Tran-SET

Transportation Consortium of South-Central States

Solving Emerging Transportation Resiliency, Sustainability, and Economic Challenges through the Use of Innovative Materials and Construction Methods: From Research to Implementation

Soil-Recycled Aggregate-Geopolymer Road Base/Subbase Mixtures: Steps Towards Sustainability

Project No. 18GTLSU10

Lead University: University of Louisiana at Lafayette

Final Report

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Disclaimer

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16. Abstract

This study deals with the development of Soil-Geopolymer mixtures using flyash, alkali activator and recycled aggregates (RAG) including recycled concrete (RCA) and reclaimed asphalt (RAP) as an alternative to soil-cement for pavement base and subbase layers. Several mix constituents were varied such as flyash type and content, RCA and RAP content and ratio of sodium silicate and sodium hydroxide. Experiment design was established and mechanical and durability characteristics of Soil-RAG-Geopolymer mixtures were evaluated and then compared to the conventional soil-cement mixtures. The results of the testing showed that for the selected Soil-RAG-Geopolymer mixtures the strength, stiffness, permanent deformation, and durability characteristics were either comparable or better than the soil-cement mixtures. However, such mixtures required more curing time at room temperature to achieve needed strength. In order to further optimize the practical applications of this technology in the field, other variables such as molarity of alkali activator, curing conditions, early strength development at room and ambient temperatures, gradation of RAG and shrinkage characteristics need be investigated.

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SI* (MODERN METRIC) CONVERSION FACTORS

APPROXIMATE CONVERSIONS TO SI UNITS

Symbol	When You Know	Multiply By	To Find	Symbol
		LENGTH		
in	inches	25.4	millimeters	mm
ft	feet	0.305	meters	m
yd	yards	0.914	meters	m
mi	miles	1.61	kilometers	km
		AREA		
in^2	square inches	645.2	square millimeters	mm^2
ft^2	square feet	0.093	square meters	m^2
yd^2	square yard	0.836	square meters	m^2
ac	acres	0.405	hectares	ha
mi^2	square miles	2.59	square kilometers	km^2
		VOLUME		
fl oz	fluid ounces	29.57	milliliters	mL
gal	gallons	3.785	liters	L
ft^3	cubic feet	0.028	cubic meters	m^3
yd^3	cubic yards	0.765	cubic meters	m^3
		NOTE: volumes greater than 1000 L shall be shown in m^3		
		MASS		
oz	ounces	28.35	grams	g
lb	pounds	0.454	kilograms	kg
T	short tons (2000 lb)	0.907	megagrams (or "metric ton")	Mg (or "t")
		TEMPERATURE (exact degrees)		
°F	Fahrenheit	5 (F-32)/9 or (F-32)/1.8	Celsius	°C
		ILLUMINATION		
fc	foot-candles	10.76	lux	lx
fl	foot-Lamberts	3.426	candela/m^2	cd/m^2
		FORCE and PRESSURE or STRESS		
lbf	poundforce	4.45	newtons	N
lbf/in^2	poundforce per square inch	6.89	kilopascals	kPa

APPROXIMATE CONVERSIONS FROM SI UNITS

Symbol	When You Know	Multiply By	To Find	Symbol
		LENGTH		
mm	millimeters	0.039	inches	in
m	meters	3.28	feet	ft
m	meters	1.09	yards	yd
km	kilometers	0.621	miles	mi
		AREA		
mm^2	square millimeters	0.0016	square inches	in^2
m^2	square meters	10.764	square feet	ft^2
m^2	square meters	1.195	square yards	yd^2
ha	hectares	2.47	acres	ac
km^2	square kilometers	0.386	square miles	mi^2
		VOLUME		
mL	milliliters	0.034	fluid ounces	fl oz
L	liters	0.264	gallons	gal
m^3	cubic meters	35.314	cubic feet	ft^3
m^3	cubic meters	1.307	cubic yards	yd^3
		MASS		
g	grams	0.035	ounces	oz
kg	kilograms	2.202	pounds	lb
Mg (or "t")	megagrams (or "metric ton")	1.103	short tons (2000 lb)	T
		TEMPERATURE (exact degrees)		
°C	Celsius	1.8C+32	Fahrenheit	°F
		ILLUMINATION		
lx	lux	0.0929	foot-candles	fc
cd/m^2	candela/m^2	0.2919	foot-Lamberts	fl
		FORCE and PRESSURE or STRESS		
N	newtons	0.225	poundforce	lbf
kPa	kilopascals	0.145	poundforce per square inch	lbf/in^2

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ACRONYMS, ABBREVIATIONS, AND SYMBOLS

ANOVA	Analysis of Variance
E	Elastic Modulus
FA	Flyash
FSI	Swell Index
GP	Geopolymers
ITS	Indirect Tensile Strengths
LL	Liquid Limit
M_r	Resilient Modulus
MDD	Maximum Dry Density
OMC	Optimum Moisture Content
PI	Plasticity Index
PL	Plastic Limit
RAP	Reclaimed Asphalt Pavements
RCA	Recycled Concrete Aggregates
RAG	Recycled Aggregate
SC	Soil Cement
UCS	Unconfined Compressive Strength

EXECUTIVE SUMMARY

Stabilized road base and subbase for flexible pavement provides substantial support to the overlaying hot-mix asphalt (HMA) layer. Such bases reduce stresses on subgrade soil, minimize vertical deflection, and provide resistance against freeze-thaw action. Commonly used additives to stabilize road bases include, cement, lime, flyash, blast furnace slag, and asphalts. Since demand for the additives and associated costs are increasing, there is a pressing need to utilize alternative cementing/binder technologies to stabilize soils for road constructions. One such alternate binding material is known as Geopolymer binders/cements. Geopolymer materials represent an innovative class of “green” technology, which mainly rely on industrial by-products (coal fly ash, Ricehusk/sugarcane ashes, some clays, etc.) to significantly reduce its carbon footprint. Out of several techniques available for improving the shear strength, our project aims at probing the efficacy of a low calcium geopolymer flyash a new eco-friendly binder material and recycled concrete aggregate in improving the mechanical characteristics of medium plastic soils.

The first phase of this study explores the feasibility of using recycled aggregate (RAG) mixed with medium plastic soil, flyash and alkali activator otherwise called Soil-RAG geopolymer, as a more sustainable alternative material to conventional soil-cement in pavement base or subbase applications. The main objective is to determine the effects of RAG, flyash and alkali contents for an optimized mixture, and compare the strength and durability characteristics of the selected Soil-RAG geopolymer and soil-cement mixtures. The experiment was conducted by varying mixed constituents of flyash, RAG and ratio of sodium silicate to sodium hydroxide (Alkali). Soil-RAG mixed with different dosages of two types of flyashes were evaluated for maximum dry density (MDD), optimum moisture content (OMC), unconfined compressive strength (UCS), resilient modulus (Mr), durability, and indirect tensile strengths (ITS). Moreover, the influence of mixture variables on Soil-RAG geopolymer was modeled to predict the UCS and establish a basis for sensitivity analysis and comparison of the selected mixtures. The results revealed that the addition of RAG improved the mechanical and durability characteristics of the Soil-RAG geopolymer mixture especially for one flyash type with better strength observed at zero silicate ratio. However, it has not yet been confirmed if continuous addition of RAG will considerably yield greater strength. Microstructure and morphological analysis of selected Soil-RAG-Geopolymer mixture established the geopolymerisation process in the mixtures, which facilitated the improvement of the durability and mechanical characteristics of the mixture.

Even though Soil-RAG geopolymer mixtures exhibit better ultimate strength, modulus, and durability characteristics relative to the soil-cement mixtures, such mixtures required more curing time at room temperature to achieve needed strength. In order to further optimize the practical applications of this technology in the field, other variables such as molarity of alkali activator, curing conditions, early strength development at room and ambient temperature, gradation of RAG and shrinkage characteristics need be investigated.

