Incorporation of recycled concrete aggregate (RCA) fractions in semi-dense asphalt (SDA) pavements: Volumetrics, durability and mechanical properties

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HIGHLIGHTS

- Replacement my mass of various fractions of RCA in SDA mixtures.
- RCA coarse absorb binder and required more energy for compaction.
- RCA coarse and sand decreased the ITSR% and fracture energy in ITS loading.
- The rutting resistance improved with RCA coarse and sand a aggregate replacement.
- The RCA filler performance was very similar to the virgin filler.

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ABSTRACT

Recycled Concrete Aggregates (RCA) form a significant part of construction and demolition waste and its recycling is crucial for long-term construction sustainability. This study examined the incorporation of various fractions of RCA in Semi-Dense Asphalt (SDA) mixtures. The control SDA aggregates were replaced by RCA in selected fractions of 2/4 mm (coarse) and 0.125/2 mm (sand) at 100% and 50% each, and the filler at 100% of the fraction. The replacement was performed by mass with only one fraction being replaced for any single mixture. The mixtures were evaluated by their volumetrics, indirect tensile strength (ITS), water sensitivity (EN 12697-12), fracture energy and rutting resistance (EN 12697-22), in order to assess the effects of each RCA fraction on the mixture properties. The results showed that RCA coarse aggregates absorb significant amounts of binder and require more energy for compaction, which is not the case for the RCA sand or filler. The ITS results showed increased peak load for the RCA replacement samples but also increased brittleness in terms of resistance to crack initiation and propagation. RCA sand incorporation decreased the fracture energy at a higher rate than the coarse per total amount replaced. The ITSR% was similar to the control for lower amounts of RCA replacement, but significantly lower with higher replacement. The rutting resistance improved with RCA sand and especially coarse aggregate replacement. The study shows some limitations for use of RCA in asphalt mixtures, but also the potential for using them when the replacement rate is limited and replacement by volume is recommended. The RCA filler performance was very similar to the virgin filler, which makes its use in asphalt mixtures especially promising.

1. Introduction

Some of the greatest challenges to construction sustainability is the production and recycling of waste. For example, construction and demolition (C&D) waste accounts for 46% of total waste in the EU [1] and can be more than 80% in places like Switzerland [2]. Portland cement concrete (PCC) is the most produced material in the world, but with this, also comprises 60–70% of the C&D waste in the EU [3]. This concrete can be reused in the form of Recycled Concrete Aggregates (RCA), which is prepared through the crushing and grading of waste concrete [4], which can be wholly or partially used as a raw material in virgin concrete [5] or as backfill [6]. Due to the high volume of RCA produced exceeding the amount that can be placed back into the construction cycle

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finding uses for RCA is extremely important in maintaining the construction industry sustainable globally.

Solutions for using RCA need to consider the ability to incorporate them in high volumes, which makes their use in asphalt pavements, by replacing the virgin aggregates, a potentially fruitful area of study [8]. Usually, this has been done by partially replacing the bulk virgin aggregates with RCA aggregates of a similar gradation at a certain percentage [9]. The principal benefits of using RCA in asphalt mixtures is reducing bulk landfilled waste while at the same time reducing the use of virgin mined materials that are normally used as the aggregates [10].

However, the performance of RCA replacement in asphalt mixtures has shown some weaknesses. The most significant one is moisture resistance where asphalt mixtures containing RCA have been shown significantly worse performance than conventional ones [11,12]. Other results have been mixed, with some finding improvements in terms of asphalt mixture rutting [12] and fatigue resistance [13,14] with RCA replacement, while other studies have come to the opposite conclusions [15,16]. The importance of limiting RCA replacement has been shown, as these performance trends will also vary with the amount of RCA used [17].

RCA consists primarily of aggregates and the cement paste covering them. The RCA quality will vary based on gradation, mineralogy and the quality of cement paste [18]. An innovative way to address this is the separation of the RCA into different fractions. Some promising results have been found so far with RCA filler (sieved from the bulk material) replacement being shown to improve rutting and fatigue resistance [19], as well as similar cement-based waste fillers [20]. Replacing asphalt mixture aggregates by fraction has been applied successfully in a study with quarry waste materials in asphalt [21] and recycled asphalt pavement (RAP) in PCC [22].

