# A Sustainable Pavement Concrete using Warm Mix Asphalt and Hydrated Lime Treated Recycled Concrete Aggregates

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## Abstract

Recently, increasing material prices coupled with more acute environmental awareness and the implementation of regulation has driven a strong movement toward the adoption of sustainable construction technology. In the pavement industry, using low temperature asphalt mixes and recycled concrete aggregate are viewed as effective engineering solutions to address the challenges posed by climate change and sustainable development. However, to date, no research has investigated these two factors simultaneously for pavement material. This paper reports on initial work which attempts to address this shortcoming. At first, a novel treatment method is used to improve the quality of recycled concrete coarse aggregates. Thereafter, the treated recycled aggregates were used in warm mix asphalt at varied rates to replace virgin raw coarse aggregates. The asphalt concrete mixes produced were tested for modulus, tensile strength, permanent deformation, moisture susceptibility and fatigue life. The comparison of these properties with that of the mixes using the same rates of untreated course aggregates from the same source has demonstrated the effectiveness of the new technology. Lastly, the cost, material and energy saving implications are discussed.

Keywords: Sustainable asphalt pavement, Warm mix asphalt, Recycled concrete aggregates, Hydrated lime, Mechanical properties.

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## Introduction

Global warming and consequent climate change have become an increasing threat to the environment and most species of plant and animals. Adapting to climate change is not just a matter of managing the risks, but more importantly to take the opportunity to develop new, innovative infrastructure systems and services. Adaptation to, and mitigation against, climate change provides opportunities in the new Green Economy (RAE, 2010). The increasing use of fossil fuels for energy is one of the most significant reasons for global warming. The increase of global population, economic growth and urbanization have been driving the demands for all kinds of natural resources. The European Commission has set actions in four key areas, with the aim of decoupling economic growth from the use of resources, support the shift towards a low carbon economy, and modernize the EU’s transport sector and promote energy efficiency. These are: 1. boost economic performance while reducing resource use; 2. identify and create new opportunities for economic growth and greater innovation and boost the EU's competitiveness; 3. ensure security of supply of essential resources; 4. fight against climate change and limit the environmental impacts of resource use (Herczeg et al., 2014).

The pavement construction sector plays a key role in contributing to the factors attributing to global warming. It was estimated by Al-Bayati et al. (2018) that a 1 km long x 10 m wide x 150 mm thick flexible pavement needs about 3750 t Hot Mix Asphalt (HMA) and 12,500 t of natural aggregates. In an effort to save cost, since the mid 1990’s, a range of techniques have been developed to reduce mixing and laying temperatures, and hence the energy consumption of the manufacture of HMA (EAPA, 2010). The discovery of Warm Mix Asphalt (WMA) began in the 1950’s, with foamed asphalt. Since 2007 the implementation of WMA has steadily increased in practical applications (Buss, 2014). WMA is produced and mixed at temperatures in the range 100-140 °C compared to the 120-190 °C required by HMA. The relatively low mixing temperature reduces the energy consumption to heat the aggregates and produces lower emissions. It therefore also helps to improve the working conditions for pavement construction.

Purushothaman et al. (2014) estimate that the construction industry produces about 1183 million metric tons of construction and demolition wastes each year worldwide, in which concrete waste is the most significant proportion. The management of such huge quantities of waste has become a serious challenge to landfill capacity and environmental sustainability.

Recycling this waste and using it in new construction has been regarded a viable solution for the sake of sustainable development.

Using recycled concrete aggregate (RCA) in Hot Mix Asphalt pavements has steadily generated research interest since entering the 21st century. A general finding has been that using RCA to replace the virgin coarse aggregate (VCA) results in increased permanent deformation (Lee et al., 2012) due to increased binder consumption (Motter et al., 2015). High binder consumption is attributed to the existence of the adhered mortar layer on the surface of RCA. RCA is a composite material, which consists of original natural course and fine aggregates and cement mortar. The original natural aggregates take about 65~70% of the total weight of the composite and the mortar takes about 30~35% (Al-Bayati et al., 2018). The cement mortar has a higher porosity and lower density than the original natural aggregates (Malesev et al., 2010). A study using 100% RCA has showed that HMA concrete has a low bulk density, and resilient modulus, but a high air void (Paranavithana and Mohajerani, 2006). Conversely, the crushing process for RCA may deteriorate the bonding strength between the mortar and the original natural aggregates and increase microcracks in the RCA (Lee et al., 2012). To enhance the low quality of the physical and mechanical properties of RCA, considerable research has been conducted into using various treatment methods and procedures to make improvements (Al-Bayati et al., 2018). These treatment technologies may be classified in two groups. The first one aims to maximize adhered mortar removal, while the second one focuses to improve the quality of the adhered mortar layer, for which a general method is the surface treatment (coating/impregnation) using binding materials, such as reactive pozzolanic materials (Li et al., 2009) and polymers (Kou and Poon, 2010).

So far, almost all of the reported research using RCA in pavement applications were focused on HMA. Research using RCA and WMA together for pavement concrete has not yet appeared in the literature. To pursue impact on environmental significance, this paper reports research using both RCA and WMA for pavement concrete. Previous studies by Al-Tameemi et al. (2016, 2017) demonstrated the superior benefits to mechanical properties and durability using hydrated lime in HMA, compared to other minerals such as fly ash. This paper investigates a novel method using hydrated lime to improve the porosity and reactivity of recycled aggregates to enhance the bonding between the RCA and asphalt cement.

# 1. Specimen Preparation

## 1.1. Raw Materials

The raw materials used in this study were asphalt cement, coarse aggregates, fine aggregates, mineral filler and additive. The properties of these materials are given below.

- **Asphalt cement**

The asphalt cement was supplied by Doura refinery in the Southwest of Baghdad, which was tested for the Superpave performance grade requirement. Table 1 lists the test results showing that the asphalt cement reached the grade of PG 64-16.

Table 1. Physical properties of asphalt cement.

| Binder | Properties | Temperature Measured °C | Measured Parameters | Specification Requirements, AASHTO M320-05 |
|---|---|---|---|---|
| Original | Flash Point (°C) | - | 298 | 230 °C, min |
| | Viscosity at 135 °C (Pa.s) | - | 0.487 | 3 Pa.s, max |
| | DSR, G/sinδ at 10 rad/s (kPa) | 58 | 3.3522 | 1.00 kPa, min |
| | | 64 | 2.020 | |
| | | 70 | 0.889 | |
| RTFO Aged | Mass Loss (%) | - | 0.654 | 1%, max |
| | DSR, G/sinδ at 10 rad/s (kPa) | 58 | 4.1596 | 2.2 kPa, min |
| | | 64 | 3.1483 | |
| | | 70 | 1.9809 | |
| PAV Aged | DSR, G.sinδ at 10 rad/s (kPa) | 28 | 4684 | 5000 kPa, max |
| | | 25 | 6477 | |
| | BBR, Creep Stiffness (MPa) | -6 | 134.0 | 300 MPa, max |

- **Aggregates**

Both virgin coarse aggregates (VCA) and recycled concrete coarse aggregates (RCA) were used in the designed asphalt concrete mixtures. The VCA were crushed quartz obtained from Al-Nibaie quarry in the North of Baghdad. The RCA were supplied by a concrete recycling factory in Alrathwanya district in Baghdad. They were crushed Texas T-wall barriers of an original designed compressive strength of 30 MPa (Fig. 1). The properties of the VCA and RCA aggregates are shown in Table 2, which also presents the virgin fine aggregate properties. The coarse and fine aggregates used in this work were sieved and recombined to meet the wearing course gradation specified by Iraqi State Corporation for Roads and Bridges (SCRB/R9, 2003). Fig. 2 shows the designed particle size distribution.

