



## Mechanical and Durability Characteristics of Roller Compacted Geopolymer Concrete Using Reclaimed Asphalt Pavement

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### ABSTRACT

Every year a large quantity of reclaimed asphalt pavement (RAP) is generated in the USA. Utilization of RAP can solve the storage problem, prevent environmental pollution and reduce construction costs. This study focuses on the strength and durability characteristics of RAP mixtures by introducing the concept of roller-compacted fly ash-based geopolymer concrete (RCGPC). Several selected RCGPC mixtures were investigated to evaluate the effect of mixture variables, including sodium hydroxide (NaOH) molarity, sodium silicate ( $\text{Na}_2\text{SiO}_3$ ) to sodium hydroxide (NaOH) ratio on the strength, modulus and durability characteristics of the mixtures. The effects of different curing temperature and curing duration on compressive strength were also studied. It was found that the mixtures with  $\text{Na}_2\text{SiO}_3/\text{NaOH}$  ratio of 1 yielded about 12 % higher compressive strength than the ratio of 0. Further, the mixtures using 10M NaOH and alkali ratio of 1 produced about 25% higher compressive strength than 8M NaOH which produced about 17 MPa. Similar results were obtained for elastic modulus and split tensile strength of the mixtures. Freeze-thaw durability tests also revealed acceptable results for the RCGPC mixtures. Formation of new geopolymeric compounds and chemical bonds in the newly formed novel RCGPC mixtures were also discovered using XRD analysis. The comparison of mechanical and durability testing further showed that RCGPC performed better than the roller-compacted cement concrete (RCC) using RAP. Based on the results and analysis the developed RCGPC using RAP could be used as a cost-effective solution for the construction of pavement structures.

**Keywords:** Roller compacted concrete; Geopolymer concrete; Reclaimed asphalt pavement; Pavement; Fly ash

### 1 INTRODUCTION

Every year vast quantities of construction and demolition (C&D) wastes are generated in the United States (EPA, 2019). Reclaimed asphalt pavement (RAP) is one of the main components of such C&D wastes. The use of RAP can solve storage problems and environmental pollution while at the same time it can reduce construction costs (EPA, 2019; Davorin, 2008 & Ryszard, 2016). However due to the low strength and durability properties of RAP, its usage as a construction material is limited to landfill, low strength base or subbase and replacement of few percentages of natural aggregates in hot mix asphalt (HMA) and conventional Portland cement concrete (Copeland, 2011; Chesner,

2019; Hansen, 2014; Hoyos, 2011; Arulrajah, 2013; Puppala, 2011; Hajj, 2010; Maher, 1997; Ramzi, 1999; Huang, 2006 & Huang, 2005). Although Ordinary Portland Cement (OPC) is being used as a popular binder for a long time, its increasing production generates an enormous amount of CO<sub>2</sub> in the atmosphere, which is also raising environmental concerns (Malhotra, 2010; Naik, 2015 & Salloum, 2007). Geopolymer technology can be a possible alternative to address this issue.

Geo-polymer technology has become a promising technology that provides a mature and cost-effective solution to many problems. Geo-polymeric materials represent an opportunity to simultaneously improve both environmental and engineering performance compared to traditional technologies. Geo-polymer-based materials are environmentally friendly and need only moderate energy to produce. The development of Geopolymer technology could contribute to reducing CO<sub>2</sub> emissions by about 80% as compared to that of ordinary Portland cement with almost no economic sacrifices, while at the same time converting a potentially hazardous industrial waste by-product (fly ash) to a value-added construction material (Davidovits, 2008). The use of RAP in geopolymer can be more beneficial because in this way both waste products RAP and fly ash will be utilized resulting in not only saving the cost but also reducing the amount of CO<sub>2</sub> emission. Recently, RAP is being used in geopolymer concrete by researchers in many ways. They investigated different gradations of RAP, different mix variables like fly ash to alkali activator ratio, the different molar concentration of alkali activator (Delwar, 1997; Hossiney, 2008; Avirneni, 2016 & Horpibulsuk, 2016). However, in none of the above-mentioned studies, the reported improvements in strength and durability were significantly high enough to use RAP alone as a full replacement of natural aggregates.