Semi-Dense Asphalt (SDA) is a type of asphalt mixture, which is commonly used in Switzerland to reduce pavement noise generation [23]. SDA is composed of relatively more high quality aggregates and polymer modified binder to compensate for the strength loss from the elevated air void content [24]. Therefore, the addition of waste materials that could potentially be of lower quality, presents challenges. However, the special gradation of the mixture means that it has to consist of selected gap graded aggregate fractions. This presents an opportunity to observe how selected fractions of RCA can perform in an SDA mixture, specifically in terms of water sensitivity and rutting resistance, the water sensitivity being used as a performance threshold according to the Swiss standards 640 431-1c-NA [25].

The experimental program was designed to replace the virgin aggregates of an SDA by RCA in selected fractions of 2/4, 0.125/2 and 0/0.125 mm, replacing coarse aggregates, sand and filler, respectively, at 100% and 50%. Only one fraction was replaced for any single mixture while the air voids % and binder % were kept respectively, at 100% and 50%. Only one fraction was replaced for any single mixture while the air voids % and binder % were kept constant. These mixtures were then evaluated for their volumetric properties, compactability and mechanical properties/durability. The mechanical properties/durability by indirect tensile strength, moisture resistance [26] and wheel tracking test (WTT) rutting resistance [27].

The primary significance of the experimental program is the observation of the effect of each RCA fraction on the volumetric and mechanical properties of the resulting mixture, potentially helping to take advantage of the benefits of graded RCA fractions economically as well as mechanically. This would allow for the more effective recycling of RCA in new materials, and more acceptance as an alternative material for asphalt. Of secondary significance are the evaluation of RCA in higher porosity asphalt and using fracture energy – calculated through two different methods – in assessing the water sensitivity of the mixtures.

2. Materials and methods

2.1. Materials

The binder used for the asphalt mixture was an SBS (styrene-butadiene-styrene) polymer modified binder (PmB) graded at 45/80 – 65 according to EN 1426 [28]. Polymer modified binder is part of the requirements for SDA in the Swiss standards SN 640 436 [29]. The control aggregates (Fig. 1) were quarried sandstone with a 25–30% quartz content from the company FAMSA (Massongex, Switzerland). The RCA (Fig. 2) was concrete plant waste from the company FBB (Hinwil, Switzerland), coming from the excess of various mixes from the Canton of Zurich region and containing a variety of different minerals. The RCA was sieved into the fractions of 2/4, 0.125/2 and 0/0.125 mm, corresponding to the 2/4, 0.063/4 mm and filler fractions of the FAMSA control aggregate, respectively. Both of the 2/4 aggregates were also washed to removed loose dust/dirt particles, as it is important for adequate aggregate adhesion [30].

The mixture used for this testing was Semi-Dense Asphalt (SDA 4–16), currently a commonly used gap graded mixture in Switzerland, primarily as a noise abatement measure. The maximum aggregate size was 4 mm and the air voids content was 16 ± 2% (SN 640 436).

The aggregates were divided into 3 fractions corresponding to coarse aggregates, sand and filler: 2/4, 0.063/4, filler from the control aggregate; 2/4, 0.125/2, 0/0.125 for the RCA, respectively. The apparent and relative aggregate densities were determined by EN 1097-6 (by gas pycnometer for the filler) and are shown in Table 1, along with the sand equivalent and flow indices for the sand. The bulk densities of the RCA were significantly lower than for the control aggregates, especially with regard to the coarse aggregates, which is consistent with previous studies on RCA aggregate fractions [34]. The apparent densities were also somewhat lower for the RCA due to some proportion of these aggregates being cement paste. The cement mortar, which is present in a higher proportion in the coarse fraction, is more porous than the stone and absorbs more water [5].