Figure 1. Texas T-wall and crushed aggregate.

Table 2. Physical properties of aggregates.

| Property | ASTM Design | Test Results | | SCRB Specification |
|---|---|---|---|---|
| | | VCA | RCA | |
| Coarse aggregate | | | | |
| Bulk specific gravity | C-127 | 2.632 | 2.331 | |
| Apparent specific gravity | | 2.636 | 2.501 | |
| Water absorption, (%) | | 0.261 | 2.91 | |
| Percent wear by Los Angeles abrasion, (%) | C-131 | 18 | 28 | 30 max |
| Soundness loss by sodium sulfate solution, (%) | C-88 | 4.3 | 6.1 | 12 max |
| Flat & elongated (5:1), (%) | D4791 | 4 | 8 | 10 max |
| Fractured pieces, (%) | D5821 | 97 | 100 | 90 min |
| Fine aggregate | | | | |
| Bulk specific gravity | C-128 | 2.561 | | |
| Apparent specific gravity | | 2.622 | | |
| Water absorption, (%) | | 0.809 | | |
| Sand equivalent (%) | D2419 | 59 | | 45 min |
| Clay lump and friable particles, (%) | C-142 | 1.2 | | 3 max. |

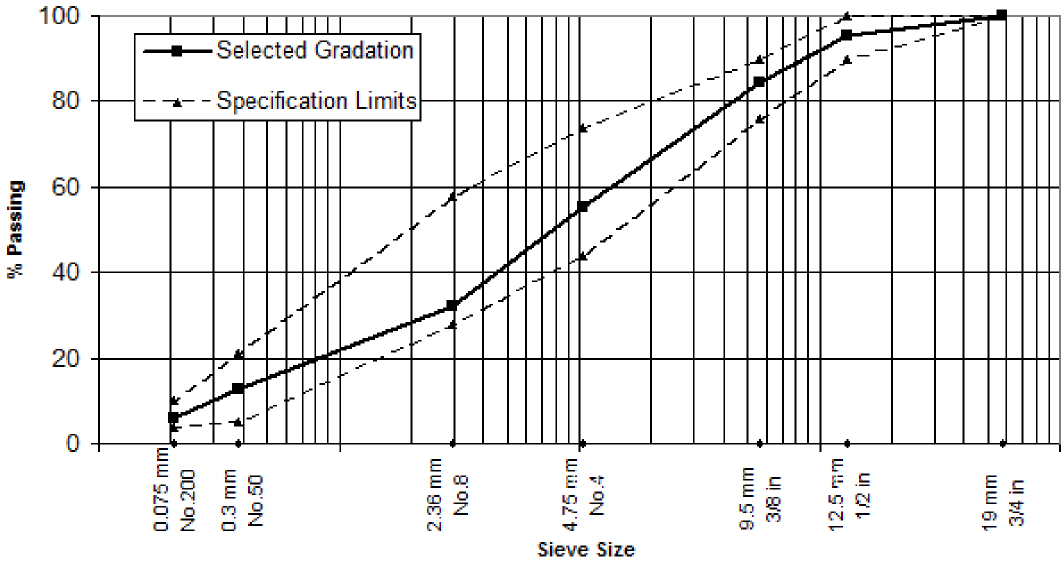



Figure 2. The particle size distribution of the aggregate.

- **Mineral Filler**

Limestone dust was used for the mineral filler. The chemical and physical properties of the limestone dust are listed in Table 3.

Table 3. Properties of mineral filler.

| Chemical Composition, % | | | | | | |
|---|---|---|---|---|---|---|
| CaO | $SiO_2$ | $Al_2O_3$ | MgO | $Fe_2O_3$ | $SO_3$ | L.O.I |
| 29 | 10 | 6 | 16 | 1 | 0.12 | 37 |
| Physical Properties | | | | | | |
| Specific Gravity | Surface Area* ($m^2$/kg) | Passing Sieve No. 200 (0.075) % | | | | |
| 284 | 247 | 95 | | | | |

* Blain air permeability method (ASTM C204)

- **WMA Additive**

Aspha-min ($Na_2O.Al_2O_3.2SiO_2$) powder was used as the additive to produce WMA. It is a Sodium Aluminosilicate hydrothermally crystallized into fine powder containing approximately 21% water by weight. The physical and chemical properties of the Aspha-min are listed in Table 4.

Table 4. Physical and chemical properties of WMA additive.

| Chemical Composition, % | |
|---|---|
| $SiO_2$ | 32.8 |
| $Al_2O_3$ | 29.1 |
| $Na_2O$ | 16.1 |
| L.O.I | 21.2 |
| Physical Property | |
| Color | White |
| Odor | Odorless |
| Specific Gravity | 2.03 |

- **Hydrated Lime Slurry**

Hydrated lime slurry of 1.5% concentration was used for the treatment of the RCA, the treatment procedure includes the marination of RCA in the hydrated lime slurry for 24 hours, thereafter the treated RCA were placed in an oven at a controlled temperature of 110 °C for four hours before being used for concrete mixes. The chemical and physical properties of the hydrated lime are listed in Table 5.

Table 5. Properties of hydrated lime.

<table>
<tr><td colspan="7">Chemical Composition, %</td></tr>
<tr><td>CaO</td><td>$SiO_2$</td><td>$Al_2O_3$</td><td>MgO</td><td>$Fe_2O_3$</td><td>$SO_3$</td><td>L.O.I</td></tr>
<tr><td>69</td><td>1.0</td><td>-</td><td>2.0</td><td>-</td><td>.150</td><td>27</td></tr>
<tr><td colspan="7">Physical Properties</td></tr>
<tr><td colspan="2">Specific Gravity ($g/cm^3$)</td><td colspan="2">Specific Surface Area ($m^2/kg$)</td><td colspan="3">Passing Sieve No. 200 (0.075) (%)</td></tr>
<tr><td colspan="2">2.43</td><td colspan="2">395</td><td colspan="3">99</td></tr>
</table>

## 2.2. Specimen Preparation

Six asphalt concrete mixtures were prepared using the RCA to replace the VCA. The replacement rates were 0, 20, 40, 60, 80 and 100% in terms of the weight of the VCA. Two sets of specimens were prepared. One set used the untreated RCA, which were labeled as WRU. The other one used the hydrated lime treated aggregates, which was labeled as WRT. The Marshall mix design method (ASTM D6926) was followed to determine the optimum asphalt content (OAC) for each mixture. Thereafter, the determined OAC was used in the preparation of the specimens for mechanical property tests.

Prepared aggregates together with the mineral filler were mixed in a bowl. Thereafter they were heated to a temperature of 120 °C for six hours. At the same time, asphalt cement was also heated separately at the controlled temperature of 155 °C for two hours to obtain a viscosity of 170 c.St in terms of the linear viscosity-temperature relationship characterized in Fig. 3. When doing the mixing, at first, the prepared Aspha-Min additive was added into the heated mixes of the aggregates and mineral filler at a proportion of 0.3% by the weight of the mixes, and blended thoroughly for approximately 30 seconds before a specified amount of asphalt cement was poured into the mixing bowl. Lastly, with the added asphalt cement, the mixtures were blended thoroughly for another two minutes. In the process, the temperature was controlled at 125 °C, which is 30 °C below the HMA temperature of 155 °C (as per the Aspha-Min technical specification). The container bowl and mixture were transferred to an oven at a controlled temperature of 115 °C for ten minutes. The mixture was then poured into prepared molds of the same temperature and compacted to make the specimens. The first type of mold was cylindrical with a size of 101.6 mm diameter x 76.2 mm height, which were used for the Marshall test and indirect splitting tensile test specimens. The second type of cylindrical mold had the same diameter but a height of 254 mm for the resilient modulus test and permanent deformation test specimens. The third type of mold was rectangular with the size of 76 mm width x 101.6 mm height x 381 mm length, which were used to make the prism specimens for the fatigue test.

