rutting. R20 to R80 mixtures performed better than the control based on their final rut depths. R20 and R40 samples performed better than R0 through the entire wheel cycling times, but R60 and R80 experienced higher rut depths than the control at earlier cycling times but gained better dynamic stability as the cycling period increased. R40 offered the best resistance to rutting with a final rut depth of 2.3 mm. Beyond R40, the rutting resistance decreased

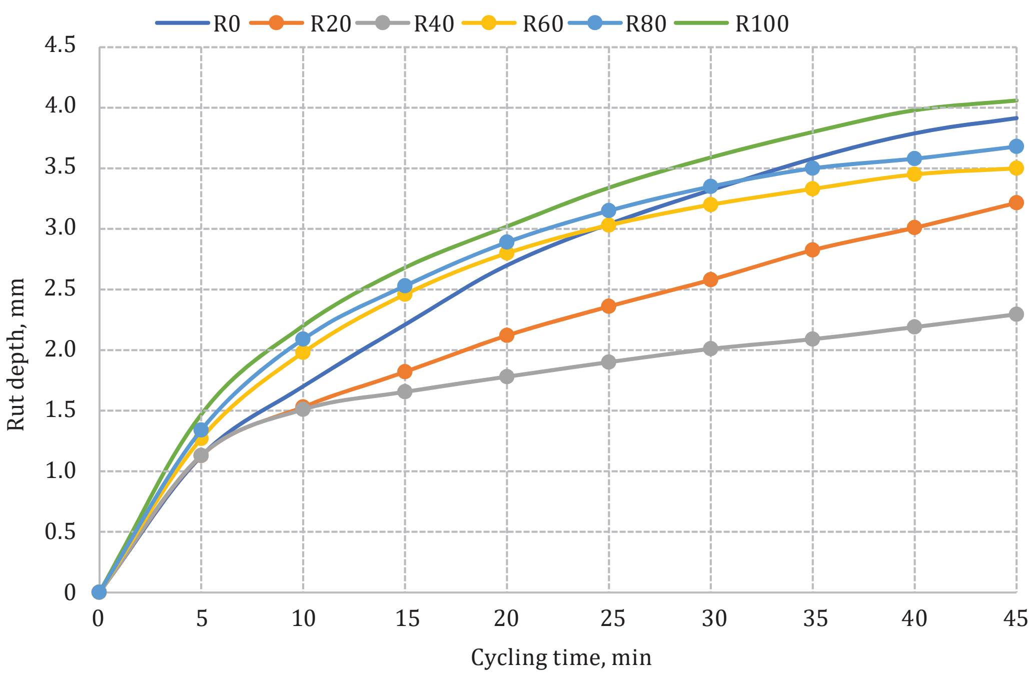


**Figure 5.** Rutting resistance of the mixes

sequentially with increase in the RCA content. It can be said that the samples with higher abrasion losses also exhibited lower resistance to rutting. The worst performance was observed for R100 mix with the final rut depth of 4.06 mm. Apart from R100, all other mixtures satisfied the 4 mm maximum rut depth requirement at 45°C, as specified by BS 598–110.

## 2.6. Resistance to impact loading

RCA has lower impact strength than granite due to the presence of the adhered mortar. The aggregate impact values reported in Table 1 confirm that. Utilisation of RCA in a gap-graded mixture of porous asphalts was presumed to result in lower impact strength for the porous asphalt. This issue was investigated in this study in order to ascertain the resistance to impact loading for porous asphalt mixtures containing RCA. The impact hammer was dropped on the asphalt samples and the number of blows that caused the first crack was recorded. The blows were continued until the specimens failed. The potential energy mobilised during the falling weight impact testing was used as the basis for the computation of the impact strength. The impact energies were calculated based on Equation (2). The hammer with mass ($m$) of 4.5 kg dropped from a height ($h$) of 450 mm was constant for all tests. The only variable in this experiment was the number of blows ($N$) before the first crack and the final failure.

$$E_{\text{impact}} = mgh \times N, \tag{2}$$

where $g$ is the acceleration due to gravity (9.81 m/s$^2$). Figure 6 shows the computed values of the impact energies, which served as the indicators of the impact strength of the mixtures.