1. INTRODUCTION

1.1. Background

The rapid development of industrialization has led to the generation of pollution, which directly or indirectly generate undesirable pollutants released into the environment. The production of these pollutants has been minimized using alternate construction materials as discovered by many research works conducted in a variety of civil engineering applications. In conventional construction, weak soils like clayey soils are often stabilized with Ordinary Portland Cement (OPC) and lime. However, the production of cement discharges almost 5% of the total CO_2 into the air. Based on this, interests have grown in finding new solutions on replacing current cementitious additives with the less CO_2 release for soil stabilizations.

Furthermore, it is estimated that 150 million ton of concrete waste is produced in the United States annually *(1)*. Concrete structures that are designed to have service lives of at least 50 years must be demolished. As it is, the Louisiana State have long been faced with the challenge of limited aggregates sources, which have always resulted in higher construction cost due to the logistics in transportation. Expectedly, soil cement has become common practice utilized as a base or subbase material in highway pavements. However, cement aside its microcracking due to shrinkage, its produces carbon dioxide which has tremendously contributed to global warming, hence is not an environmentally friendly material. To overcome this problem, Davidovits *(2)* introduced geopolymer binders that could be utilized as an alternative replacement of OPC due to low-cost production and environmental friendliness. The production of the geopolymer requires 60% less energy with almost 80% reduction of CO_2 compared to OPC *(3-4)*. This by-product undergoes a geopolymerization process that consists of silicates and aluminates sources that may be used to manufacture pre-cast structures and non-structural elements, concrete products, and concrete pavements. Meanwhile, it may restrain the production of toxic waste that are resistant to heat and aggressive environment and stabilize weak soils *(2)*. This has proven in numerous researches to be worthwhile without compromising strength, stiffness, and long-term performance of the materials. Industrial byproducts like fly ash and blast furnace slag could be used as pozzolanic materials, along with alkali to form a geopolymer binders. Such binders have driven much attention in the concrete industry, and significant research has been under process to address the short and long-term performances of these geopolymers binders. Recent advances in employing geopolymer materials for civil engineering purposes make it possible to use it for soil stabilization especially when mitigating subgrade layer for road pavement. By replacing unproductivity cementitious additives with new green additives is likely to give new hope to reduce pollutants in the environment. Soil stabilization using geopolymer material additive for subgrade in combination of recycled aggregates is proposed to replace the traditional method.

1.2. Problem Statement

Research on flyash based geopolymer has gradually increased throughout the years. There is a trend that geopolymers based layers will replace conventional cement as it is more environmentally friendly and more cost effective. The dependable characteristic of geopolymer shows that it has a relatively high strength compared to the ordinary cement. Sustainability is defined as “Meeting the needs of the present without compromising the ability of the future generations to meet their own needs” *(5)*. The current usage of cement and virgin aggregates is not sustainable as demonstrated by the growing demand of cement and shortage of natural aggregates in urban area. For instance, crack occurs most of the time in cement stabilized soil after a certain period. This occurs more significantly especially after an exposure to high temperature *(6)* which decreases its strength characteristic with the propagation of further cracks. Geopolymer on the other hand has shown improved resistance against fire and heating and exhibited better performance under ultraviolet (UV) rays, highly corrosive environment and acids. In addition, these mixtures consume less energy and produced less greenhouse gas (CO_2) and are 10% to 30% cost effective than OPC concrete *(7)*. Geopolymers have been extensively used in concrete and modification of construction materials like bricks and mortar *(8)* but its use in soil stabilization is limited and only few studies have been conducted.

The cost of virgin aggregate has tremendously increased overtime and it is projected that this trend will continue as further restrictions are placed on this resource in the future *(9)*. Recycle concrete aggregate (RCA) use is based on economics, including the cost of transporting of construction and demolition (C&D) waste and virgin aggregate, the cost of C&D disposal, and government intervention on tipping fees and mandatory usage through legislation *(10)*. It has been noted that about 60% of aggregate cost is related to transportation *(11)*.

Recycling aggregates (RAG), from deteriorated concrete structures/pavements and reclaimed asphalt pavements (RAP), would reduce the negative impact on the environment and increase sustainability of aggregate resources *(12)*. Using RAG conserves virgin aggregate, reduces the impact on landfills and decreases energy consumption *(13)*. Using RCA, creates cost savings in the transportation of aggregate and waste products, and in waste disposal *(13-14)*. It is estimated that using RCA can save up to \$4.80 m^2 *(15)*. Based on the survey conducted in 2012, the United States of America (USA) alone produces about 52 million ton of fly ash (FA), annually, and about 71 million tons of RAP. Based on the survey by National Asphalt Pavement Association about 98% of RAP and only about 50% of FA is reused beneficially *(16)*. FA is the byproduct of the coal industry and RAP, the waste of HMA surface course, have been discarded in the landfill site occupying huge time, effort, and space.

2. OBJECTIVES

The research study focuses on the development and evaluation of sustainable Soil-Recycled Aggregate-Geopolymer (Soil-RAG-GP) mixtures for road base and subbase layers. The specific objectives are:

- Conduct the review of the existing practices in stabilizing soil bases using RAP, RCA and geopolymer binders;
- Determine the effect of various Soil-RAG-GP mixture constituents such as; the flyash types, FA content and RAG content, alkali ratio, and curing conditions on the unconfined compressive strength of such mixtures; and
- Evaluate and compare the mechanical and durability characteristics of selected Soil-RAG-GP and conventional soil-cement mixtures including; unconfined compressive strength, resilient modulus, indirect tensile strength, and durability characteristics.

This research provides the South-Central State DOTs, other highway agencies, and pavement industry with information on using flyash-based geopolymer binders and RAG as an alternative soil stabilization source in roadways and other applications as needed.

3. LITERATURE REVIEW

3.1. Soil Stabilization

Soil stabilization is the alteration of soils to enhance their physical properties. Stabilization increases the strength and/or control the shrink-swell properties of a soil, thus improving the load bearing capacity of a sub-grade to support pavements and foundations. Primarily, this aims at improving soil strength and increasing resistance to softening by water through bonding the soil particles together, waterproofing the particles or combination of the two *(17)*. Generally, this stems from the obvious design deficiency as obtained on most construction sites and this technology provides an alternative structural solution to such practical problem. The simplest stabilization processes are compaction and drainage (if water drains out of wet soil it becomes stronger). The other process is by improving gradation of particle size and further improvement can be achieved by adding cementious binders to the weak soils *(18)*. Ordinary Portland cement (OPC), lime, and flyash (Class C) are the most popular soil stabilizing additives. These additives augment the physical, mechanical and durability properties of the soil, and enhance the long-term performance. Soil stabilization process can be accomplished by several methods but falls basically into two broad categories namely; mechanical stabilization and chemical stabilization. These methods are utilized on roadways, parking areas, airports, site development projects and many other situations where the subsoils are not suitable.

3.1.1. Mechanical Stabilization

Mechanical Stabilization is the process of improving the properties of the soil by changing its gradation. This process includes soil compaction and densification by application of mechanical energy using various sorts of rollers, rammers, vibration techniques and sometime blasting. The stability of the soil in this method relies on the inherent properties of the soil material. Two or more types of natural soils are mixed to obtain a composite material which is superior to any of its components. Mechanical stabilization is accomplished by mixing or blending soils of two or more gradations to obtain a material meeting the required specification *(19)*.

3.1.2. Chemical Stabilization

This method involves adding chemicals with the soil which in return causes its structure to be changed. The chemicals seal the space between particles, leaving no room for water to penetrate through and it depends mainly on chemical reactions between stabilizer (cementitious material) and soil minerals (pozzolanic materials) to achieve the desired effect Among the most common chemicals that are used for soil stabilization include sodium chloride, calcium chloride and sodium silicate. Other chemicals that are added into the soil include polymers, chrome lignin, alkyl chlorosilanes, siliconites, amines and quarternary ammonium salts.