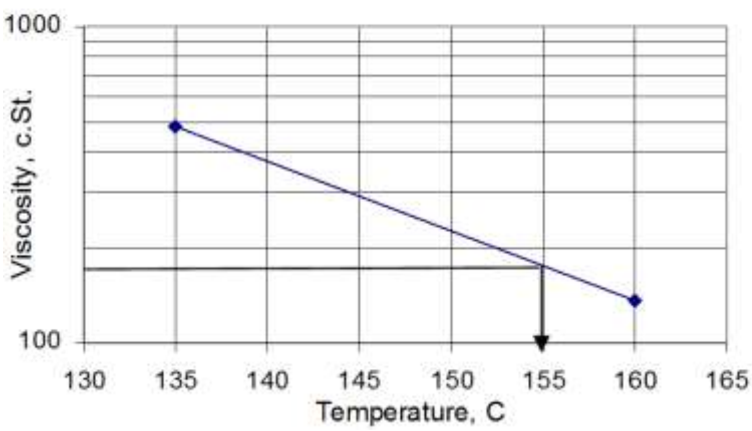
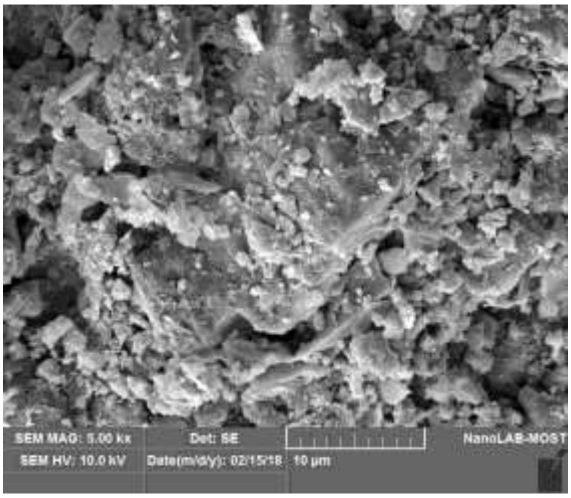


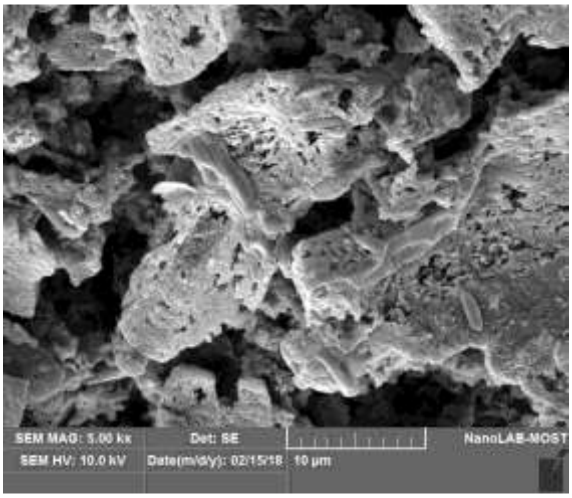

Figure 3. Viscosity – temperature chart of PG 64-16.

## 2. Experiments and Results

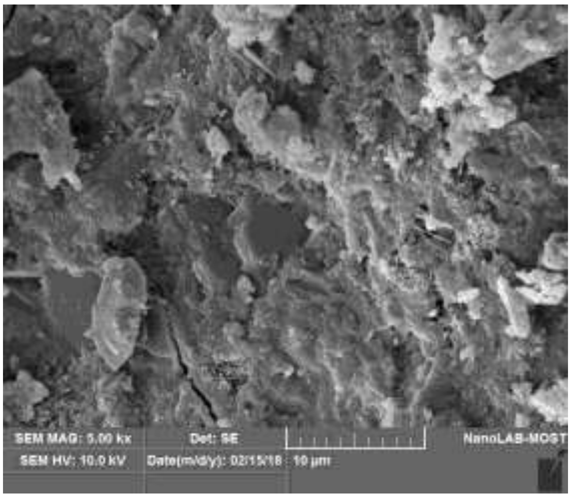
### 3.1. Scanning Electron Microscope (SEM) Analysis

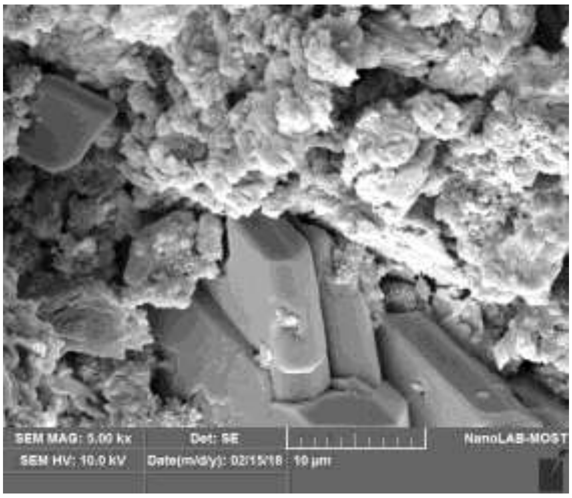
The microscopic texture of the coarse aggregates were investigated using SEM technology. Fig. 4 shows the 5k magnification SEM images of the two coarse aggregates under the conditions of untreated and treated using hydrated lime. It can be seen that untreated VCA shows a more intact microstructure of relatively large crystal phases with small quantities of varied Fine-Crystalline-Medium (FCM) particles. However, the untreated RCA presents a porous crystal structure with significant size of fractures between the crystal phases. A visual examination can conclude that the RCA has a much lower density than the VCA. After the hydrated lime treatment, the FCM particles in the VCA have been significantly reduced, the crystal structure becomes more integrated and smooth. The treated RCA also presents a considerable improvement on the microstructure with the size of crystal phases increased, and the crystal phases become much denser with significantly reduced porosity.




Untreated VCA    Untreated RCA



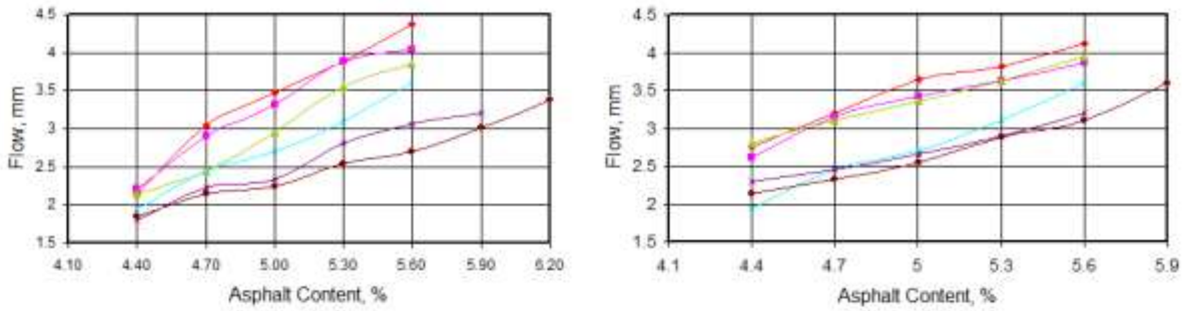

Treated VCA    Treated RCA

Figure 4. SEM images of the coarse aggregates used.