For the sand fraction, the sand equivalent of the RCA was higher, indicating a lower presence of clay particles, which is due to the fact that the RCA sand was sieved in the lab while the control sand was received directly from the asphalt plant. The flow coefficients of the sands were similar, indicating similar shape characteristics, although both were higher than the sand flow standard material of 32 s, indicating some amount of angularity in both samples [35].

The RCA aggregates were replaced by weight (Fig. 3), with the gradation conforming to SDA 4–16 in SN 640 436 and determined according to EN 933-1 [36]. The asphalt binder content was 5.7%, increasing to 6.0% for the 63C when it became apparent that the mixture was dry. Nevertheless, the binder contents were kept similar despite more expected binder absorption, as asphalt binder is the most expensive part of asphalt pavement, and keeping the contents similar would give a better idea of the implications of RCA

![Fig. 1. Control sandstone aggregate fractions.](image-url)
replacement for asphalt producers. One fraction of the mixture (coarse, C, sand, S, or filler, F) was replaced at a time, with 50 and 100% replacement rates, for 1 control mixture and a total of 5 mixes with partial RCA replacement (Table 2).

2.2. Methods

The binder and aggregates were heated to 170 °C before mixing. The aggregates including the filler were added to the drum first and mixed for 5 min followed by the addition of the binder and another 5 min of mixing. The maximum relative density of the loose mixture was determined by EN 12697-5 [37] from two samples. The mixture was then compacted by gyratory compactor (Pine Instruments) at a temperature of 155 °C to a sample size of 99.5 ± 0.5 mm diameter and 64 ± 2 mm height with 16 ± 2% target air voids.

The bulk density of the sample was determined geometrically as is recommended for porous mixtures according to EN 12697-29 [38] due to the higher voids content preventing the samples having a stable saturated surface dry condition during conventional density measurement. The compactability of the asphalt mixture was determined by the Bahia et al. (1998) version of the Compaction Energy Index (CEI) [39]. It was adapted by Goh and You (2012) to mixtures with high air voids where the index was determined according to EN 12697-12, where a set of three samples each were used for the dry and wet conditions. The wet condition consisted of 70 ± 2 h of submersion in water at 40 °C. Within a certain range mixtures that have lower CEI are more desirable, but the index being too low indicates that it is difficult to compact the coarse RCA mixtures (i.e. higher CEI, more energy needed).

The indirect tensile strength (ITS) and water sensitivity were measured (i) by the pre and post cracking fracture energy method [42,43] and (ii) the CT (Crack Testing) index [44]. The fracture energy method calculated the area under a stress–strain curve before the maximum stress and after, and can be expressed in Pa or J/m² (Fig. 5). The pre-peak area is taken as the fracture energy (FE) and the post-peak area over the peak strain (εₚ), is taken as the post-fracture energy (PE). Their sum is known as the toughness. The CT index was calculated by taking the post peak slope of the load–displacement curve at between 85 and 65% of the maximum load as shown in the following Eq. (3):

\[ CT_{index} = \frac{t}{62} \times \frac{G_f}{(m_{75})^2} \times \frac{l_{75}}{D} \]  

where \( t \) is the thickness of the sample, \( G_f \) is the total area (fracture energy, FE) under the load–displacement curve, \( m_{75} \) is the post peak slope of the load–displacement curve between 85 and 65% of the maximum load, \( l_{75} \) is the displacement at 75% of the post peak load and \( D \) is the diameter of the sample [44]. These methods were also used to calculate the water sensitivity by determining the % ratio of wet to dry and compared with the classical ITS&R% method.

The rutting resistance of the mixtures was characterized by the Wheel Tracking Test (WTT) according to EN 12697-22. The test assesses the susceptibility of asphalt mixtures to deform by repeated passes of a loaded wheel at constant temperature of 60 °C. Two samples with dimensions 500 mm x 180 mm x 50 mm were compacted for each mixture using a steel wheel. The sample was then loaded with a solid rubber and treadles tire, with a diameter of 200 mm and a rectangular cross profile with a width of \( w = (50 \pm 5) \) mm for 30,000 passes, where each cycle consists of two passes (outward and return) of the loaded wheel. The mean rut depth was calculated using the recorded rut depth at 15 locations on the two samples.