It comprises changing the physico-synthetic around and within clay particles whereby the earth obliges less water to fulfill the static imbalance. Through this soil stabilization method, unbound materials can be stabilized with cementitious materials (cement, lime, fly ash, bitumen or combination of these). The stabilized soil materials have a higher strength, lower permeability and lower compressibility than the native soil (Keller brochure 32-01E). The method can be achieved in two ways, namely; (1) in situ stabilization and (2) ex-situ stabilization. While the first method identifies the process carried on site, the later involves off site stabilization before and this hugely depends on which soil properties to be modified. The chief properties of soil which are of interest to engineers are volume stability, strength, compressibility, permeability and durability *(17, 20, 21)*. To avoid any wrong application of stabilization technology, a laboratory tests followed by field tests may be required in order to determine the engineering and environmental properties. These will effectively provide a good assessment of the soil properties and enhance the knowledge on the choice of binders and amounts *(21)*. A typical decision tree for soil stabilization is shown in Table 1 *(24)*.

Table 1. Decision tree for soil stabilization *(24)*.

Sieve Analysis >= 25%	**Passing No. 200 sieve Subgrades**	
Atterberg Limits (LL, PL, PI)		
PI < 15	**15 <= PI <= 35**	**PI >= 35**
Cement Asphalt (PI<6) Lime-Flyash (Class F) Flyash (Class C)	Lime Lime-Cement Lime-Flyash (Class F) Flyash (Class C) Cement	Lime Lime-Cement Lime-Flyash (Class F) Lime-Flyash (Class C)

3.2. Stabilizing Agents

These are hydraulic (primary binders) or non-hydraulic (secondary binders) materials that when in contact with water or in the presence of pozzolanic minerals reacts with water to form cementitious composite materials. The commonly used binders are: cement, lime, flyash, and blast furnace slag.

3.2.1. Cement

Cement is the oldest binding agent since the invention of soil stabilization technology in 1960's. It may be considered as primary stabilizing agent or hydraulic binder because it can be used alone to bring about the stabilizing action required *(17)*. Cement reaction is not dependent on soil minerals, and the key role is its reaction with water that may be available in any soil *(21)*. This can be the reason why cement is used to stabilize a wide range of soils. Numerous types of cement are available in the market; these are OPC, blast furnace cement, sulfate resistant cement and high alumina cement. Usually the choice of cement depends on type of soil to be treated and desired final strength. Hydration process is a process under which cement reaction takes place. The process starts when cement is mixed with water and other components for a desired application resulting into hardening phenomena. The hardening (setting) of cement will enclose soil as glue, but it will not change the structure of soil *(21)*. The hydration reaction is slow proceeding from the surface of the cement grains and the center of the grains may remain unhydrated *(17)*. Cement hydration is a complex process with a complex series of unknown chemical reactions *(22)*. However, this process is affected by: (a) presence of foreign matters or impurities, (b) water-cement ratio, (c) curing temperature, (d) presence of additives, and (e) specific surface of the mixture.

Depending on factor(s) involved, the ultimate effect on setting and gain in strength of cement stabilized soil may vary. Normally the amount of cement used is small but sufficient to improve the engineering properties of the soil and further improved cation exchange of clay. Cement stabilized soils have the following improved properties: decreased cohesiveness (Plasticity), decreased volume expansion or compressibility, and increased strength *(23)*.

3.2.2. Lime

The application of lime provides economical way of soil stabilization and can significantly improve engineering properties in two ways namely- modification and stabilization. Lime modification describes an increase in strength brought by cation exchange capacity rather than cementing effect brought by pozzolanic reaction *(17)*. The most dramatic improvement through modification is in clay soils of moderate to high plasticity. In soil modification, as clay particles flocculates, transforms natural plate like clays particles into needle like interlocking metalline structures. Clay soils turn drier and less susceptible to water content changes (24). Modification is also caused as the hydrated lime reacts with the clay mineral surface in a high pH environment; the clay surface mineralogy is altered, as it reacts with the calcium ions to form cementitious products. The results are plasticity and swelling reduction, reduction in moisture-holding capacity, and improved stability.

Lime stabilization may refer to pozzolanic reaction in which pozzolana materials reacts with lime in presence of water to produce cementitious compounds *(17, 21)*. Stabilization occurs when the proper amount of lime is added to a reactive soil. Stabilization differs from modification in that a significant level of long-term strength gain is developed through a pozzolanic reaction. This reaction is the formation of calcium silicate hydrates and calcium aluminates as the calcium from the lime reacts with the aluminates and silicates solubilized from the clay mineral surface. The effect can be brought by either quicklime, CaO or hydrated lime, $Ca(OH)_2$. Slurry lime also can be used in dry soils conditions where water may be required to achieve effective compaction *(25)*. Quicklime is the most commonly used lime; the followings are the advantages of quicklime over hydrated lime *(18)*. - higher available free lime content per unit mass - denser than hydrated lime (less storage space is required) and less dust - generates heat which accelerate strength gain and large reduction in moisture content according to the reaction equation below;

$$CaO + H_2O \rightarrow Ca(OH)_2 + \text{Heat (65kJ/mol)} \qquad [1]$$

Quicklime when mixed with wet soils, immediately takes up to 32% of its own weight of water from the surrounding soil to form hydrated lime; the generated heat accompanied by this reaction will further cause loss of water due to evaporation which in turn results into increased plastic limit of soil i.e. drying out and absorption *(17, 21)*. The results of stabilization can be very substantial increases in resilient modulus values, very substantial improvements in shear strength, continued strength gain with time, and long-term durability over decades of service. Like cement, lime when reacts with wet clay minerals result into increased pH which favors solubility of siliceous and aluminous compounds. These compounds react with calcium to form calcium silica and calcium alumina hydrates, a cementitious product similar to those of cement paste. Natural pozzolanas materials containing silica and alumina (e.g. clay minerals, pulverized fly ash, PFA, blast furnace slag) have great potential to react with lime. Lime stabilizations technology is mostly widely used in geotechnical and environmental applications. Some of applications include encapsulation of contaminants, rendering of backfill (e.g. wet cohesive soil), highway capping, slope stabilization and foundation improvement such as in use of lime pile or lime-stabilized soil columns *(20)*. However, presence of Sulphur and organic materials may inhibit the lime stabilization process. Sulphate (e.g. gypsum) will react with lime and swell, which may have effect on soil strength.

3.2.3. Flyash

Fly ash is a byproduct of coal fired electric power generation facilities; it has little cementitious properties compared to lime and cement. Most of the fly ashes belong to secondary binders; these binders cannot produce the desired effect on their own. However, in the presence of a small amount of activator, it can react chemically to form cementitious compound that contributes to improved strength of soft soil. Fly ashes are readily available, cheaper and environmentally friendly. There are two main classes of fly ashes; class C and class F *(26, 27)*. The former is produced from burning anthracite or bituminous coal and the latter is produced from burning lignite and sub bituminous coal. Both the classes of fly ash are puzzolans, which are defined as siliceous and aluminous materials. Thus, Fly ash can provide an array of divalent and trivalent cations (Ca^{2+}, Al^{3+}, Fe^{3+} etc.) under ionized conditions that can promote flocculation of dispersed clay particles. Thus, expansive soils can be potentially stabilized effectively by cation exchange using flyash *(28)*. Class C fly ashes are produced from burning subbituminous coal; it has high cementing properties because of high content of free CaO. Class C from lignite has the highest CaO (above 30%) resulting in self-cementing characteristics *(27)*. Class F fly ashes are produced by burning anthracite and bituminous coal; it has low self-cementing properties due to limited.

Depending upon the soil type, the effective fly ash content for improving the engineering properties of the soil varies between 15 to 30% *(29)*. Also, it was proven that ash can be used successfully as an additive for the base and sub-base layer construction of pavement, as well as for the construction of embankments in compressed soils *(30)*. A similar study was carried out by Phanikumar and Sharma *(31)* and the effect of fly ash on engineering properties of expansive soil through an experimental programme. The effect on parameters like free swell index (FSI), swell potential, swelling pressure, plasticity, compaction, strength and hydraulic conductivity of expansive soil was studied. The ash blended expansive soil with flyash contents of 0, 5, 10, 15 and 20% on a dry weight basis and they inferred that increase in flyash content reduces plasticity characteristics and the FSI was reduced by about 50% by the addition of 20% fly ash.