In this study, the concept of roller-compacted geopolymer concrete (RCGPC) was introduced to improve the strength and durability characteristics of concrete containing RAP as aggregates. Mechanical and durability properties, as well as the morphology of prepared geopolymer mixtures, were investigated and compared with roller-compacted cement concrete (RCC) with RAP.

## 2 MATERIALS

The chemical composition of Class F fly ash (FA) used in this study is shown in Table 1. This low calcium FA contains 14.82% aluminum oxides and 36.40% silicon dioxide. RAP was secured from a local HMA recycling plant. Chemical analysis of RAP has also been tabulated in Table 1. Sodium hydroxide (NaOH) solutions of 8 and 10 molar concentrations were prepared in the laboratory. On the other hand, a ready-made sodium silicate (Na<sub>2</sub>SiO<sub>3</sub>) solution was also used as part of the alkali activator. Portland cement Type-II was used for RAP-based RCC specimens.

Table 1: Chemical composition of FA and RAP

Element (%)	FA	RAP
Si	36.40	48.37
Al	14.82	16.63
Fe	12.17	15.33
Ca	13.87	13.30
Mg	0.79	-
S	0.57	-
K	1.59	2.38

A suitable mix-design was developed based on the literature search, which consisted of RAP gradation (Figure 1) recommended by American Concrete Pavement Association (ACPA), 15% fly ash content, 8 and 10 molar concentration of NaOH, and Na<sub>2</sub>SiO<sub>3</sub> to NaOH ratio of 0 and 1 by mass. Both accelerated oven and ambient temperature curing methods were adopted to evaluate the mechanical properties of the mixtures.

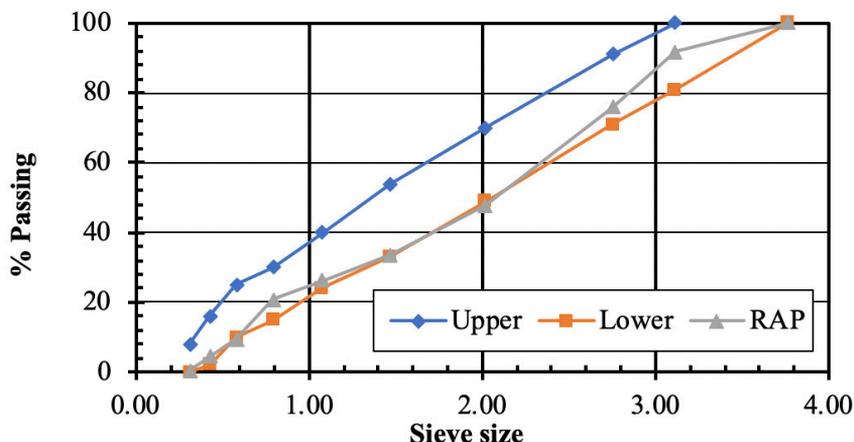


Figure 1: RAP gradation with ACPA recommended upper and lower limits for RCC

### 3 METHODS

#### 3.1 Maximum dry density (MDD) and optimum alkali content (OMC)

The maximum dry density (MDD) of the mixtures was determined using the modified proctor test (ASTM, D1557). The mixtures were compacted in a cylindrical mold with a dimension of 142.4 mm diameter and 116.4 mm height. The compaction was done in 5 layers, by applying 25 blows per layer, using a 2.5 kg hammer. The height of the fall of the hammer was 45.7 cm. Geopolymer mixtures were prepared using 4 different alkali contents, which were then compacted to determine the dry density of those. However, for RCC mixtures 4 different moisture contents were used. MDD and OMC were determined by plotting a dry density versus alkali or moisture content graphs.