3. Results and discussion

3.1. Asphalt mixture compactability and volumetrics

The compaction and volumetric properties of the asphalt mixtures are shown in Fig. 6 and Table 3, respectively. The compactability, expressed as a modified Compaction Energy Index (CEI, Fig. 3) is an indication of the energy needed to compact the mixture to a required density. As shown in Fig. 6, it was much more difficult to compact the coarse RCA mixtures (i.e. higher CEI, more energy was needed). This was especially the case for 63C, which

![Table 1: Physical properties of aggregates.](image-url)

| Aggregate Fraction | Apparent Density (kg/m³) | Bulk Density (kg/m³) | Water Abs. 24 h (%) | Sand Eq. (%) | Flow Coeff. (%) |
|--------------------|--------------------------|----------------------|---------------------|--------------|-----------------|
| FAMSA Filler       | 2729.3                   | –                    | –                   | –            | –               |
| FAMSA 0.063/4      | 2698.6                   | 2657.4               | 0.57                | –            | –               |
| FAMSA 2/4          | 2710.7                   | 2647.0               | 0.89                | 54           | 35.7            |
| RCA 0/0.125        | 2671.0                   | –                    | –                   | –            | –               |
| RCA 0.125/2        | 2654.4                   | 2439.2               | 3.32                | 89           | 35.0            |
| RCA 2/4            | 2609.3                   | 2297.4               | 5.20                | –            | –               |

* Determined by gas pycnometer.
was only able to be compacted to 17% air voids. The compaction was also more difficult with the RCA sand fraction, but to a much lesser extent, partially due to the lower replacement amount. The RCA filler replacement did not appear to have an effect on the compaction. The reason for the comparatively higher CEI for RCA modified mixtures is likely in the higher absorbed binder content as is typical for RCA [45,46], which resulted in less lubrication between the stones from the effective binder, but also due to the higher relative volume of RCA coarse aggregates and their lower density. The significantly higher compaction energy required for the coarse RCA suggests that they ultimately require a higher binder content and should be replaced by volume instead of by mass.

The mixture maximum density is reduced with RCA replacement, which is roughly proportional to the RCA replacement rate as found in other studies [46], whether for the coarse or the sand. This is due to the lower density of the RCA.

The voids in mineral aggregate (VMA), which refers to the intergranular void space of the compacted mixture, was lower for the mixtures with more coarse RCA. This is likely due to the higher volume of the coarse RCA fraction relative to the control coarse due to the mass replacement, reducing the intergranular void space as shown in the volumetric diagram in Fig. 7. Lower VMA values indicate that there may be a lower binder film thickness between the aggregates, which may result in lower durability properties [47].

The voids filled with asphalt (VFA), which is a measure of the proportion of the VMA filled with binder, was significantly lower with the coarse RCA, especially at maximum replacement. This was because of the lower availability of binder within the intergranular voids, as more of it was absorbed in the aggregates [46]. Both the VFA results and the high absorbed binder content shown in Table 3, indicate that more binder needs to be added to mixtures with coarse RCA. The RCA sand and filler performance was much more similar to the control mixture by the VMA and VFA measures, which also coincided with the binder absorption being the same for the control.

### 3.2. Indirect tensile strength and water sensitivity

The water sensitivity results are shown in Table 4, where the maximum indirect tensile strength (ITS) stresses are shown for the dry samples and for those after wet conditioning, with 3 samples tested for each case. In terms of ITS, the dry RCA samples had a higher strength than the control with the exception of RCA filler which had similar results to control. This could be from the higher compaction energy that went into the samples. However, this could also be due to more angularity in the aggregates, resulting in a more stable aggregate skeleton. It should also be noted that while the maximum ITS is higher as found previously [48], the peak from the curves is achieved much quicker in the samples with coarse RCA aggregate, especially for the 63C sample (Fig. 8). With more RCA, failure occurs at a lower strain in comparison to the control, indicating that they are less ductile.