3.2.4. Recycled Asphalt Pavement (RAP)

RAP improves the dry density of the soil significantly. RAP has already been successfully used in base and subbase as a replacement of aggregates. A research done in Thailand had shown that RAP-FA blend compacted at OMC can satisfy compressive strength criteria of the road base *(32)*. Since RAP has aggregates and bitumen binder it also may help in geopolymerization process. However, the main purpose of using RAP was to increase the density and hence the compressive strength. Study in RAP-FA geopolymer had shown good strength development, however not much work has been done using FA-RAP geopolymer in soil.

3.2.5. Recycled Concrete Aggregate (RCA)

Many countries successfully use RCA including the United States, South Africa, Netherlands, United Kingdom, Germany, France, Russia, Canada, and Japan *(33)*. Currently, RCA is used as an aggregate in granular subbases, lean-concrete subbases, soil-cement, and in new concrete as the only source of aggregate or as a partial replacement of new aggregate *(14, 34, 35)*. The Ministry of Land, Infrastructure, and Transportation has been instrumental in Japan recycling 96% of the nation’s concrete waste through initiatives Recycling Plan 21 and Construction Recycling Promotion Plan ’97 *(36)*. Japan developed a special technique that removes the original mortar from the concrete. This technique produces only 20–35% coarse aggregate compared to the 60 – 70% coarse aggregate that is produced in the current system because of the large amount of adhered mortar *(37)*. In 2002, 28 states used RCA in pavement construction, 26 states use RCA as base or subbase material only and two states allow for subbase use only *(34)*. By 2004, 41 of the 50 states are recycling waste concrete into aggregate *(13)*. Apparently, no study has been channeled towards the application of RCA geopolymer in the highway construction.

3.2.6. Geopolymer Binders

Geopolymer binders could be utilized as an alternative to cement for soil base and subbase stabilization. Industrial byproducts like flyash, blast furnace slag could be used as pozzolanic materials, along with alkali as an activator to form a geopolymer binders. Recently, such binders have driven much attention in the concrete industry, and several major research studies were conducted to address the short and long-term performances of geopolymers binders *(38-43)*.

Geopolymerization however, is a stabilization technology that has not gained widespread acceptance as a road base stabilization method despite indications and inferences from few past researches. Several studies have been reported on the improvement of mechanical characteristics of soils using alkali activated flyash and flyash-based geopolymers *(44)*. Studies have shown that the flyash dosage is vital for the geopolymer formation when reacted with alkali. The UCS of the soil-mixtures increased with the increase in flyash content and exhibited an optimum of 30% content *(45).* The ratio between sodium silicate and sodium hydroxide has an impact on the strength development of soil-geopolymer mixtures. It has been found that alkaline ratio of 0.7 and alkali to fly ash ratio of 1.5 generates higher strength. Soil mixtures tested with different NaOH molarities has shown that the maximum strength could be achieved at 12.5 molarity for both 3 and 7 days of curing. On the other hand, soil with fine particles exhibited lower strength values for mixtures made with higher than the 10 molarity NaOH *(46).* Alkali activated clay and class F flyash mixtures increased the strength and stiffness at elevated temperature and exhibited improved UCS when cured at extended period *(47).* Further, the long-term strength development occurred in the alkaline activated flyash-based soil mixtures relative to conventional soil-cement mixtures. Soil-geopolymer mixture developed low permanent strain and the ratio of indirect tensile strength and UCS for geopolymer mixtures was higher than the soil-cement mixtures *(48, 49).* Resilient modulus and UCS of the crushed brick recycled crushed aggregates (CBA) and RAP with 4% soil-geopolymer showed that RAP with 4% soil-geopolymer exhibited the highest resilient modulus. On the other hand, CBA with 4% soil-geopolymer illustrated highest 28-day compressive strength *(50).*

Recently, Adhikari et al. *(51)* conducted systematic research on the development of Soil-RAP-Geopolymer mixtures using class F flyash for medium and high plastic soils. It was found that the increase in flyash and RAP content increased the mechanical properties of the Soil-RAP-Geopolymer mixture. On the other hand, an optimum sodium silicate content of 40% was observed. In general, high plastic soil exhibited less UCS value than the medium plastic soil used in the study, regardless of stabilizing agent or process. The UCS also increased with the increase in NaOH molarity (6 to 10 M) and exhibited an optimum of 8M for both type of soils. Selected Soil-RAP-Geopolymer mixtures either illustrated same or better durability and mechanical characteristics relative to conventional soil-cement mixtures *(51).*

4. METHODOLOGY

4.1. Materials

The soil used in this research was obtained from a local construction site. The soil's liquid limit (LL) and plastic limit (PL) were obtained using Casagrande's liquid limit device as per ASTM D-4318 procedure *(52)*. The LL, PL, and PI of the soil were 36.9, 18.8, and 18.1, respectively. Based on the AASHTO and Unified Classification systems, the soil was classified as Lean Clay (CL) and A-6, respectively. The element composition of soil is shown in Table 2.

Class F flyash from two different sources were used to produce geopolymer binder. Unlike Class C, Class F flyash has low calcium content, and therefore requires an alkali to activate its cementitious properties. The recycled aggregate such as RCA and RAP were obtained from a local contractor. The element composition of flyash, RCA, and RAP is also shown in Table 2.

Table 2. Element composition of oil, flyash, and RAG (concentration by % weight).

Element	BR Flyash	SL Flyash	Soil	RCA	RAP
C	-	-	16.22	-	53.54
O	16.67	15.57	22.43	21.24	9.27
Na	1.11	0.50	-	-	-
Mg	-	-	-	0.34	-
Al	18.99	6.80	9.77	4.02	1.33
Si	53.64	52.71	43.16	34.38	30.55
S	-	0.31	-	0.76	1.72
K	1.85	5.57	2.49	0.79	0.31
Ca	2.00	7.2	0.93	32.52	1.5
Fe	5.73	8.29	4.97	2.76	1.76
Te	-	3.47	-	3.13	-

Table 3. Recycle aggregate (RAG) gradation (% finer).

Size Sizes	3/8"	#4	#40	#200
RCA	100	90	45	35
RAP	100	90	45	0

Alkali solution was comprised of the combination of two chemicals: sodium hydroxide (NaOH) and Sodium Silicate (Na_2SiO_3). Alkali activator was prepared by mixing required proportions of Na_2SiO_3 and NaOH, which was referred as Alkali ratio. NaOH of 6 molar concentrations and ordinary Portland cement (OPC) was used.

4.2. Optimum Moisture Content and Maximum Dry Density

The optimum moisture content (OMC) and maximum dry density (MDD) were determined using the modified proctor test following ASTM D-1140 and ASTM D-1557 procedures *(53, 54)*. The MDD was shown to be higher for mixtures, which contained only soil (Table 4). This indicates that the low density of the flyash had a higher effect on the MDD than the high-density RAG. At the same time, as the minority constituents increased, the OMC slightly increased, leveling off at about 14%. It was also noticed that the MDD of RAP mixture were higher than the RCA mixtures with not much difference in OMC.

Table 4. Maximum dry density and optimum moisture content.