#### 3.2 Experimental design parameters

To find out the optimum oven curing time at 60°C temperature, 3 oven curing periods (24, 48 and 72 hr) were used. To determine the optimum alkali content (OMC) of the mixtures, using modified proctor test, 4 different alkali and moisture contents ranging from 5% to 10% for RCGPC and 5% to 9 % for RCC, respectively, were used. The effect of molarity on compressive and split tensile strengths of RCGPC were evaluated for 8 and 10 molar NaOH concentration. Similarly, the impact of Na<sub>2</sub>SiO<sub>3</sub> to NaOH ratio on strengths of RCGPC was evaluated using two different Na<sub>2</sub>SiO<sub>3</sub> to NaOH ratio of 0 and 1. For ambient temperature curing 7, 14, 28 and 56 days were also investigated. Loading frequency for dynamic modulus testing was varied as 0.5, 1, 5, 10, and 25 Hz. For durability and morphology analysis the RAP-RCGPC mixture produced from 8 M NaOH, Na<sub>2</sub>SiO<sub>3</sub> to NaOH ratio of 1 was used.

### **3.3 Unconfined compressive strength test**

An unconfined compressive strength (UCS) test was performed according to ASTM C39 using Material Testing System (MTS). The compressive load was applied at a continuous rate of 0.51 mm/min until complete failure of the specimen was visible. The data acquisition rate for load and deformation was set as 0.1 per second. The maximum compressive stress at failure was defined as UCS and the slope of the linear portion of the stress-strain curve was termed as elastic modulus (E) of the mixtures.

### **3.4 Split tensile test**

Split tensile strength test was performed similarly to ASTM C496 using Material Testing System (MTS). The load was applied along the diametral axis of the specimen at a continuous rate of 0.51 mm/min until complete failure was observed. Real-time data acquisition at a rate of 0.1 per second was set. This test was used to evaluate split tensile strength (T) of the mixtures.

### **3.5 Durability test (Resistance to freeze-thawing)**

Resistance to freeze-thawing was performed in accordance with ASTM C666 standard procedure. Cylindrical specimens with 100 mm diameter and 200 mm height were subjected to consecutive freeze and thawing cycles. The temperature was increased from -12°C to 12°C within 2 to 5 hr and then decreased from 12°C to -12°C in 2 to 5 hr. The length change of the specimens was measured in every 36 cycles. Each specimen was to be subjected to 300 cycles or 1% length change.

### **3.6 X-ray diffraction (XRD)**

XRD analysis was carried out using the MiniFlex600 XRD machine. The range of diffraction angle,  $2\theta$  used in this analysis was varied from 5 to 55°. This test facilitated the identification of chemical compounds formed during geopolymerization.

## **4 RESULTS AND DISCUSSIONS**

### **4.1 Optimum moisture content**

Figure 2 shows the change in dry density with the increase in alkali content for RCGPC and water content for RCC mixtures. The alkali content was varied from 5 to 10 % for RCGPC and water content 5 to 9% for RCC mixtures. It was observed from the figure that, as the alkali content increased, the dry density also increased and finally reached a maximum value of 6-7% and dropped afterward. Optimum alkali content and maximum dry density (MDD) were found to be 6.3% to 7.2 % and 2056 to 2070 kg/m<sup>3</sup> for RCGPC mixtures, respectively. The RCC mixture using OPC exhibited optimum moisture content (OMC) and MDD of 7% and 2080 kg/m<sup>3</sup>, respectively.