In terms of the ITSR%, the 32C mixture performed almost as well as the control, the 63C sample was much more water sensitive when wet and dry mixtures were compared although the maximum load exceeded that of the control sample. The RCA sand samples also showed a decrease in ITSR% with higher replacement. This is similar to the results previously found in studies with RCA aggregate replacement [11,12], while the RCA filler replacement did not have such an effect as also previously reported [19]. The Swiss SN 640 431-1c prescribes a minimum of 70% ITSR% for asphalt mixtures. The poor performance of higher contents RCA in ITSR% is due to the lower effective binder content and film thickness from the higher binder absorption (see Fig. 7), allowing for more saturation of the mixture by the water, as indicated by the absorption rates in Table 1.

### 3.3. Fracture energy and CT index

The ductility of the samples were further analyzed by the fracture energy and CT Index described in Section 2.2. Higher fracture energy and CT Index indicate more ductile behavior. While the fracture energy factors is indicative of the energy needed to achieve the peak load and sample failure, the CT index takes the energy and also factors in the rapidity of the failure by factoring in the slope of the curve.

The Fracture Energy (FE) and Post-fracture Energy (PE) for the dry ITS samples are shown in Figs. 9 and 10, respectively. FE have been defined as the cracking resistance prior to micro crack development while PE has been defined as the resistance to crack propagation [43]. As the figures show, both the pre and post fracture energy is reduced with higher RCA %. This is due to RCA aggregates being more brittle as reported before [49] and confirmed when observing the higher level of aggregate fracture in the ITS samples (Fig. 11), especially with the coarse, but also to some degree with the larger sand particles.

A strong linear correlation exists between the coarse and sand RCA% and FE or PE reduction, with R² values between 0.97 and 0.98. The addition of the finer RCA materials (sand and filler) seems

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### Table 2

SDA 4 mixture composition.

| Mixture Type | Code | Control Fraction % | RCA Fraction % | Binder % |
|--------------|------|--------------------|----------------|----------|
|              |      | 2/4 | 0.063/4 | 2/4 | 0.125/2 | 0/0.125 | PmB 45/80 – 65 |
| Control SDA 4 | Con | 63.1 | 23.9 | 7.3 | — | — | 5.7 |
| 50 RCA 2/4 | 32C | 31.6 | 23.9 | 7.3 | 31.5 | — | 5.7 |
| 100 RCA 2/4 | 63C | — | 23.9 | 7.2 | 62.9 | — | 6.0 |
| 50 RCA 0.125/2 | 12S | 63.1 | 12.0 | 7.3 | — | 12.0 | 5.7 |
| 100 RCA 0.125/2 | 24S | 63.1 | — | 7.3 | — | 23.9 | — |
| 100 RCA 0/0.125 | 7F | 63.1 | 23.9 | — | — | — | 7.3 | 5.7 |

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![Graph showing gradation curves for RCA modified mixes compared with the limits for SDA 4–16 (SN 640 436).](image-url)
to increase the brittleness at a higher rate (steeper slope) than the coarse RCA.

The CT indexes for the mixtures are shown in Fig. 12. As with the fracture energy, the CT index is significantly reduced with RCA%. The reduction for the RCA sand seems to be higher compared to similar replacement quantities of coarse RCA as can be seen from the slopes in the curves. The relationship between the CT index and RCA% appears to be more non-linear. The low index for the highest coarse RCA% is due to the very steep post-peak slope of the sample, suggesting that cracking would propagate very quickly once initiated. The authors of the CT index have shown it to be very sensitive to any waste materials in asphalt such as

![Fig. 4. Modified Compaction Energy Index (CEI in Gmm'N) at 82% Gmm based on Bahia et al., 1998 and Goh and You, 2012.](image)

![Fig. 5. Example of fracture energy density method applied to ITS stress–strain curve based on Park et al., 2015.](image)

![Fig. 6. Compactability of asphalt mixtures.](image)