Flyash Type	Mixture Type	MDD (g/cm^3)		OMC (%)	
		RCA	RAP	RCA	RAP
SL Flyash	0%FA-0%RAG-Soil	1.90	1.90	13.8	13.8
	15%FA-15%RAG-Soil	1.79	1.88	14.1	14.2
	25%FA-25%RAG-Soil	1.75	1.81	14.0	13.9
BR Flyash	0%FA-0%RAG-Soil	1.90	1.90	13.8	13.8
	15%FA-15%RAG-Soil	1.87	1.89	11.5	12.0
	25%FA-25%RAG-Soil	1.81	1.85	11.0	11.5

4.3. Specimen Preparation and Curing

To prepare the specimen, the constituents stored in waterproof bins were measured out to the nearest 0.1g of the required mass. The dry constituents (soil, FA, and RAG) were mixed together before the alkali was added. Then, the alkali solution was measured based on required ratio (replacement of OMC). The alkali solution was poured into dry mix of FA, RAG and soil and thoroughly mixed to achieve homogenous mixture. Cylindrical specimens of 72 mm diameter and 144 mm height were compacted at MMD like ASTM D1557 procedure with slight modification. This mixture was poured into a cylindrical mold in three equal layers. Each layer was rodded 25 times as an attempt to get the aggregates settled before further compaction. Steel caps were placed on each end of the mold and the specimen was compressed by a 6-ton jack. The specimen was then extruded to about 1-2 mm and shaved from both sides. This was done to ensure level surfaces on the mold where the load would be applied. The specimen mass, length, and diameter were measured. These specimens were then stored in a waterproof container fit for the specimen and cured for 72 hr at 60^{o}C. 72-hr curing time was chosen because our preliminary test showed that it yields 90% of the desired strength. Also, same preliminary testing proved that the UCS of the soil mixture increased with the increase in oven curing time and at 72 hours, the UCS plateaus with minimum rate of strength gain.

4.4. Experiment Design

Four types of tests were conducted to evaluate the mechanical and long-term performance properties of soil-geopolymer and soil-cement mixtures including UCS, dynamic modulus test, resilient modulus test and durability test. An experimental design matrix was developed to find the optimum mix constituents based on UCS of the mixtures. This study utilizes two types of recycled aggregates: RCA and RAP. Further experiments were conducted at an obtained optimum mixture and conventional soil-cement mixtures including resilient modulus and durability tests. A three-parameter surface methodology with central experimental design was implemented. The design involved a fraction of first order (2^n) factorial design with center point approach. The parameters were explored at five levels that covered a range of variables used in the study. The variables in the design matrix include: FA content, RAP and RCA content, Na_2SiO_3 content or (Na_2SiO_3/NaOH) ratio (Table 5). Total of 40 different cases for Soil-RAG-Geopolymer and soil-cement mixtures were tested. For each case triplicate specimens were prepared and tested. Additional cases were also tested, as needed.

4.4.1. Unconfined Compressive Strength (UCS)

UCS test was conducted in accordance with ASTM D2166 procedure. A cylindrical specimen of 72 mm diameter and 144 mm height was loaded axially under compression until failure. Ramp loading of 5 mm/min was maintained using the material testing system (MTS). An extensometer was attached at the middle third of the specimen. Real time strain and load data acquisition was conducted at an equal time interval. The compressive load at failure was recorded and the UCS was calculated as:

$$UCS = \frac{P}{A} \qquad [2]$$

where:
P= maximum load at failure (N); and
A= cross sectional area of sample (m^2).

The modulus of elasticity (E) was found by calculating the slope of the linear portion of the stress-strain curve, usually up to one-third of the UCS.

4.4.2. Resilient Modulus Test

The resilient modulus (Mr) test was conducted as per AASHTO T 307 procedure (55). This test was performed under compressive loading by applying cyclic stress of about 10% to 15% of UCS on cylindrical specimen (72 mm dia and 144 mm high). Haversine load waveform was used with 0.1 second of load-unload period and 0.5 second of rest period. The time series load and strain data were collected at several cycles until 1000th cycle. Mr was calculated using the following equation.

$$M_r = \frac{\sigma_{cy}}{\epsilon_e} \qquad [3]$$

where,
M_r = Resilient modulus (Pa);
σ_{cy} = Cyclic stress (Pa); and
ε_e = Elastic strain (mm/mm).

Cumulative permanent deformation for each load cycle was also measured and the rate of permanent deformation was calculated by simply dividing the cumulative permanent deformation by the number of load cycle at 500th cycle.

4.4.3. Indirect Tensile Strength (ITS) Test

The indirect tensile strength (S_t) of the cylindrical specimens 101 mm diameter and 54 mm thick was determined using the procedure outlined in ASTM D 6931 *(56)*. The specimen height was determined in accordance with Test Method D3549/D3549M *(57)*, to the nearest 1 mm and the diameter was measured to the at the mid height along axes that are 90° apart, and the average recorded to the nearest 1 mm. Bring the specimen to cure temperature 61°C by placing in a heavy-duty leak-proof plastic bag and cured for 72hrs. The. Afterwards, the specimen was removed from the oven with the plastic bag stripped off and placed in air or water bath for minimum of 2hrs since the recommended test temperature is 25°C. Then, the specimen was loaded along a diametric plane with a compressive load at a constant rate of 25.4 mm/min acting parallel to and along the plane. A 12.5 mm wide strip loading was used to provide a uniform loading with which produces a nearly uniform stress distribution. The loading strips were ensured to be parallel and centered on the vertical diametric plane to avoid uneven stress. The elapsed time between removal of test specimens from the bath and the final load recording was made not to exceed 2 minutes. Application of the vertical compressive ramp load continued until the maximum load was reached. The peak load was recorded while the ITS was calculated using the following equation:

$$S_t = \frac{2P}{\pi t D} \qquad [4]$$

where:
S_t = indirect tensile strength (Pa);
P = maximum load (N);
t = height (m); and
D = diameter of specimen in meters (m).

Table 5. Summary of Soil-RAG Geopolymer mixtures.

Mixture No.	Mixture Type	Flyash Content (FA), %	Recycled Concrete Aggregate Content (RAG), %	Sodium Silicate Content (Si), %	Alkali Ratio (AR)
1	0F-0RCA-0Si	0	0	0	-
2	0F-0RAP-0Si	0	0	0	-
3	5F-15RCA-33Si	5	15	33	0.5
4	5F-15RAP-33Si	5	15	33	0.5
5	15F-15RCA-33Si	15	15	33	0.5
6	15F-15RAP-33Si	15	15	33	0.5
7	25F-15RCA-33Si	25	15	33	0.5
8	25F-15RAP-33Si	25	15	33	0.5
9	15F-5RCA-33Si	15	5	33	0.5
10	15F-5RAP-33Si	15	5	33	0.5
11	15F-25RCA-33Si	15	25	33	0.5
12	15F-25RAP-33Si	15	25	33	0.5
13	15F-15RCA-0Si	15	15	0	0
14	15F-15RAP-0Si	15	15	0	0
15	15F-15RCA-50Si	15	15	50	1
16	15F-15RAP-50Si	15	15	50	1
17	10F-10RCA-20Si	10	10	20	0.25
18	10F-10RAP-20Si	10	10	20	0.25
19	20F-20RCA-43Si	20	20	43	0.75
20	20F-20RAP-43Si	20	20	43	0.75
21	25F-25RCA-50Si	25	25	50	1
22	25F-25RAP-50Si	25	25	50	1

4.4.4. Durability Test

The wet and dry durability test was conducted based on ASTM 559 standard procedure *(58)*. The sample was prepared, compacted in five layers and extracted as seen in the modified proctor test. Two samples were prepared for each mixture of soil-cement, soil Geopolymer and soil RCA geopolymers being sample A (mass loss sample) and sample B (volume change sample) and these were cured in room temperature for 7 days. After curing, samples were submerged in water at room temperature for 5 hours, and then removed from water. With the weight and dimension of the sample A and B measured and recorded respectively, the samples were placed in an oven for 43 hours at 71℃. The samples were then removed from the oven, and weight and dimension of the sample were measured and recorded again which completed one cycle (48 hours) of repeated wetting and drying.