## 3.2. Marshall Test for OAC

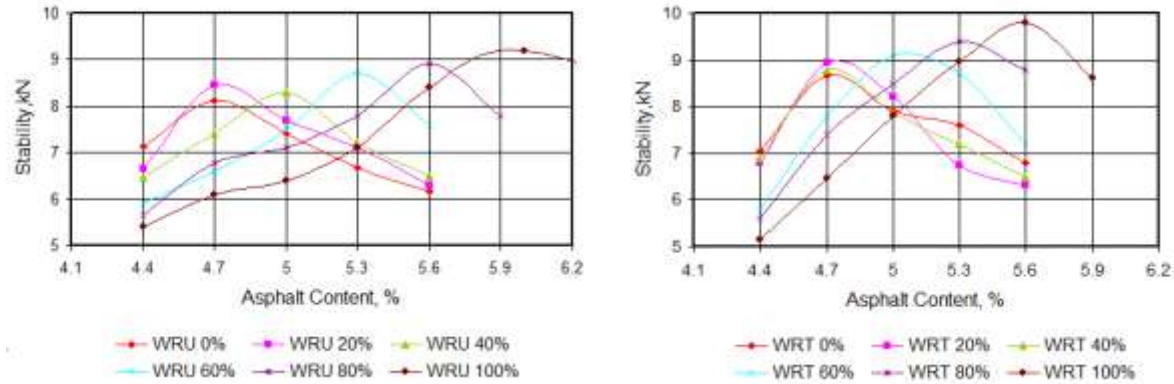
The Marshall test for the optimum asphalt content (OAC) determination was conducted according to the ASTM D6926 standard. Each of the designed mixes prepared following the procedures described in section 2.2 were compacted in the mold using the Marshall compactor. The designed mixes were compacted in the molds on their two ends, 75 times on each side to produce the specimens for test. For each of the aggregate mixes, five different asphalt contents were added, starting from 4.4% by the total mix weight with an increment rate of 0.3%. However, for the 80% WRU, 100% WRU and 100% WRT aggregate mixes extra asphalt contents were tested to obtain a clear variation trend of the chosen properties for the determination of OAC. They are 5.9% for 80% WRU and 100% WRT, and 5.9% and 6.2% for 100% WRU. Finally, the OAC was determined taking the average of the three asphalt cement contents corresponding to the maximum stability, maximum unit weight and 4% air voids, respectively (AI, 1981).

Fig. 5 shows the plastic flow and Marshall stability of the specimens at different added asphalt cement contents. The results indicate that plastic deformation increases with increase of asphalt content. However, all the WRU and WRT specimens satisfy the minimum stability requirement of 8 kN, specified in the SCRB at a certain range of asphalt contents. The specimen using 100% hydrated lime treated RCA (WRT 100%) achieved the highest stability, a result in agreement with previous studies (Wong et al, 2007; Pérez et al, 2012; Zulkati et al, 2012) and it could be attributed to the rougher surface of the RCA compared to the VCA. Comparing the average maximum stability values between the WRU and WRT specimens shows that the hydrated lime treatment increased the stability about 5.8% on average. The average flow value at the maximum stability values for the WRT specimens was slightly higher (3%) than that of the WRU specimens. However, all the plastic flow values at the maximum stability points satisfy the criterion range of 2~4 mm specified in the SCRB.




WRU WRT

(a) Plastic flow test results.

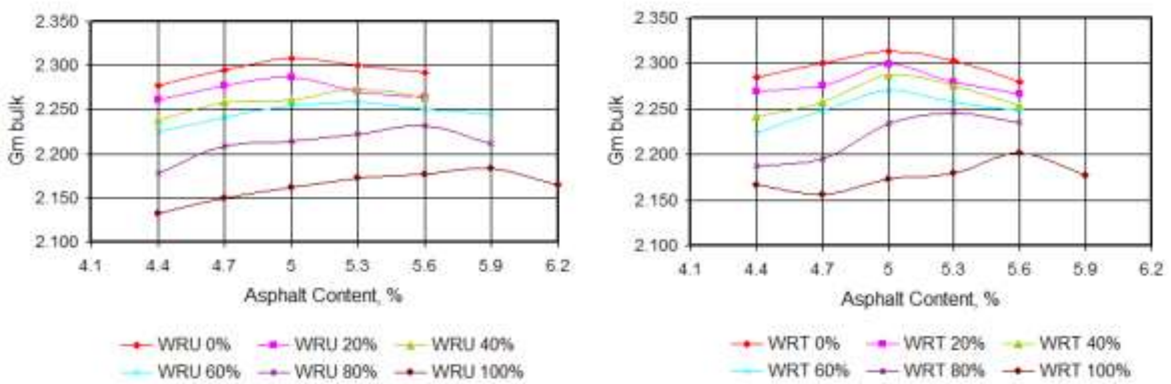



WRU WRT

(b) Marshall stability test results.

Figure 5. The Marshal stability-deformation properties.

Fig. 6 shows the measured bulk specific gravity of the specimens. Obvious maximum $G_{mbulk}$ values can be observed for all the mixtures in the range of the asphalt cement contents. It is clear that $G_{mbulk}$ values decrease with increasing use of RCA. However, the maximum $G_{mbulk}$ value is observed with increasing use of hydrated lime treated RCA compared to that using untreated RCA, at all the replacement rates. This result indicates that hydrated lime together with asphalt cement generate a reinforced grain phase which is denser than the untreated RCA.




WRU WRT

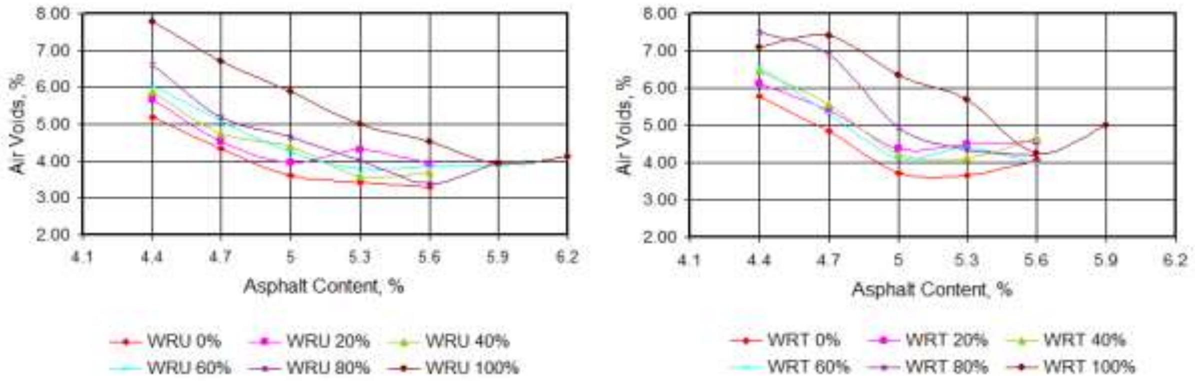
Figure 6. The bulk density, $G_{mbulk}$ (gm/cm$^3$).