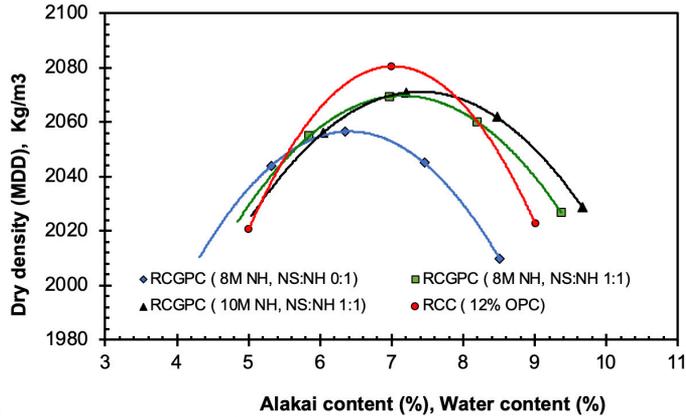


Figure 2: Effect of alkali and water content on the dry density of RAP-RCGPC and RAP-RCC mixtures, respectively

#### 4.2 Effect of curing time

Figure 3 illustrates the effect of oven curing time on the compressive strength development of the RCGPC mixture at 60°C. It was observed from the figure that, as the oven curing time increased, the average UCS also increased until 48 hours of curing, after which no significant increase in UCS was observed. Hence, 48 hours of oven curing at 60°C was considered to be the optimum accelerated oven curing time for RAP-RCGPC mixtures to evaluate the mechanical and durability characteristics of the mixtures.

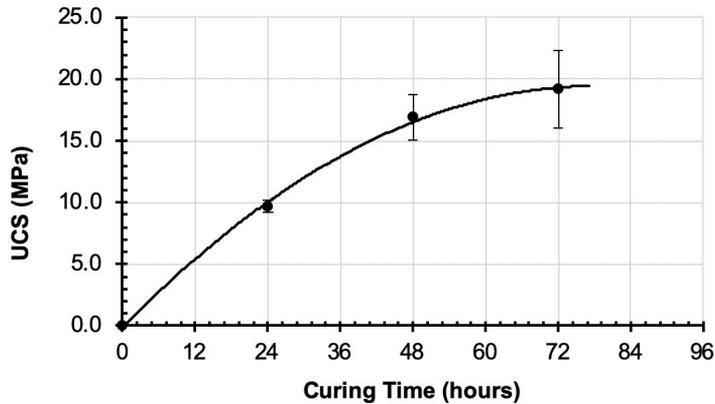


Figure 3: Effect of oven curing time on the UCS of RAP-RCGPC mixtures.

#### 4.3 Effect of NaOH molarity and Na<sub>2</sub>SiO<sub>3</sub> to NaOH ratio on UCS

Figure 4 shows the effect of NaOH molarity on the UCS and E of RAP-RCGPC mixtures. It was observed from the figure that, as the molarity of NaOH increased from 8 to 10 molar, the UCS also increased by about 25%. However, the increase in the average E value was only 5%. The heat condition remaining the same, the strength development in geopolymer is mostly dependent on the geo-polymerization reaction between precursor and alkali activator. With the increase of NaOH molarity, increasing alkali solids in the activator solution enhanced the geo-polymerization reaction and

process, which increased the strength and modulus of the final mixture.

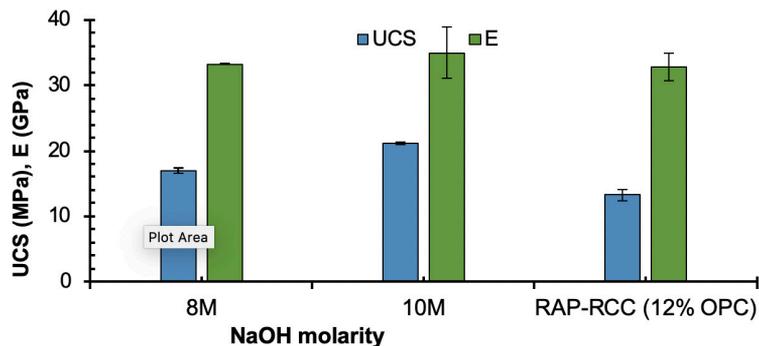


Figure 4: Effect of NaOH molarity on the UCS of RAP-RCC mixtures

UCS and E of RAP-RCC using 12% ordinary portland cement (OPC) were found to be about 13.24 MPa and 32.82 GPa. UCS of 8M and 10M RAP-RCC were about 28% and 60% more than UCS of RAP-RCC, however, RAP-RCC had shown similar E value as RAP-RCC.