The impact strengths of all samples containing RCA were found to be better than that of the control. The amounts of energy absorbed by the RCA samples both before the first crack formation and at failure were higher than the control energy absorption. R60 exhibited the best impact strength with 271 J and 380 J of energy absorbed before the first crack and failure respectively. R80 achieved the same first crack impact strength as R60 but failed at a lesser impact strength of 380 J. Nevertheless, the values of impact energies for all mixtures were very close, which allows concluding that their impact energies are highly comparable. These results imply that pavements with porous asphalt wearing course can absorb similar or higher impact energy than the control both before initiation of the cracks and before unbearable failures.

Generally, the porous asphalt samples exhibited a reasonable amount of post crack ductile behaviour. The samples sustained higher impact efforts after the first crack and remained unbroken under several more blows. This ductile behaviour is reported based on the ratio of the impact energy sustained before failure to the impact energy at the first crack. This ratio is reported as the ductility index. The ductility indices of the porous asphalt samples tested in this study are 1.54%, 1.54%, 1.69%, 1.4%, 1.33%, and 1.34% for R0, R20, R40, R60, R80, and R100, respectively.

R0 and R20 had the same ductility index of 1.54, whereas R80 and R100 had similar indices. The ductility index of R80 is the least, whereas R40 demonstrated the highest ductility. In as much as these ductility indices are indicators of the post crack initiation impact strength of the samples, the first crack impact energy has been adopted for the performance assessment in this study. This was done in view of the fact that the porous asphalts with high amounts of air voids would tend to ravel and disintegrate faster under traffic loading once cracks begin to develop on the surface of the asphalts. R60 and R80 with the maximum first crack energy of 271 J were considered the best mixes based on their impact performance. However, R60 was judged as the best mix because, apart from absorbing the highest energy before the first crack, it achieved also the highest failure impact strength. Hence, it was inferred that RCA did not have any negative effect on the impact performance of porous asphalts. The presence of larger amount of binder in the mixes made the aggregates bond better with the bitumen and develop a stronger matrix. The mixtures exhibited the same behaviour under

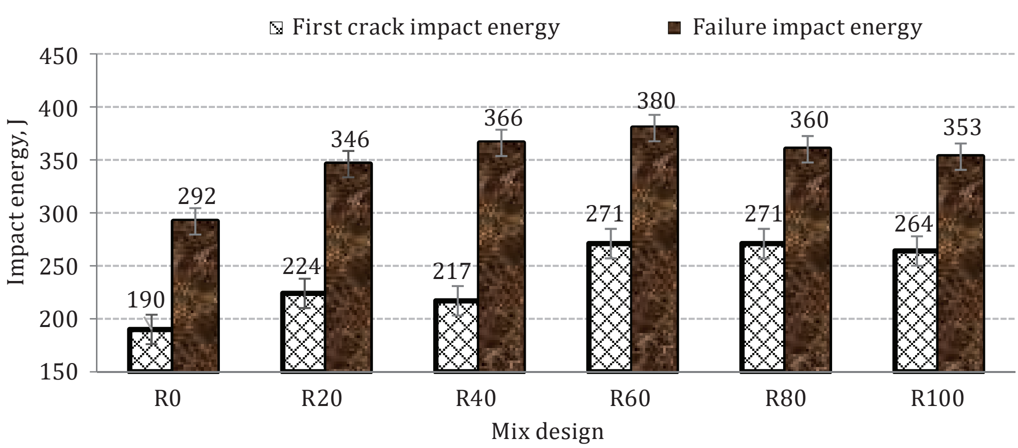


**Figure 6.** Impact strength of the samples

impact loading and indirect tensile loading, because the impact failure for the asphalt mixture is also tensile in nature. The specimens split due to application of the impact effort at a point on their cross-section.