Fig. 7 shows the void contents in the bulk specimens and the aggregates. The void content in aggregates is calculated using equation 1:

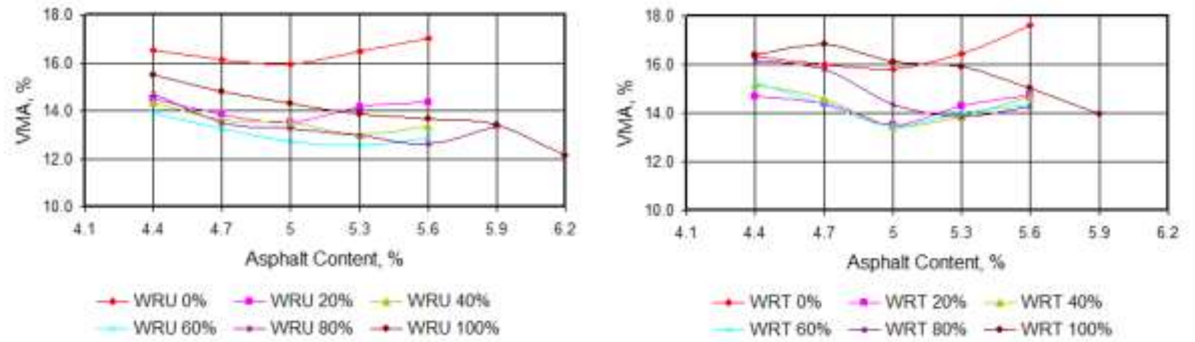
$$VMA = 100 - P_A G_{mbulk} / G_{Abulk} \quad (1)$$

where *VMA* is the voids in aggregate, $P_A$ is the aggregate mass percentage in the specimens, $G_{mbulk}$ is the bulk density of specimens, $G_{Abulk}$ is the bulk density of aggregates.

It can be seen that at the asphalt contents which yield the peak $G_{mbulk}$ values, the air voids content for the WRU and WRT with 100 % RCA was higher than for of 0 % RCA by 9 and 13 %, respectively. All the specimens have 3-5 % air void content at the asphalt content which yields the maximum $G_{mbulk}$. The VMA values show that treated RCA have a higher void content than untreated RCA. Comparing with the results shown in Fig. 6, where the specimens using treated RCA have a higher $G_{mbulk}$ than those using untreated RCA, suggests these results are contradictory. A logical explanation could be that the hydrated lime particles mainly enter and stay in the surface region of the treated aggregate. At the mixing stage, the reinforced surface region of the treated RCA, blocks the asphalt cement infiltrating deeply inside the RCA.




(a) The air void in specimens.




(b) The void in aggregates.

Figure 7. The tested volumetric properties.

Fig. 8 shows the OAC for the WRU and WRT mixes at all the RCA replacement rates. It can be noticed that OAC increases moderately with the increased use of RCA. However, the hydrated lime treated RCA requires less OAC than the untreated RCA when the RCA use rate is more than 20%. The result confirms the reasoning for the higher air void content of the WRT.

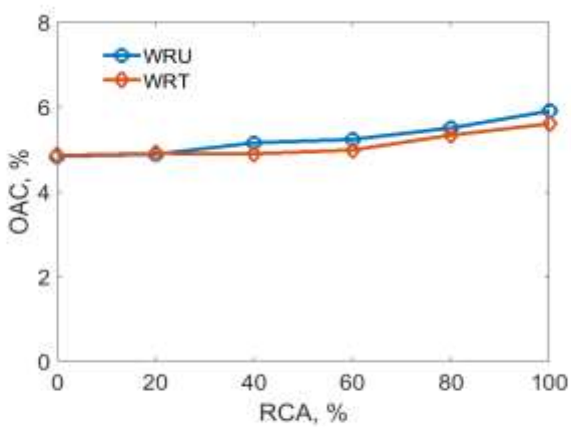



Figure 8. OAC vs RCA contents.

## 3.3. Mechanical Property Tests

- **Resilient Modulus**

Resilient modulus ($M_r$) was tested using the 101.6 mm diameter x 203.2 mm height cylindrical specimens. The specimens were prepared following a procedure described elsewhere (Albayati, 2006). In the test, specimens are subjected to repeated uniaxial compressive pressure applied by a pneumatic system. The compressive load was controlled at 137.9 kPa (20 psi) with a frequency of 1 Hz, in which the loading lasted for 0.1 sec. followed by 0.9 sec. rest. The temperature was controlled at 20 °C. The resilient modulus was calculated using equation 2:

$$M_r = \sigma/(r_d/h) \quad (2)$$

where $\sigma$ is the applied axial compressive stress, $r_d$ is the average axial resilient deflection measured at the load repetition of 50 to 100 using a LVDT (linear variable differential transformer), $h$ is the original height of the specimens.

Fig. 9(a) shows the measured $M_r$ results. It can be seen that the $M_r$ value decreases with increasing RCA replacement for both WRU and WRT specimens. However, the specimens using hydrated lime treated RCA have a higher resilience than those using the same rate of untreated RCA. The average improvement rate is about 7%. The obtained results for the WRU mixes were comparable with that found for the HMA concrete using RCA **(**Paranavithana and Mohajerani, 2006; Mills-Beale et al., 2010**)**. Fig. 9(b) shows that using hydrated lime treated aggregates gave improvements of the $M_r$ deterioration at most RCA rates.

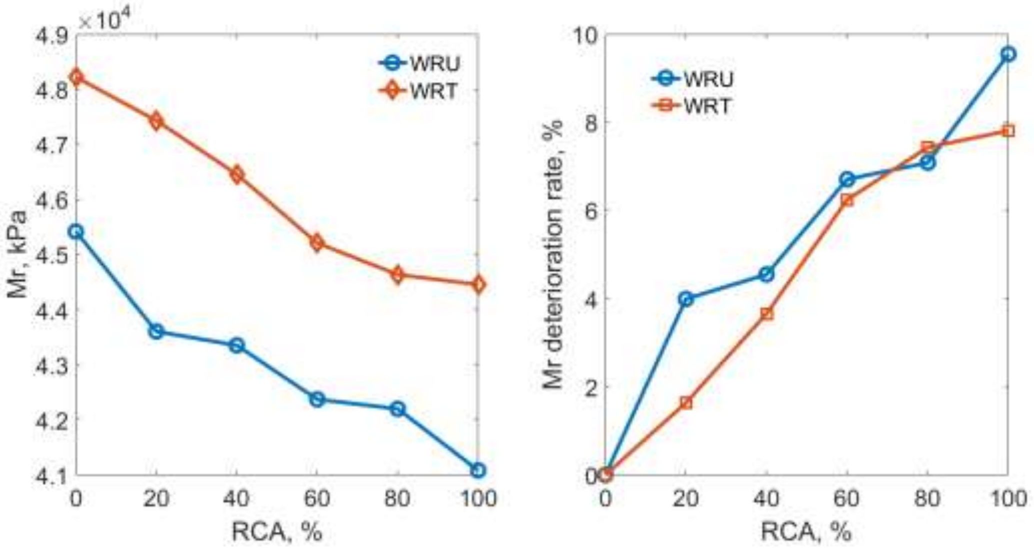
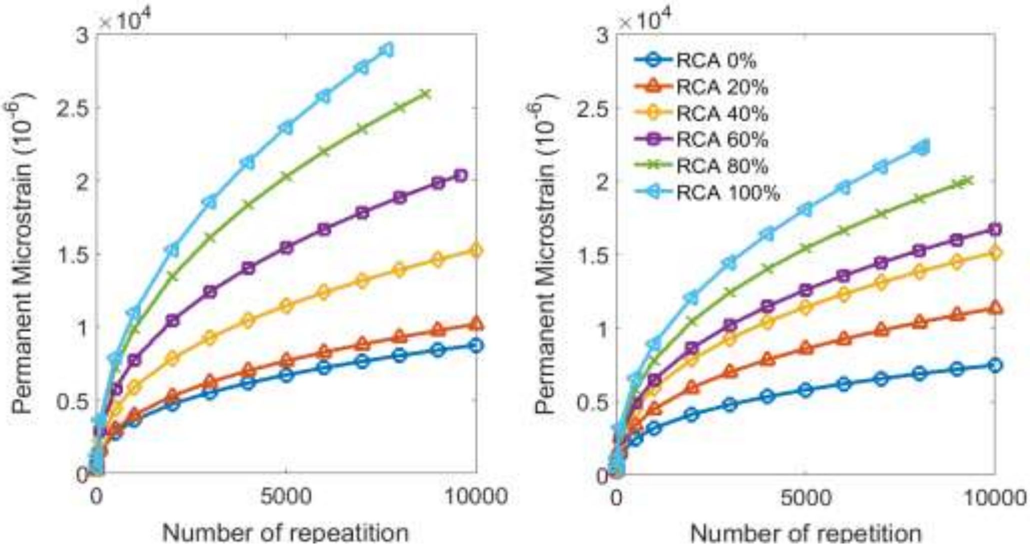