![Fig. 7. Critical volume fractions of asphalt mixtures.](image)

| Sample | Max Load Dry (kPa) | Max Load Wet (kPa) | ITSR % |
|--------|--------------------|--------------------|--------|
| Control | 1127.3 | 915.0 | 81.2% |
| Std Dev | 43.9 | 15.7 | 79.6% |
| 32C | 1453.5 | 1157.8 | 79.6% |
| Std Dev | 66.8 | 8.7 | 79.6% |
| 63C | 1820.3 | 1063.0 | 58.4% |
| Std Dev | 22.6 | 25.5 | 58.4% |
| 12S | 1339.3 | 1001.3 | 74.8% |
| Std Dev | 13.3 | 10.8 | 74.8% |
| 24S | 1292.9 | 811.2 | 62.7% |
| Std Dev | 10.1 | 83.9 | 62.7% |
| 7F | 1126.2 | 910.6 | 80.9% |
| Std Dev | 16.7 | 22.1 | 80.9% |

Table 4

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| Std Dev | 16.7 | 22.1 | 80.9% |

Table 3

| Sample | RCA% | Max. Density (kg/m³) | Bulk Density (kg/m³) | Air Voids % | VMA % | VFA % | Abs. Binder % | Eff. Binder % |
|--------|------|----------------------|----------------------|-------------|------|------|---------------|---------------|
| Control | 0 | 2475.2 | 2087.1 | 15.7 | 25.9 | 39.5 | 0.7 | 5.0 |
| Std Dev | 7.0 | 2.8 | 0.1 | 0.1 | 0.2 |
| 32C | 31.5 | 2432.6 | 2041.3 | 16.1 | 23.9 | 32.6 | 1.9 | 3.9 |
| Std Dev | 9.2 | 4.5 | 0.2 | 0.2 | 0.3 |
| 63C | 62.9 | 2399.5 | 1991.8 | 17.0 | 22.3 | 23.7 | 3.5 | 2.7 |
| Std Dev | 0.0 | 4.1 | 0.2 | 0.2 | 0.2 |
| 12S | 12.0 | 2445.8 | 2053.5 | 16.0 | 26.3 | 39.0 | 0.6 | 5.1 |
| Std Dev | 3.9 | 10.7 | 0.4 | 0.4 | 0.8 |
| 24S | 23.9 | 2436.8 | 2041.5 | 16.2 | 25.9 | 37.4 | 0.9 | 4.9 |
| Std Dev | 1.2 | 3.8 | 0.2 | 0.1 | 0.3 |
| 7F | 7.3 | 2459.0 | 2069.0 | 15.9 | 26.3 | 39.8 | 0.6 | 5.2 |
| Std Dev | 1.7 | 1.9 | 0.1 | 0.1 | 0.1 |

Quantities % of total mixture mass unless indicated otherwise.

* % of VMA

b % of total aggregates.
Reclaimed Asphalt Pavement (RAP) or Reclaimed Asphalt Shingles (RAS) [44]. Ultimately, both the results for the fracture energy and the CT index confirm the need to limit RCA replacement due to the brittleness and crack resistance considerations, which could make the resulting asphalt pavement susceptible to cracking at higher RCA contents.

3.4. Water sensitivity based on fracture energy

The water sensitivity of the asphalt samples can also be examined through the fracture energy of the samples based on the percent difference of the FE, PE and CT index before and after water conditioning (Table 5), as in Eq. (2). Based on the FE and PE, the water conditioning has a much lower effect on the mixes overall than shown with the classic ITSR% analysis (Fig. 13). In the case of the 12S and 7F, the FE increases after water conditioning. This may be due to some hydration of unhydrated cement paste during the water conditioning process in the case of the RCA filler. This method clearly shows that the higher sand replacement levels of RCA sand and coarse aggregates are significantly more affected by the water.