## 2.7. Assessment of permeability and skid resistance

Permeability and skid resistance are two major desirable properties of the porous pavements. With the high air voids content, it is expected that the water passing through the cavities of the pavement should be able to drain off as fast as possible though the pavement. The rate at which this drainage occurs is evaluated based on the coefficient of permeability of the porous pavement. On the other hand, skid resistance is one of the most important factors considered in pavement engineering for accident mitigation (Elizondo-Martínez et al., 2020). The British pendulum tester used in this study is one of the most popular methods for evaluating the skid resistance of wet highway pavements both at the laboratory and in the field. Although the skid number obtained from the British pendulum test is not an exact indication of the vehicle braking characteristics, it is a useful tool to compare between the skid resistances of different surfaces (Asi, 2007). JKR states that one

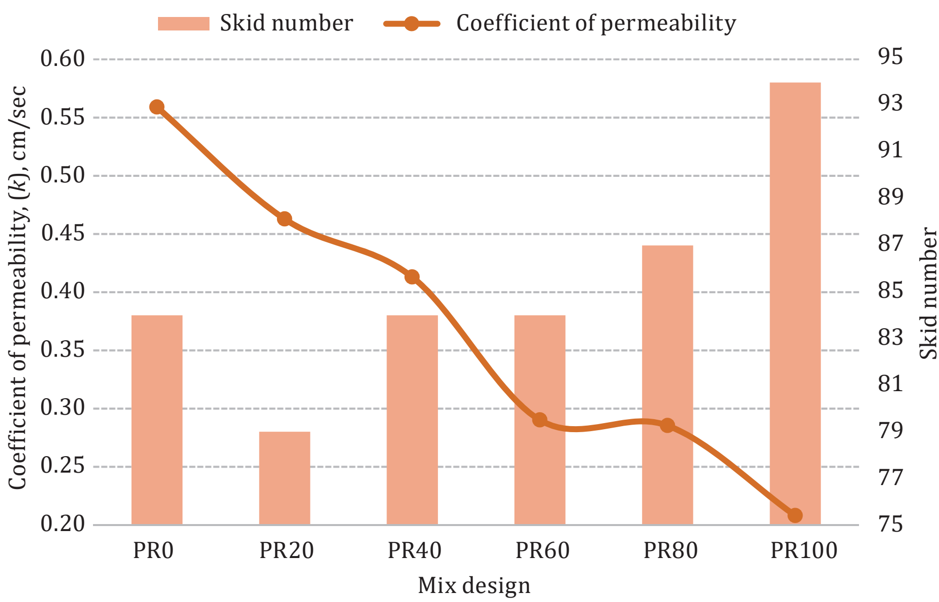


**Figure 7.** Influence of addition of RCA on the permeability and skid resistance of porous asphalts

of the benefits of porous asphalt surfacing of pavements is that it improves storm water control and skid resistance of the road. It is, therefore, necessary to study the influence of addition of RCA on these two functional parameters of the porous asphalts. The results of the permeability and skid resistance tests conducted on the different mixes in this study are presented in Figure 7.

The coefficient of permeability ($k$) of the mixes decreased with increasing RCA content. The $k$ of the control is the highest whereas the $k$ of R100 is the least within the range of 0.208–0.559 cm/sec. This sequential drop in $k$ with the increase in RCA content offers a unique behaviour for porous asphalts with RCA aggregates, bringing two factors into play – the air voids and the bitumen contents. It has been established that, other things being equal, porous asphalt mixtures with higher air voids content would achieve higher permeability (Liu and Cao, 2009). It has also been established that, other things being equal, higher bitumen content would reduce the permeability of porous asphalt mixtures (Hamzah et al., 2011). Increase in the binder content tends to fill up the connected air voids in the mixture. But RCA has existing internal air voids within the porous adhered mortar. These voids contributed to the higher air void contents of the mixtures but did not contribute to their permeability. For this reason, the higher binder content of the mixtures influenced the permeability of the specimens more than the air voids. The result is that porous mixtures with higher binder content, though containing higher air voids content, would be less permeable because of the filling of the cavities by the high amounts of binder in the mixtures. A similar clogging phenomenon was also reported by Suresha et al. (2010).