However, the sides of the weight loss specimen were scratched with eighteen strokes with 3-lbf load were applied in all sides of the sample, and four strokes were applied on each end prior to recording the volume. For each cycle, the dimensions were measured three times and averaged to calculate the volume and volume change of the specimen as specified in the procedure. Above mentioned procedures (submersing, heating, measuring weight and dimensions) were repeated for 12 cycles for both samples. The percentage weight loss of the specimen was calculated as:

$$\textit{Soil cement loss} = (\textit{Original mass} - \textit{final dry mass}) * 100\% / \textit{Original mass} \qquad [5]$$

4.5. Statistical Analysis

To obtain generality and precision for the developed experimental database, the experiments need to generate the required data, which must be conducted in a systematic and organized manner. The unifying feature of statistically designed experiments is that all factors of interest are varied simultaneously. The developed data has been presented in tabulated forms and plots. Analysis of variance (ANOVA) has been conducted on each set of data and a residual analysis technique was employed to check the accuracy of the developed systems and the degree of significance of each parameter. The experimental results were compiled, and statistical regression model/s were developed to relate the mechanical characteristics of Soil-RAG-GP with different mix variables. The model/s assisted in sensitivity analysis and selection of soil-RAG-GP mixtures for further comparison with soil-cement mixtures. The following polynomial regression model was used.

$$y = a_0 + \sum_{i=1}^{k} a_i x_i + \sum_{i=1}^{k} a_{ii} x_i^{\,2} + \sum \sum_{\substack{ij \\ i<j}} a_{ij} x_i x_j \qquad [6]$$

where:
y = mechanical property;
x_i, x_j, = mix variables; and
a_i, a_j, = coefficients.

The developed statistical models and the statistical analyses are detailed in Subsection 5.4.

5. ANALYSIS AND FINDINGS

5.1. Effect of Flyash Content

Figure 1 shows the effect of flyash content on the UCS and E of Soil-RAG-Geopolymer mixtures. A significant improvement was observed when soil was treated only with alkali (0% soil mixture) by replacing the OMC with alkali solution. The improvement was about 4 times to that of the control mixture. Interestingly, with the addition of 5% flyash and 15% RCA further increase of about 45% was noticed and no significant change in UCS and moduli occurred thereafter. On the other hand, the UCS increased with the increase in flyash content and exhibited an optimum value of 15% for Soil-RAP-Geopolymer mixtures. Similar trend was observed for E of the geopolymer mixtures. Improvements of up to 2.5 times for UCS and 5.2 times for E, respectively, relative to 5% FA mixtures were observed for Soil-RAP-Geopolymer mixtures.

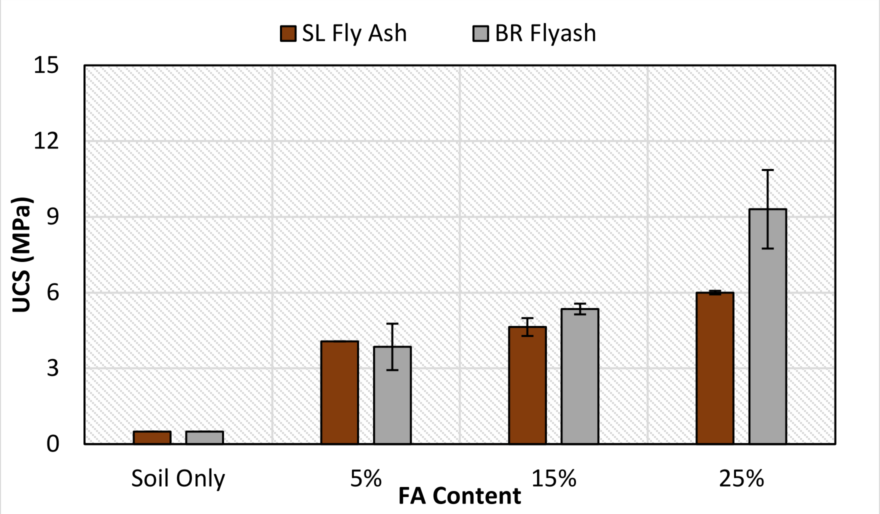


Figure 1. Effect of flyash on UCS of soil-RCA geopolymer.

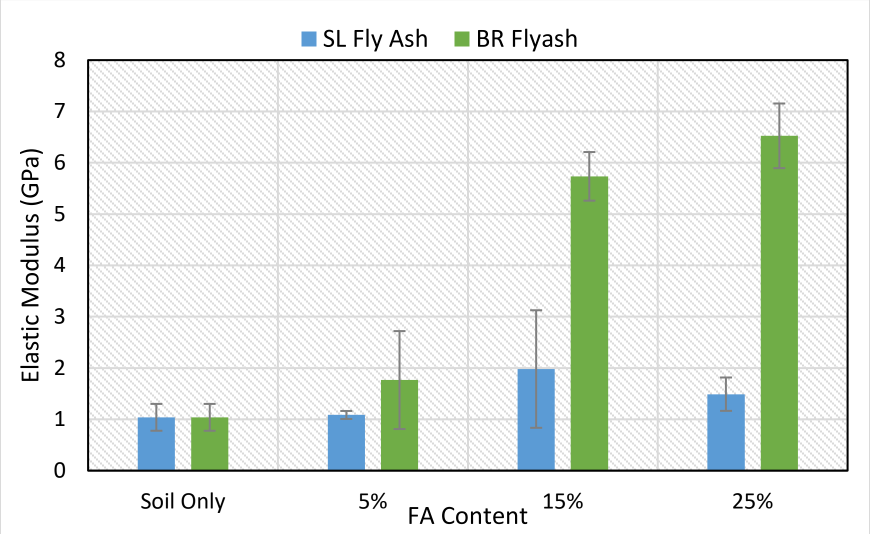


Figure 2. Effect of flyash on Elastic Modulus of soil-RCA geopolymer.

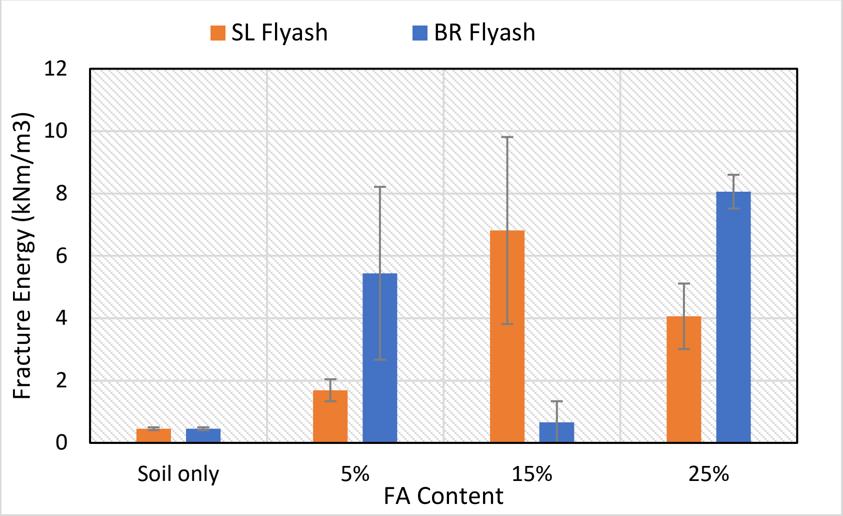


Figure 3. Effect of flyash on fracture energy of soil-RCA geopolymer.

Figures 4 show the variation of UCS, E and fracture energy values of specimens with FA content at 15% RAP, and 33% alkali mixture with 33% Na_2SiO_3 for Soil-RAP-GP mixtures. As the BR flyash content increased to 5%, the UCS and E were found to increase beyond 100% relative to the control one (soil only). The UCS and E values continuously increased with the increase in FA content, which could be attributed to the availability of more geopolymer binder in the mixture particularly at 25% FA content. On the other hand, the specimens of SL flyash did not show much increase in the UCS and E values and even decreases after 15% FA content. FA content beyond 5% exhibited same increases in UCS, as that of the BR flyash but the resulting E was different for both flyashes. Apparently, the mixture with BR flyash yielded more UCS and E values. The deviation on the elastic modulus for the BR flyash at 25% FA content is quite noticeable. This is an outcome of a poor sample preparation on one of the three specimens tested. The Soil-RAP-Geopolymer mixtures at 15% FA content exhibited significantly higher strength and modulus values as compared to the Soil-RCA-Geopolymer mixtures.