Figure 5 displays the effect of  $\text{Na}_2\text{SiO}_3$  to NaOH ratio on the UCS and E of RAP-RCC mixtures. It can be seen from the figure that, as this ratio increases from 0 to 1, the UCS increased by about 12%. The E value also followed a similar trend. The reason behind the high strength and modulus at an equal mass ratio of  $\text{Na}_2\text{SiO}_3$ : NaOH was the dissolution process of alumina and silica tends to be high, which also accelerates the strength development. As a result, the formed bonds were strong enough to enhance initial microcrack resistance (Morsy, 2014). UCS of RAP-RCC using 8M NaOH and  $\text{Na}_2\text{SiO}_3$ : NaOH ratio as 0 and 1 are about 14% and 28% more than UCS of RAP-RCC, respectively. However, RAP-RCC has a similar elastic modulus value as that of RAP-RCC.

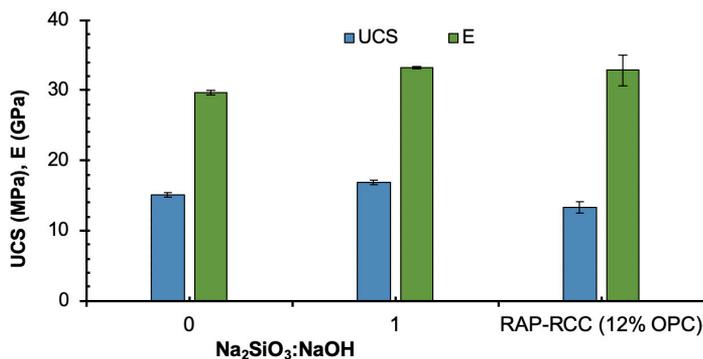


Figure 5: Effect of  $\text{Na}_2\text{SiO}_3$  to NaOH ratio on the UCS of RAP-RCC mixtures

#### 4.4 Effect of ambient temperature curing

Effect of ambient temperature curing period of 7, 14, 28 and 56 days on the strength development of RAP-RCC was also investigated. Figure 6 demonstrates the effect of ambient temperature curing days on the UCS and E of RAP-RCC mixtures. It can be

seen from the test results that, with the increase in curing days the UCS and E increased. Most of the strength development was observed in the first 7 days (9.8 MPa) of curing, which was around 50% of the 56 days (19.76 MPa) strength.

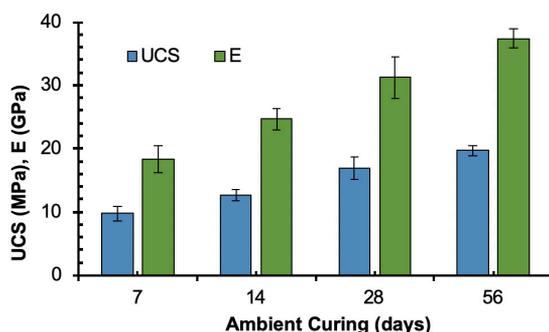


Figure 6: Effect of ambient temperature curing days on the UCS of E RAP-RCGPC mixtures

It was also estimated that 28 days of ambient temperature curing strength was the same as that of the UCS (16.90 MPa) at 60°C accelerated oven curing. It should be noted that the average day and night-time specimen temperatures were recorded around  $34.4 \pm 5.3^\circ\text{C}$  and  $28.8 \pm 2.1^\circ\text{C}$ , respectively through these curing days.