Despite the fact that $k$ of the mixtures reduced with higher RCA content, the permeability is still considered satisfactory for all the mixes. There is not yet a general standard adopted as the limits for $k$, but following the recommendation of Mallick et al. (2000), $k$ of 0.116 cm/sec or more is considered satisfactory. In this regard, all mixtures performed well in allowing the drainage of water through them, but R0 offered the best permeability.

As concerns the anti-skid properties, R20 mixture had the least skid number of 79. This is by 44% higher than the minimum skid number of 55 specified for motorways and heavy trafficked roads and by 76% higher than 45 specified for low trafficked roads. R40 and R60 had the same skid numbers as the control. R80 and R100 achieved better skid numbers of 4% and 12% higher than the control, respectively, making R100 the best mixture in terms of skid resistance. These skid number values are very high, confirming that porous asphalt surfaces generally perform well in skid resistance. The higher skid numbers recorded for R80 and R100 are a result of the micro textures offered by the coarse RCA with higher elongation index and rougher surface texture. The drop in the skid number of R20 could be a result of inconsistent balancing between the higher bitumen content and inclusion of RCA. Nevertheless, all mixtures demonstrate adequate anti-skip properties, since they all met the specified minimum skid resistance values. Even at the worst scenario of steep gradients, junctions, and curves, ASTM E303 considered skid number of 65 as satisfactory. Therefore, all the observed skid numbers are satisfactory for all pavement conditions. This is a very desirable feature to be possessed by porous asphalt pavements.

## Conclusions

The main aim of this study was to ascertain the feasibility of utilisation of RCA for porous asphalt pavement construction. The properties and behaviour of porous asphalt mixtures incorporating varying amounts of RCA was investigated. Many performance tests were conducted in order to evaluate various RCA based porous asphalt mixes and their response to different types of loading. The following conclusions were drawn from the results of the study.

1. At a particular binder content, the RCA based porous mixtures demonstrated better performance than the control mixture with respect to binder drain downs, but they exhibited lower resistance to abrasion. For this reason, the porous asphalts require higher OBCs for mixtures with higher amounts of RCA.
2. Inclusion of RCA reduced the resilient modulus and permeability of the porous asphalt mixtures. Whereas the reduction in resilient modulus was a result of increase in air voids, the reduction in permeability was a result of increase in the binder content.
3. The Marshall stability, fatigue resistance, and skid resistance of the mixtures improved along with the increase in RCA content.
4. Mixture R100 was found inadequate with respect to ITS and rutting resistance. Blending the granite and RCA in the porous asphalt mixture was seen to give better ITS, rutting resistance, and impact strength. Whereas R40 showed the best resistance to rutting, mixture R60 exhibited optimum performance in terms of ITS and impact strength.

Therefore, it was concluded that RCA can partially replace natural aggregates in porous asphalt mixtures but based on the results obtained in this study, up to 60% replacement is considered more suitable for desirable performance. This will improve the economic viability of porous pavement surfacing by reducing the amount of natural aggregate required. The overall cost of the pavement construction will also be reduced by the cost of granite being replaced by RCA. Utilization of RCA will obviously contribute to the implementation of circular economy due to reduction of solid waste disposals. It will also enhance the environmental friendliness of the porous asphalt surfacing. For satisfactory structural performance, it is recommended that the porous surfacing be applied over an impervious asphalt layer to enhance its ability to bear the traffic loading. The porous pavement design is suitable for tropical weather conditions like those typical of Malaysia, where the thawing and melting of ice and glaciers would not induce undue pavement failure.