Figure 9. Resilient modulus and deterioration rate vs RCA contents.

- **Permanent Deformation**

Permanent deformation was tested using the same experimental set up for the resilient modulus described above. However, the specimens were under repeated cyclic loading until failure or the maximum of 10,000 load repetitions. The test temperature was controlled at 40 °C. Fig. 10 shows the calculated permanent microstrain in terms of the measured uniaxial permanent deformation at different load repetition numbers. It can be seen that permanent deformation increases with increased use of RCA. However, in most cases (except 20% RCA), the specimens using hydrated lime treated RCA present a lower permanent deformation than those using untreated RCA. The higher the use of RCA the greater the improvement using hydrated lime treatment. The specimens using 80% treated RCA had a similar permanent deformation to those using 60% untreated RCA. The results obtained for the WRU mixes are in agreement with those observed in previous HMA concrete research (Pourtahmasb and Karim, 2014; Mills-Beale and You, 2010; Bhusal and Wen, 2013). Fig. 11 compares the permanent strains at 5000 load repetitions, which shows the benefit of using hydrated lime treated aggregates at high RCA rates.




(a) WRU (b) WRT

Figure 10. Permanent microstrain vs load repetition.

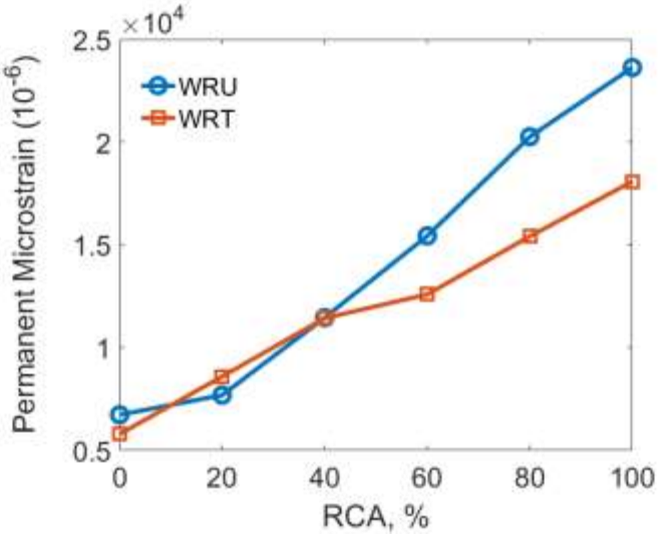



Figure 11. Comparison of the permanent strains at 5000 load repetitions.

### 3.4. Durability Tests

- **Moisture Susceptibility**

The evaluation of moisture susceptibility of all the mixtures followed the standard, ASTM-D-4867. For each mix of the designed RCA concretes, six specimens were prepared using the Marshall compaction method. The target air void (AV) content for the prepared specimens were in a range of 6~8%, which were achieved by compacting the cylindrical specimens (101.6 mm diameter x 63 mm height) with a number of blows ranging from 51 to 64 each side. The six specimens were evenly divided into two groups with three in each. One group, called unconditioned specimens, were test at 25 °C room temperature condition. The other group, called conditioned specimens, were put in a flask filled with water of a temperature of 25$^{o}$C. A vacuum of 70 kPa or 525 mmHg was applied for five minutes on the flask to achieve a saturation degree of 55~80%. Thereafter they were immediately subjected to a cycle of freezing and thawing by placing in -18 ± 2 °C condition for 16 hours instantly followed by 24 hours at 60 ± 1°C, before the testing procedure at 25 °C.

Fig. 12 shows the results of the moisture susceptibility test. The indirect tensile strength (*ITS*) and the tensile strength ratio (*TSR*) were calculated using equations 3 and 4:

$$ITS = 2P / (\pi h D) \quad (3)$$

$$TSR = ITS_C / ITS_{UC} \quad (4)$$

where $P$ is the splitting load, $h$ is the height of the cylindrical specimen, $D$ is the diameter of the specimen, $ITS_C$ is the conditioned indirect tensile strength, and $ITS_{UC}$ is the unconditioned indirect tensile strength. An interesting finding is that the tensile strength increases with the increase of the rate of RCA use, a result due to the rougher surface texture of RCA compared to that of VCA. Using treated RCA has a higher TSR (average 9% more) than using untreated RCA. Fig. 13 compares the splitting surfaces between the unconditioned specimens of 0% untreated RCA and 100% untreated RCA, respectively. It shows that the failure surface of the specimen using 100% RCA contains the broken RCA, however, the specimen using 0% RCA presents a failure surface only passing through the matrix of the binder.

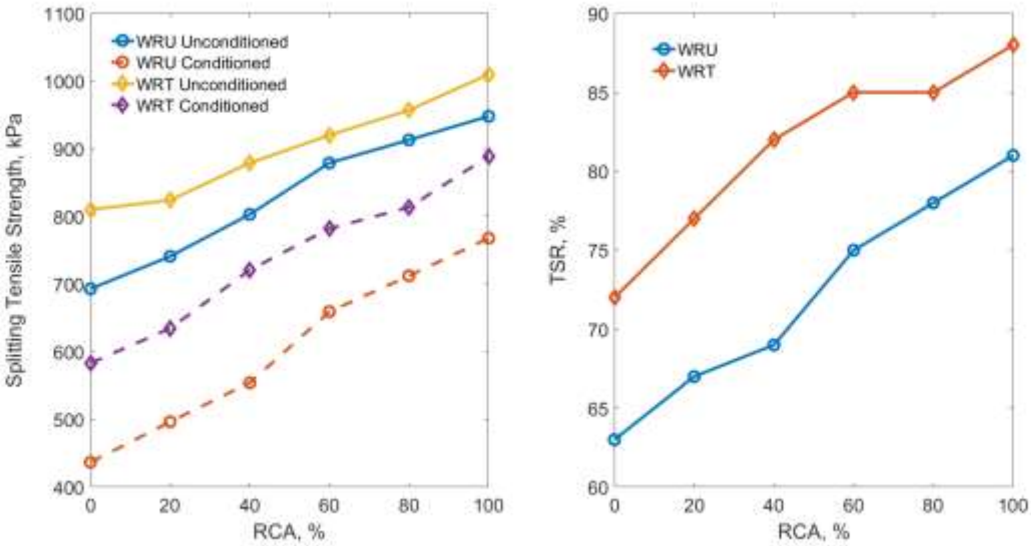



Figure 12. The results of the indirect splitting tensile test.