#### 4.5 Dynamic modulus ( $E^*$ )

Cylindrical specimen oven cured at 60°C were subjected to sinusoidal loading for a range of loading frequencies (0.5, 1, 5, 10 and 25 Hz). It was observed from Figure 7 that, the  $E^*$  increased by 29% when the loading frequency increased up to 5 Hz, afterward there was no significant change at 10 Hz and then showed a decrease of about 14% at 25 Hz. This indicates that such mixtures exhibited some viscoelastic behavior from 0.5 Hz to 10 Hz at 25°C which may be due to the presence of asphalt coating around the RAP particles. The range of  $E^*$  was 15 GPa to 21 GPa, which was significantly lower than the E value (33 GPa) of the same mixture.

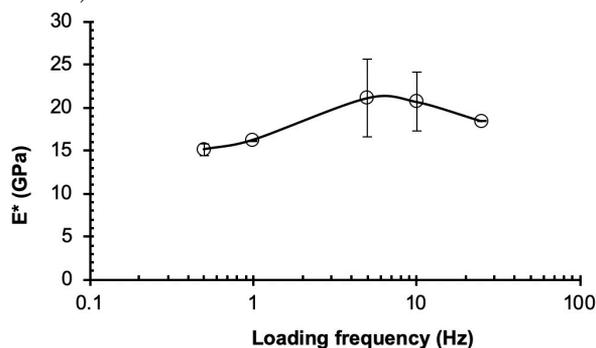


Figure 7: Dynamic modulus of RCGPC mixtures for different loading frequency

#### 4.6 Split-tensile strength

The following Figure 8 (a, b) illustrates the effect of NaOH molarity and  $\text{Na}_2\text{SiO}_3$  to NaOH ratio on the split tensile strength of RCGPC mixtures. The data in the figure

depicts that as the NaOH molarity increased from 8 to 10, split tensile strength increased about 10%, however when the  $\text{Na}_2\text{SiO}_3$  to NaOH ratio increased from 0 to 1 with 8M NaOH there was no significant change in the split tensile strength.

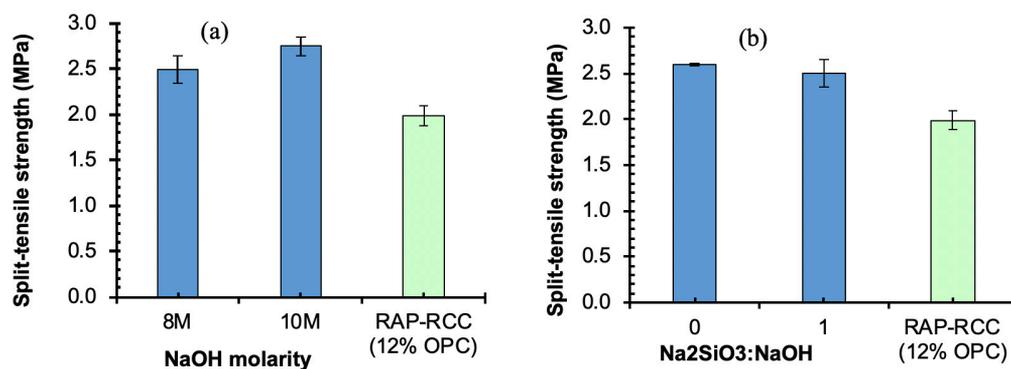


Figure 8. Effect of (a) NaOH molarity (b)  $\text{Na}_2\text{SiO}_3$ : NaOH on the split tensile strength of RAP-RCC mixtures

RAP-RCC using 12% OPC exhibited about 2 MPa of split tensile strength which is about 20% and 28% lower than RAP-RCC mixture with 8 and 10 NaOH respectively. These results indicated a stronger bond between RAP and geopolymer binders in RCGPC than the cement bond in RCC.

#### 4.7 Durability (freeze-thawing)

The freeze-thawing durability test was performed on RAP-RCC specimens. The specimens had been subjected to 300 cycles of freeze-thawing. Length change was recorded every 36 cycles. Dynamic modulus was determined at the end of the 300 cycles. It was found that the average length change and retained dynamic modulus were about 0.4% (criteria: <1%) and 81.14% (criteria: >60%) respectively. So RAP-RCC mixtures were considered to be passed in the freeze-thawing durability test.