## Funding

This research was funded by the University of Malaya Faculty Research Grant (GPF) 2019 under the project GPF008A-2019 (Development of Green and Space-efficient Low-Cost Structures from Renewable Materials). Also, the first author also gratefully acknowledges the contribution of the Tertiary Education Trust Fund (TETFund), Nigeria, in the form of the funding provided for his PhD studies.

## REFERENCES

Alvarez, A. E., Epps-Martin, A., Estakhri, C. K., & Izzo, R. (2010). Evaluation of durability tests for permeable friction course mixtures. *International Journal of Pavement Engineering*, *11*(1), 49–60. https://doi.org/10.1080/10298430902730539

Alvarez, A. E., Epps-Martin, A., Estakhri, C. K., Button, J. W., Glover, C. J., & Jung, S. H. (2006). *Synthesis of current practice on the design, construction, and maintenance of porous friction courses* (Report No. FHWA/TX-06/0-5262-1). Texas Transportation Institute.

Arabani, M., Moghadas Nejad, F., & 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

Ar-Rabti, A. G. H., & Judycki, J. (2000). Effect of some testing variables on resilient modulus of asphalt mixes determined in indirect tensile method. *Road Materials and Pavement Design*, *1*(3), 341–354. https://doi.org/10.1080/14680629.2000.12067147

Asi, I. M. (2007). Evaluating skid resistance of different asphalt concrete mixes. *Building and Environment*, *42*(1), 325–329. https://doi.org/10.1016/j.buildenv.2005.08.020

Benachio, G. L. F., Freitas, M. d. C. D., & Tavares, S. F. (2020). Circular economy in the construction industry: A systematic literature review. *Journal of Cleaner Production*, Article 121046. https://doi.org/10.1016/j.jclepro.2020.121046

Brundtland, G. H. (1987). Our common future – Call for action. *Environmental Conservation*, *14*(4), 291–294. https://doi.org/10.1017/S0376892900016805

Elizondo-Martínez, E.-J., Andrés-Valeri, V.-C., Jato-Espino, D., & Rodriguez-Hernandez, J. (2020). Review of porous concrete as multifunctional and sustainable pavement. *Journal of Building Engineering*, *27*, Article 100967. https://doi.org/10.1016/j.jobe.2019.100967

Eziefula, U. G. (2017). Developments in utilisation of agricultural and aquaculture by-products as aggregate in concrete – a review. *Environmental Technology Reviews*, *7*(1), 19–45. https://doi.org/10.1080/21622515.2017.1423399

Guha, A. H., & Assaf, G. J. (2020). Effect of Portland cement as a filler in hot-mix asphalt in hot regions. *Journal of Building Engineering*, *28*, Article 101036. https://doi.org/10.1016/j.jobe.2019.101036

Hamzah, M. O., Aman, M. Y., & Shahadan, S. (2011). Resistance to disintegration of warm porous asphalt incorporating Sasobit®. *Australian Journal of Basic and Applied Sciences*, *5*(9), 113–121.

Haritonovs, V., & Tihonovs, J. (2014). Use of unconventional aggregates in hot mix asphalt concrete. *The Baltic Journal of Road and Bridge Engineering*, *9*(4), 276–282. https://doi.org/10.3846/bjrbe.2014.34

Haritonovs, V., Zaumanis, M., Brencis, G., & Smirnovs, J. (2013). Performance of asphalt concrete with dolomite sand waste and bof steel slag aggregate. *The Baltic Journal of Road and Bridge Engineering*, *8*(2), 91–97. https://doi.org/10.3846/bjrbe.2013.12

Hayat, U., Rahim, A., Khan, A. H., & Rehman, Z. U. (2020). Use of plastic wastes and reclaimed asphalt for sustainable development. *The Baltic Journal of Road and Bridge Engineering*, *15*(2), 182–196. https://doi.org/10.7250/bjrbe.2020-15.479

Hu, M., Li, L., & Peng, F. (2019). Laboratory investigation of OGFC-5 porous asphalt ultra-thin wearing course. *Construction and Building Materials*, *219*, 101–110. https://doi.org/10.1016/j.conbuildmat.2019.04.205

Huurman, M., Mo, L. T., & Woldekidan, M. F. (2010). Porous asphalt ravelling in cold weather conditions. *International Journal of Pavement Research & Technology*, *3*(3), 110–118. http://www.ijprt.org.tw/files/sample/V3N3%282%29.pdf

Jabatan Kerja Raya (J. K. R.). (2008). *Standard specification for road works*. Section 4, S4-58. Malaysian Department of Transport.