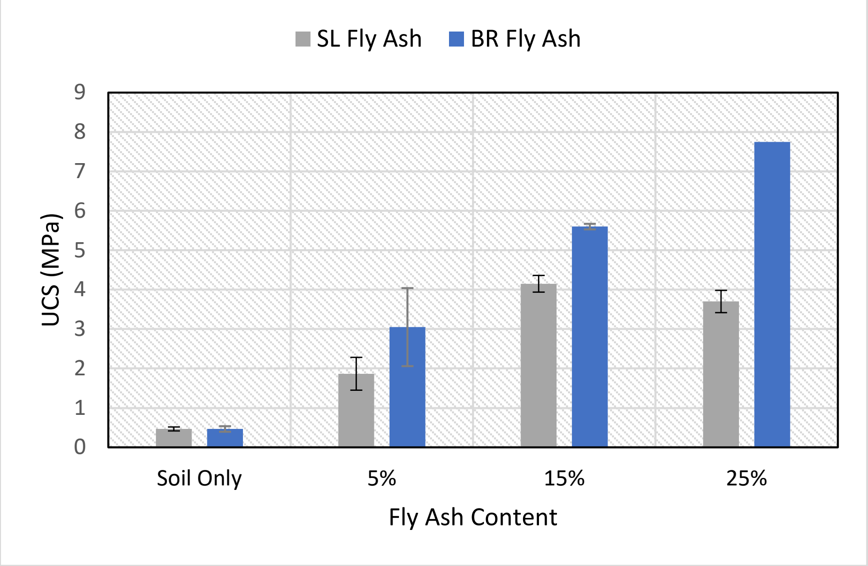


Figure 4. Effect of flyash on UCS of soil-RAP Geopolymer.

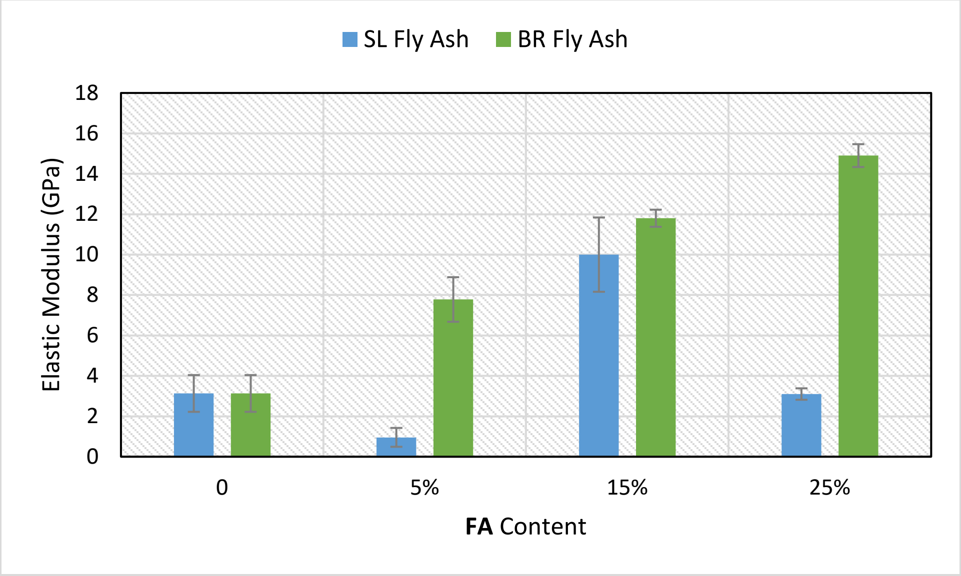


Figure 5. Effect of flyash on elastic modulus of soil RAP geopolymer.

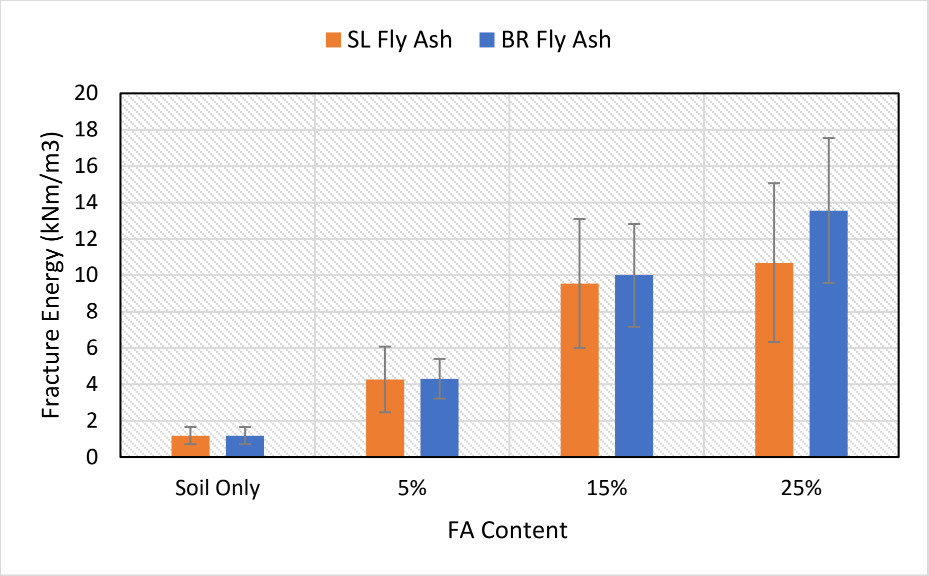


Figure 6. Effect of flyash on fracture energy of soil-RAP geopolymer.

5.2. Effect of RAG Content

From the experimental results (as shown Figure 7), both the BR and SL flyashes showed opposite trends in response to increase in RCA contents at 15% fly ash and 33% Na_2SiO_3. While the former decreased with RCA values, the later increased with both having similar values at 15% RCA. The BR flyash had the highest UCS value at 5% RCA as compared to SL with 25% RCA. The fall in the strength of RCA Geopolymer concrete for SL flyash was because of the weak adhesion presented by the recycled aggregate. With the addition of RCA of 15%, and 25% RCA on the BL flyash specimens, the strength increment was found to be 5%, and 8% respectively. When compared to the earlier studies made on RCA by past authors, the reduction in strength was reduced to an extent of approximately 5% in Geopolymer RCA. However, the E of SL flyash were higher at 15%RCA than that of the BR flyash while still maintaining consistent increase with RCA content. The fracture energy values duly follow the trend of the UCS for both fly ash types, but the elastic modulus of BR fly ash tend to decrease after 15% RCA while that of SL fly ash increases.

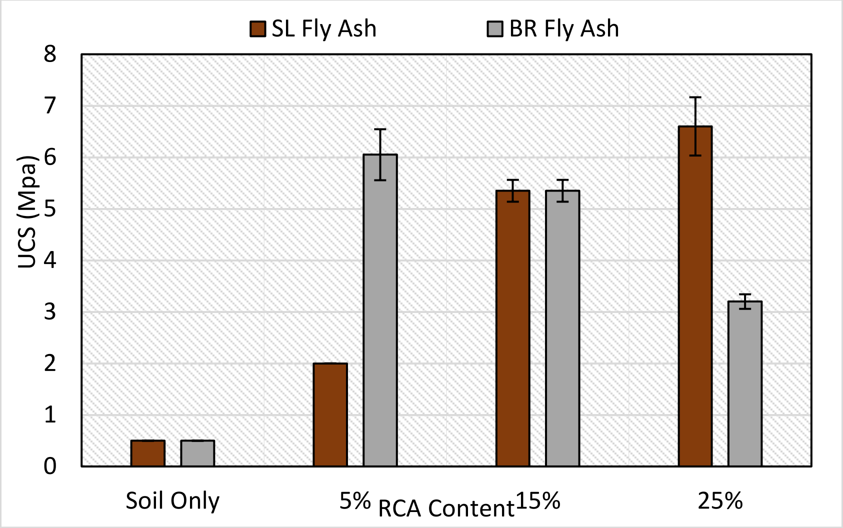


Figure 7. Effect of RCA content on UCS of soil-RCA geopolymer.