(a) 0% RCA. (b) 100% RCA.

Figure 13. Splitting surface of unconditioned samples

- **Flexural Fatigue**

Fatigue performance was evaluated using the two-point flexural bending test. Prism beam specimens of size 76 mm width × 76 mm depth × 381 mm length were prepared using the designed mixes following the procedure described by Alkishaab (2009). The fatigue test was conducted at a controlled temperature of 20°C. A pneumatic system was employed to apply the repetitive load. During the test, a controlled stress was applied to the specimen for 0.1 seconds, followed by 0.4 seconds unloaded rest. This gave a 2 Hz loading frequency. An initial vertical deflection at the bottom middle point of the tested beams was recorded at the 50$^{th}$ load repetition and the load repetition at failure of the beam specimens. Five different applied load stresses were tested. Fig. 14 plots the maximum load repetition number at failure of the specimens against the applied stress levels expressed in terms of the strain calculated according to the recorded deflection at the middle point, calculated using equation 5.

$$\varepsilon_t = 12h\Delta / (3L^2 - 4a^2) \quad (5)$$

where $\varepsilon_t$ is the initial tensile strain, $h$ is the height of the specimen, $\Delta$ is the recorded flexural deformation at the center of the specimen, $L$ is the span between the two beam supports, $a$ is the distance from the load to the support (one third of beam length).

Fig. 14 shows the fatigue test results plotted on a log-log scale, which compares the improvement using hydrated lime treated RCA with that using untreated RCA. The solid lines are the fitting results using a linear trend, $y = -C_1x + C_2$, to fit to these experimental data, respectively. Table 6 lists the fitting parameters obtained. Again, an interesting finding is that the specimens using RCA produced a better fatigue performance than those using VCR only (0% RCA) in almost all cases. However, comparing the WRU and WRT, it can be seen that using hydrated lime treated RCA produced a noticeable improvement over those using untreated RCA at the same RCA use rates. The improvement is particularly effective at low RCA use rates. The results for specimens using untreated RCA in this study are also comparable with those found by a previous study on the fatigue performance of HMA using RCA at different replacement rates (Nejad et al., 2013). The result justifies the effectiveness of the use of WMA technology in this study.

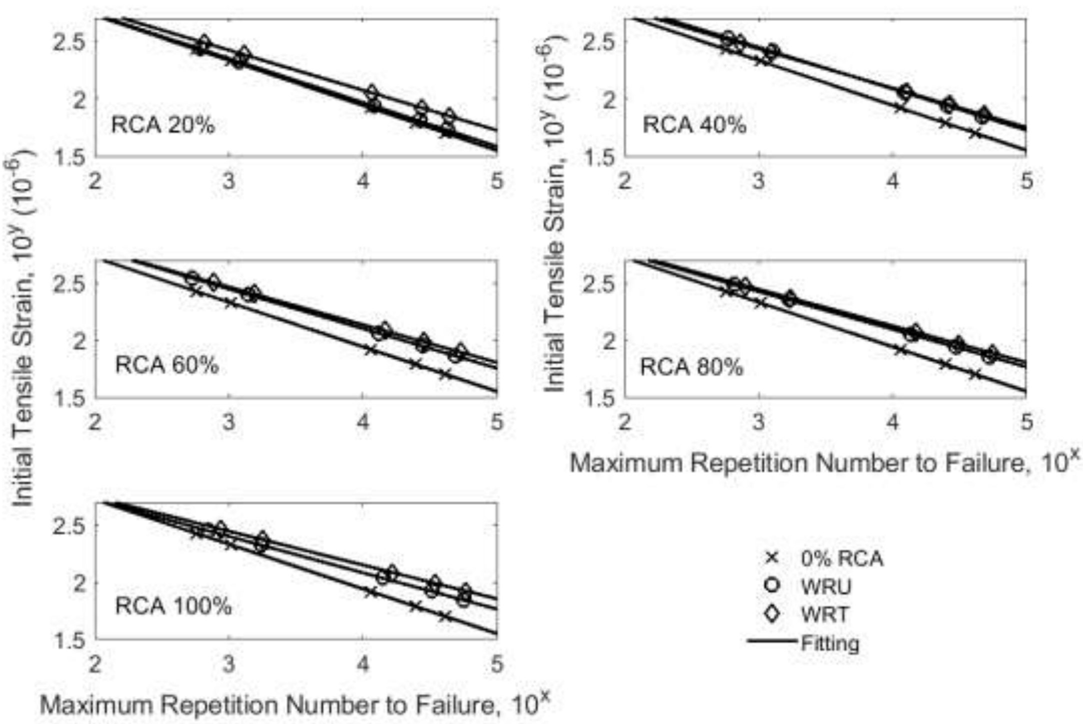



Figure 14. Fatigue test results.

Table 6. Linear fitting parameters for the measurements in Fig. 14.

| WRT | | WRU | | |
|---|---|---|---|---|
| $C_2$ | $C_1$ | $C_2$ | $C_1$ | RCA % |
| 3.51 | 0.392 | 3.51 | 0.392 | 0 |
| 3.47 | 0.349 | 3.5 | 0.383 | 20 |
| 3.46 | 0.342 | 3.53 | 0.361 | 40 |
| 3.46 | 0.331 | 3.49 | 0.347 | 60 |
| 3.41 | 0.321 | 3.42 | 0.331 | 80 |
| 3.34 | 0.297 | 3.36 | 0.319 | 100 |

Fig. 15 compares the fitting parameters $C_1$ and $C_2$ in Table 6. $C_1$ is the slope value of the trend while $C_2$ is the intercept value on initial tensile strain. A small $C_1$ indicates the flat trend with increasing load repetition number, which means that under a certain initial stain the fatigue life is longer. A small $C_2$ means the material has a low initial deformation or strain. The comparison confirms that using RCA will improve the fatigue performance of asphalt concrete. Fig. 16 illustrates the improvement using treated RCA (WRT) over that using untreated RCA (WRU), i.e., Improvement rate = |*C*(*WRT*)-*C*(*WRU*)|/*C*(*WRU*). The improvement on $C_1$ is much higher than $C_2$. So the use of hydrated lime treated RCA will offer the advantage of lower deformation at any loading condition.

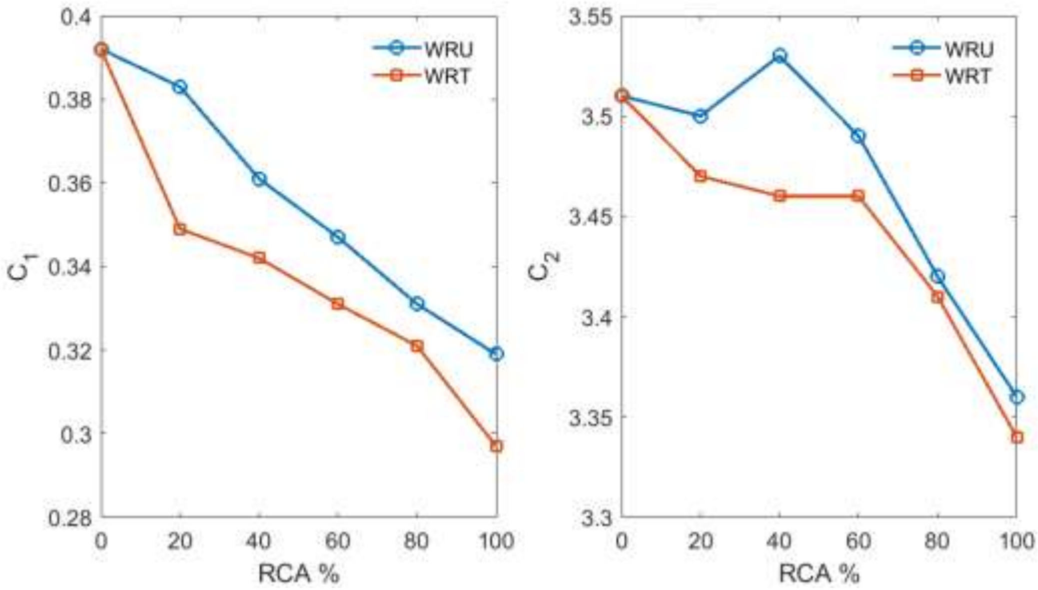


Figure. 15. The comparison of fitting parameters in the Table 6.