Kareem, A. I., Nikraz, H., & Asadi, H. (2019). Performance of hot-mix asphalt produced with double coated recycled concrete aggregates. *Construction and Building Materials*, *205*, 425–433. https://doi.org/10.1016/j.conbuildmat.2019.02.023

Khan, I., & Kabir, Z. (2020). Waste-to-energy generation technologies and the developing economies: A multi-criteria analysis for sustainability assessment. *Renewable Energy*, *150*, 320–333. https://doi.org/10.1016/j.renene.2019.12.132

Kou, S.-c., & Poon, C.-s. (2015). Effect of the quality of parent concrete on the properties of high performance recycled aggregate concrete. *Construction and Building Materials*, *77*, 501–508. https://doi.org/10.1016/j.conbuildmat.2014.12.035

Liu, Q., & Cao, D. (2009). Research on material composition and performance of porous asphalt pavement. *Journal of Materials in Civil Engineering*, *21*(4), 135–140. https://doi.org/10.1061/(ASCE)0899-1561(2009)21:4(135)

Ma, X., Zhou, P., Jiang, J., & Hu, X. (2020). High-temperature failure of porous asphalt mixture under wheel loading based on 2D air void structure analysis. *Construction and Building Materials*, *252*, Article 119051. https://doi.org/10.1016/j.conbuildmat.2020.119051

Mallick, R. B., Kandhal, P. S., Cooley Jr, L. A., & Watson, D. E. (2000). *Design, construction, and performance of new-generation open-graded friction courses* (NCAT Report 00-01). Association of Asphalt Paving Technologists. https://www.researchgate.net/publication/238741997_Design_Construction_and_Performance_of_New-Generation_Open-Graded_Friction_Courses

Morseletto, P. (2020). Targets for a circular economy. *Resources, Conservation and Recycling*, *153*, Article 104553. https://doi.org/10.1016/j.resconrec.2019.104553

Nwakaire, C. M., Yap, S. P., Onn, C. C., Yuen, C. W., & Ibrahim, A. H. (2020a). Utilisation of recycled concrete aggregates for sustainable highway pavement applications; a review. *Construction and Building Materials*, *235*, Article 117444. https://doi.org/10.1016/j.conbuildmat.2019.117444

Nwakaire, C. M., Yap, S. P., Yuen, C. W., Onn, C. C., Koting, S., & Babalghaith, A. M. (2020b). Laboratory study on recycled concrete aggregate based asphalt mixtures for sustainable flexible pavement surfacing. *Journal of Cleaner Production 262*, *Article* 121462. https://doi.org/10.1016/j.jclepro.2020.121462

Osei, D. Y. (2013). Experimental assessment of coconut shell as aggregate in concrete. *International Journal of Engineering Science Invention*, *2*(5), 7–11.

Ossa, A., García, J. L., & Botero, E. (2016). Use of recycled construction and demolition waste (CDW) aggregates: A sustainable alternative for the pavement construction industry. *Journal of Cleaner Production*, *135*, 379–386. https://doi.org/10.1016/j.jclepro.2016.06.088

Plati, C. (2019). Sustainability factors in pavement materials, design, and preservation strategies: A literature review. *Construction and Building Materials*, *211*, 539–555. https://doi.org/10.1016/j.conbuildmat.2019.03.242

Qasrawi, H., & Asi, I. (2016). Effect of bitumen grade on hot asphalt mixes properties prepared using recycled coarse concrete aggregate. *Construction and Building Materials*, *121*, 18–24. https://doi.org/10.1016/j.conbuildmat.2016.05.101