#### 4.8 X-ray diffraction

Figure 9 illustrates the XRD analysis of the RAP-RCC mixture. It was observed from the analysis that quartz, mullite, albite and calcium compound present in the fly ash and RAP were chemically acted by alkali activator ( $\text{Na}_2\text{SiO}_3$  and NaOH) solution and formed different geopolymer compounds (aluminosilicate), such as Nepheline ( $\text{NaAlSiO}_4$ ) and Anorthoclase ( $(\text{Na}, \text{K})\text{AlSi}_3\text{O}_8$ ). Some unreacted crystalline quartz and mullite were also visible in the XRD graph.

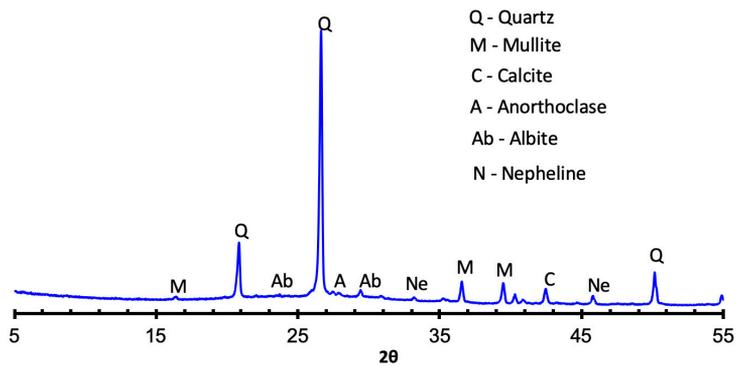


Figure 9: XRD of 8M NaOH with 1:1  $\text{Na}_2\text{SiO}_3$  cured at  $60^\circ\text{C}$

## 5 CONCLUSION

This study focused on the investigation of the mechanical, durability, and morphology characteristics of the newly synthesized RAP-RCGPC mixtures using appropriate testing methods. Based on the laboratory test results, the following conclusions were drawn:

1. Compressive strength and elastic modulus increased with the increase in oven curing time at  $60^\circ\text{C}$  temperature. Accelerated oven curing time of 48 hr at  $60^\circ\text{C}$  was considered sufficient to achieve the maximum compressive strength of RAP-RCGPC mixtures.
2. Compressive strength and elastic modulus of RAP-RCGPC mixtures increased with the increase in ambient curing period. Almost 100% of maximum strength ( $60^\circ\text{C}$  for 48 hr of oven curing) was achieved in 28 days of ambient curing period.
3. It was found that dynamic modulus increased with the increase in loading frequency up to 5 Hz and after that frequency increment did not affect the dynamic modulus significantly. In short, RAP-RCGPC mixture exhibited some viscoelastic behavior at  $25^\circ\text{C}$  at 1 loading frequency ranging from 0.5 Hz to 10 Hz.
4. The split tensile strength of the RAP-RCGPC mixture increased by about 10% when the molarity increased from 8 to 10. However, similar split tensile strength was observed for mixtures containing 8M NaOH with and without  $\text{Na}_2\text{SiO}_3$ .
5. RAP-RCGPC had exhibited up to 60% higher UCS and 28% higher split tensile strength than that of RAP-RCC mixtures using OPC.
6. The XRD test result showed the formation of geopolymer compounds indicating the occurrence of polymerization reaction in RAP-RCGPC mixtures.

Based on the mechanical, durability and morphology analysis, the RAP-RCGPC could be termed as moderate to high strength geopolymer concrete. These mixtures could be used in low volume roads and parking lots as a full-depth pavement or as a strong base with the combination of a hot mix asphalt layer on the top. In this study, the tensile property of the material was evaluated using split tensile testing, however flexural beam testing of such material is recommended to evaluate the modulus of rupture which is an important parameter for pavement design.

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