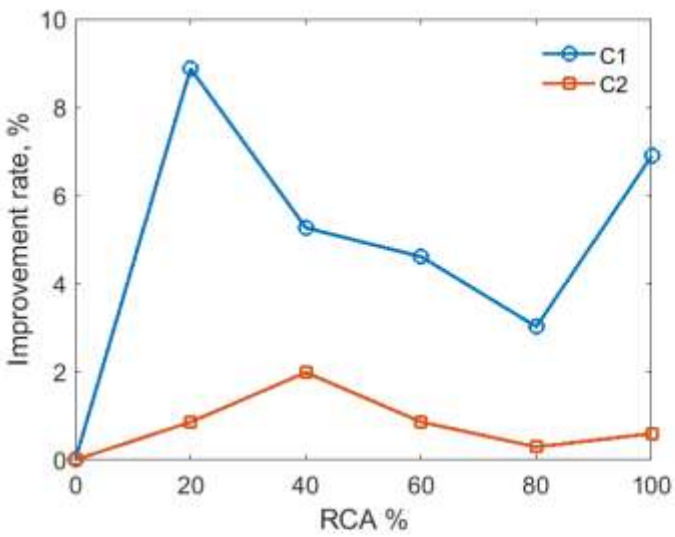


Figure. 16. The improvement of $C_1$ and $C_2$ of WRT over that of the WRU.

## 3. Cost, Material and Energy Saving Analysis

The total material costs of the asphalt concrete mixes were calculated referencing the local prices of raw materials as shown in the Table 7. Fig. 17 shows the comparison of the costs of one cubic meter mixes of different RCA rates. It can be seen that at the 20% RCA rate using hydrated lime treated aggregates produces the highest cost saving compared to using untreated aggregates. However, in terms of the cost saving rate (Fig. 18), which is defined as the ratio of cost saving to the cost of 0% RCA, it shows that at the rate of 40~60% RCA using hydrated lime treated aggregates is the most effective in cost saving compared to using untreated RCA at a saving rate of 4~6%.

Table 7. Reference prices of raw materials (STCCM, 2018).

| Reference Price, US$/ton | Raw Material |
|---|---|
| 11.00 | VCA |
| 4.00 | RCA |
| 8.16 | Fine Aggregate |
| 60.00 | Mineral Filler |
| 90.00 | Hydrated Lime |
| 270.00 | Asphalt Cement |
| 1,300.00 | Aspha-min |

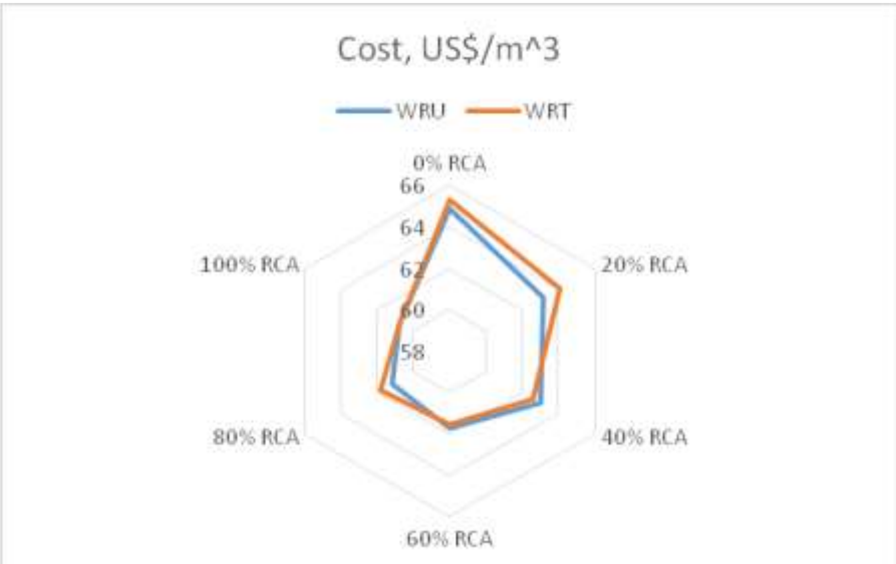



Figure 17. Comparison of mix costs.


Figure 18. Comparison of mix cost saving rates.

To illustrate the possible saving of virgin aggregates, taking an example of a 1 km long x 8 m wide x 50 mm thick pavement surface; the material savings on virgin aggregates are 374 tons at 100 % RCA usage or 78.4 tons at 20% RCA usage. These savings also imply a reduction in $CO_2$ footprint.

For asphalt concrete, the mixing temperature of WMA production is usually 30-60 °C lower than that of HMA production. It is estimated that this involves 30% less energy consumption which will result in corresponding lower $CO_2$ emissions (Sharma and Lee, 2017). Thus, it can be concluded that using 40% hydrated limed treated RCA for WMA concrete will obtain an optimum benefit on both material and economic performance, and environmental sustainability.

## 4. Conclusion

Novel initial experimental work has been reported in this paper to investigate using hydrated lime to treat RCA, and using the treated RCA together with WMA for sustainable pavement concrete. Based on this work, several encouraging conclusions can be drawn:

1. The treatment of RCA using hydrated lime to give a pre-infiltration can improve the mechanical quality of the recycled aggregate’s surface region by enhancing the density and reactivity.
2. Using RCA increases the plastic flow resistance, Marshall stability and air void content compared with those using virgin aggregate. Particularly, using treated RCA gives a

higher flow resistance and Marshall stability than using untreated RCA, but also retains a high air void content, which is a good characteristic for both mechanical properties and moisture susceptibility of pavement concrete mixtures.

3. Due to higher porosity, using RCA in general increases the OAC compared with that using virgin aggregate. Moreover, the OAC is less when using treated RCA, than using untreated RCA, particularly at high RCA use rate. A good characteristic for both mechanical and economic benefits.
4. Using RCA generally results in lower resilient modulus and higher permanent deformation (rutting) under the same load conditions than using virgin aggregate. However, using treated RCA will effectively reduce the deterioration degree compared to using untreated RCA, and the improvement effect is amplified at high RCA use rates.
5. An interesting finding in the study is that using RCA will, in general, improve the durability of asphalt concrete. Both moisture susceptibility and fatigue life increase with increasing RCA use rate. However, using treated RCA produced a better result than using untreated RCA. For example, at 100% RCA use rate, the $C_2 + C_1$ together is about 7.5% higher when using treated rather than untreated RCA.
6. Overall, this study has demonstrated that hydrate lime can effectively repair and improve the quality of recycled concrete aggregate and can be used for warm mix asphalt concrete. Using RCA for pavement construction has demonstrated economic and environmental benefits. However, results from this study suggest RCA application should be restricted to relatively light load conditions for maximum benefits in pavement durability. For heavy load applications, more research work is needed.

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