Qiu, J., Huurman, M., de Bruin, B., Demmink, E. W., & Frunt, M. H. T. (2018). Towards 90% warm re-use of porous asphalt using foaming technology. *Journal of Cleaner Production*, *190*, 251–260. https://doi.org/10.1016/j.jclepro.2018.04.086

Radhakrishnan, V., Dudipala, R. R., Maity, A., & Sudhakar Reddy, K. (2019). Evaluation of rutting potential of asphalts using resilient modulus test parameters. *Road Materials and Pavement Design*, *20*(1), 20–35. https://doi.org/10.1080/14680629.2017.1374994

Rafi, M. M., Qadir, A., & Siddiqui, S. H. (2011). Experimental testing of hot mix asphalt mixture made of recycled aggregates. *Waste Management & Research*, *29*, 1316–1326. https://doi.org/10.1177/0734242X10370379

Riekstins, A., Haritonovs, V., & Straupe, V. (2020). Life cycle cost analysis and life cycle assessment for road pavement materials and reconstruction technologies. *The Baltic Journal of Road and Bridge Engineering*, *15*(5), 118–135. https://doi.org/10.7250/bjrbe.2020-15.510

Sanchez-Alonso, E., Castro-Fresno, D., Vwga-Zamanillo, A., & Rodriguez-Hernandez, J. (2011). Sustainable asphalt mixes: Use of additives and recycled materials. *The Baltic Journal of Road and Bridge Engineering*, *6*(4), 249–257. https://doi.org/10.3846/bjrbe.2011.32

Sangiorgi, C., Lanteri, C., & Dondi, G. (2014). Construction and demolition waste recycling: An application for road construction. *International Journal of Pavement Engineering*, *16*(6), 530–537. https://doi.org/10.1080/10298436.2014.943134

Suresha, S. N., Varghese, G., & Ravi Shankar, A. U. (2010). Laboratory and theoretical evaluation of clogging behaviour of porous friction course mixes. *International Journal of Pavement Engineering*, *11*(1), 61–70. https://doi.org/10.1080/10298430902730554

Tam, V. W. Y., Soomro, M., & Evangelista, A. C. J. (2018). A review of recycled aggregate in concrete applications (2000–2017). *Construction and Building Materials*, *172*, 272–292. https://doi.org/10.1016/j.conbuildmat.2018.03.240

Wang, J., Guo, M., & Tan, Y. (2018). Study on application of cement substituting mineral fillers in asphalt mixture. *International Journal of Transportation Science and Technology*, *7*(3), 189–198. https://doi.org/10.1016/j.ijtst.2018.06.002

WEC. (2016). *World Energy Resources: Waste to Energy*. World Energy Council.

Yu, T., Zhang, H., & Wang, Y. (2020). Interaction of asphalt and water between porous asphalt pavement voids with different aging stage and its significance to drainage. *Construction and Building Materials*, *252*, Article 119085. https://doi.org/10.1016/j.conbuildmat.2020.119085

Zhang, F., Ju, Y., Dong, P., & Santibanez Gonzalez, E. D. R. (2020). A fuzzy evaluation and selection of construction and demolition waste utilization modes in Xi'an, China. *Waste Management & Research*, *38*, 792–801. https://doi.org/10.1177/0734242X20908925

Zhang, H., Li, H., Zhang, Y., Wang, D., Harvey, J., & Wang, H. (2018). Performance enhancement of porous asphalt pavement using red mud as alternative filler. *Construction and Building Materials*, *160*, 707–713. https://doi.org/10.1016/j.conbuildmat.2017.11.105

Zhu, X., Ye, F., Cai, Y., Birgisson, B., & Lee, K. (2019). Self-healing properties of ferrite-filled open-graded friction course (OGFC) asphalt mixture after moisture damage. *Journal of Cleaner Production*, *232*, 518–530. https://doi.org/10.1016/j.jclepro.2019.05.353