The PE analysis shows similar results with the FE, with the exception of the 63C result, where the water did not show a significant effect. This can be attributed to the PE values being so low already and thus, not being able to be significantly more deteriorated by the presence of water. FE and PE water sensitivity seem to be a relevant compliment to ITSR% water sensitivity, and is more robust than merely relying on the maximum load in ITS. Looking at the water sensitivity ratio is not enough with either analysis method, as very weak samples can produced very good results in

Fig. 8. Loading Curves for Water Sensitivity test.
3.5. Wheel tracking rutting resistance

The rutting resistance of the mixtures was characterized by WTT, with the results shown in Table 6 and Fig. 14. The test was conducted on each mixture, except for the 63C, which was found to crack during the compaction process. This was due to the same compaction issues with the gyratory compactor, where too much binder was absorbed, and the volume of the RCA coarse aggregates was too high to be incorporated in the mix design, as can also be seen in Fig. 7. This means that the RCA content in this mixture is too high for the mixture to be considered viable. Two samples were tested for each remaining mixture, except for 7F, where only one sample was produced due to a shortage of material.

The mixtures with coarse and sand RCA replacement improved the rutting resistance after 30,000 passes compared to the control, where the rutting was at almost 8% of the original sample's height. The 32C mixture showed the best performance at around 4.5% of rutting depth ratio, while the 12S and 24S mixtures with RCA sand had around 6 and 7%, respectively. This was despite the RCA mixtures having a higher air voids than the control. The result is due to a higher difficulty in compaction with the RCA corresponding to rutting resistance, possibly related to better aggregate interlocking, although the interlocking has generally been found to be worse with RCA [9]. The sample with the RCA filler replacement, however, performed the same as the control in rutting. The standard requires that the rutting % after 30,000 cycles be reported but no limits are defined.

The improved rutting performance can be attributed to a general stiffening of the mixture from RCA replacement, especially the coarse, which was also found in the compaction and the ITS results. This is from the coarse RCA reducing the binder content on one hand [50], and the aggregates taking up a higher volume in the mixture due to their lower density and being replaced by mass, which is why the rutting decreases with higher RCA%. Increasing the aggregate volume can be a way to improve the rutting resistance of a mixture, but may create issues with other durability properties, as found from the cracking and ITSR% results earlier. The RCA filler performed the most similar to the control sandstone. In this case, this can be interpreted as a positive result from an ecological footprint point of view, due to the RCA filler being a waste material. From Fig. 14, the rutting samples follow a similar trend in their increased rutting with the increase in passes. The curve for 12S sample was not able to be produced due to measurement issues early in the test.

4. Conclusions

This paper studied the volumetric, durability and mechanical properties of asphalt mixtures, incorporating various RCA fractions. The conclusions are as follows:

- RCA replacement lowers the density of asphalt mixtures, especially with the coarse fraction.
RCA coarse aggregates absorb significant amount of binder, whereas the sand and filler RCA fractions are not very different from the control. The replacement by mass of coarse RCA aggregates results in significantly more energy required for compaction, somewhat higher in the case of RCA sand and no difference in the case of RCA filler. This increase can make the production of SDA samples very challenging for a test such as WTT. Therefore replacement by volume is recommended.

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- RCA replacement by mass can result in a higher maximum ITS, but also result in a comparatively less ductile mixture which is less resistance to crack initiation and propagation, due to the brittleness of the RCA. However, the RCA filler replacement does not have such a significant effect on this property.
- The water sensitivity of the asphalt mixes is lowered by higher levels of RCA replacement but show little or no reduction at lower levels (<20% by weight of aggregates) of replacement.
- The rutting resistance increases with the replacement of RCA sand and especially coarse aggregates, where the rutting with 32% RCA can be almost halved compared to the control.
- The CT index is much more sensitive to RCA replacement than fracture energy (FE or PE) and is overly sensitive when looking at water sensitivity.
- Fracture energy analysis should be considered as a compliment to the maximum ITS when evaluating water sensitivity.
- Based on results obtained in this work, RCA complete filler replacement is recommended as a waste reduction measure that also saves natural resources.

CRediT authorship contribution statement

Peter Mikhailenko: Conceptualization, Methodology, Investigation, Visualization, Writing - original draft, Writing - review & editing. Muhammad Rafiq Kakar: Investigation, Methodology, Writing - review & editing. Zheng Yin: Investigation, Writing - review & editing. Moises Bueno: Investigation, Writing - review & editing. Lily Poulikakos: Conceptualization, Writing - review & editing, Project administration, Funding acquisition.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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