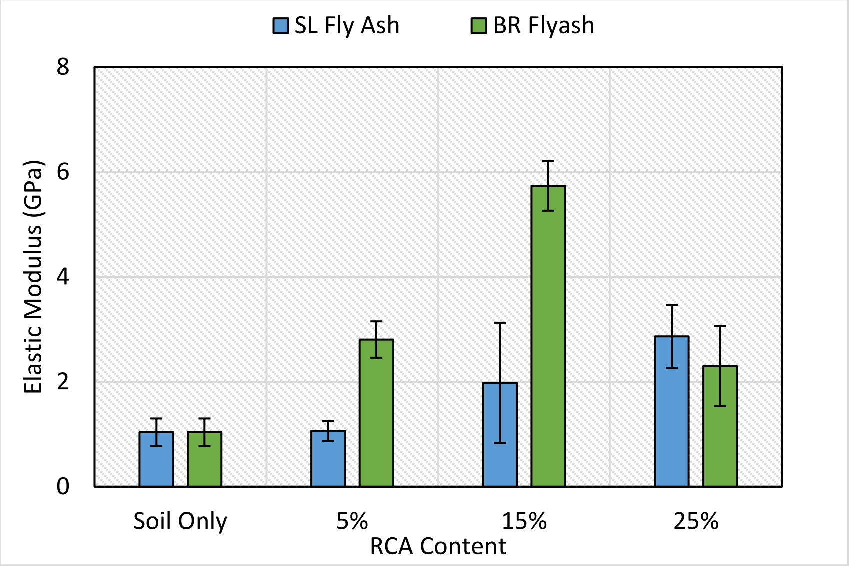


Figure 8. Effect of RCA content on elastic modulus of soil-RCA geopolymer.

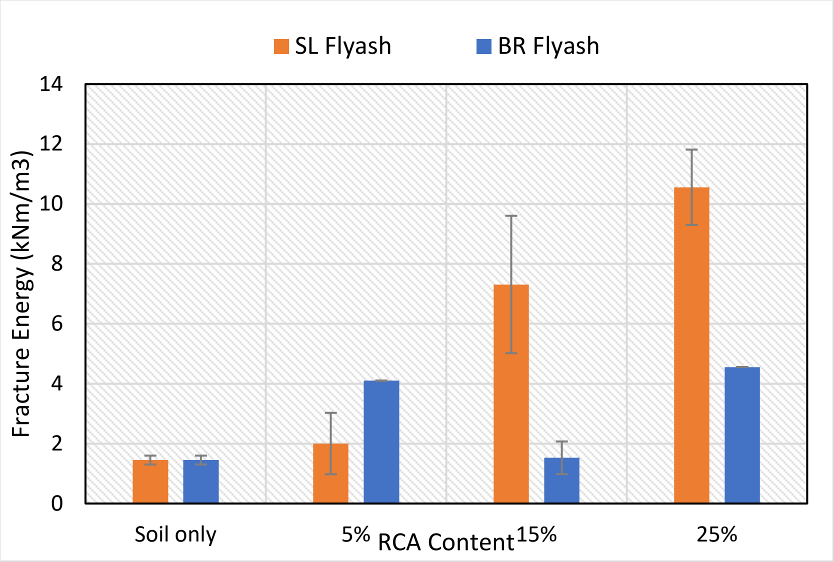


Figure 9. Effect of RCA content on fracture energy of soil-RCA geopolymer.

The addition of RAP showed a clear increase in strength and modulus values for a constant FA content of 15% as depicted in Figure 10. This was expected as the addition of aggregates typically contributes to the strength and modulus of a material. For the BR fly ash, the 5% RAP modified soil-geopolymer mixtures exhibited about 3.75 times higher strength as compared to the control ones while the 25% RAP mixtures did not show much increase. On the other hand, the RAP mixtures for the SL displayed increase in strength until 15% where it recorded it maximum before decreasing. This could be due to the non-sensitivity of the RAP to other geopolymer constituent as seen in the regression model.

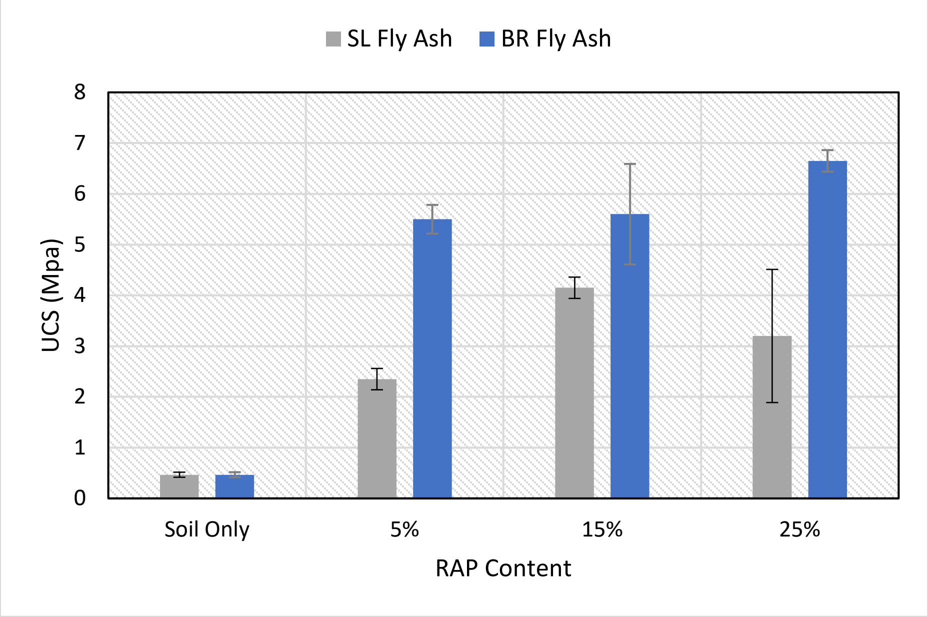


Figure 10. Effect of RAP content on UCS of soil-RAP geopolymer.

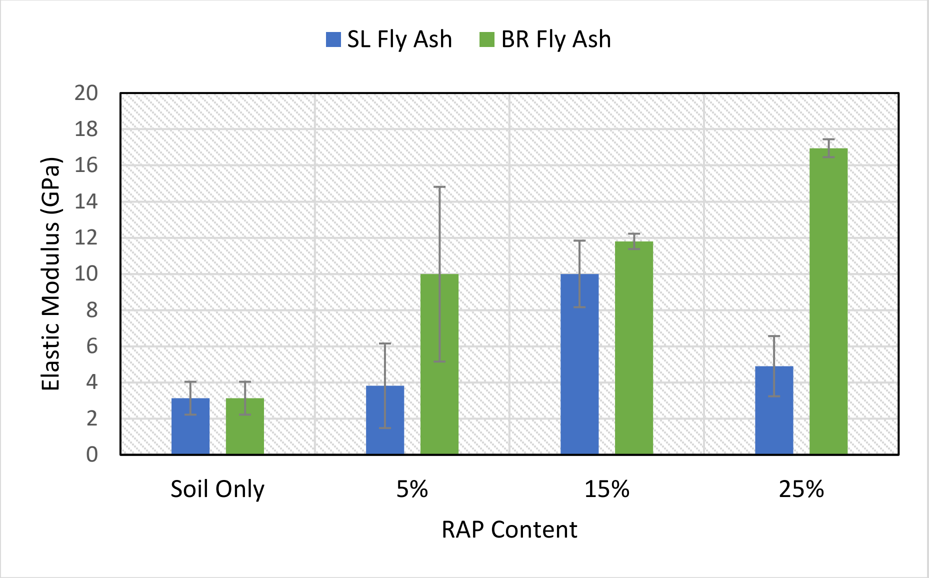


Figure 11. Effect of RAP content on the elastic modulus of soil-RAP geopolymer.

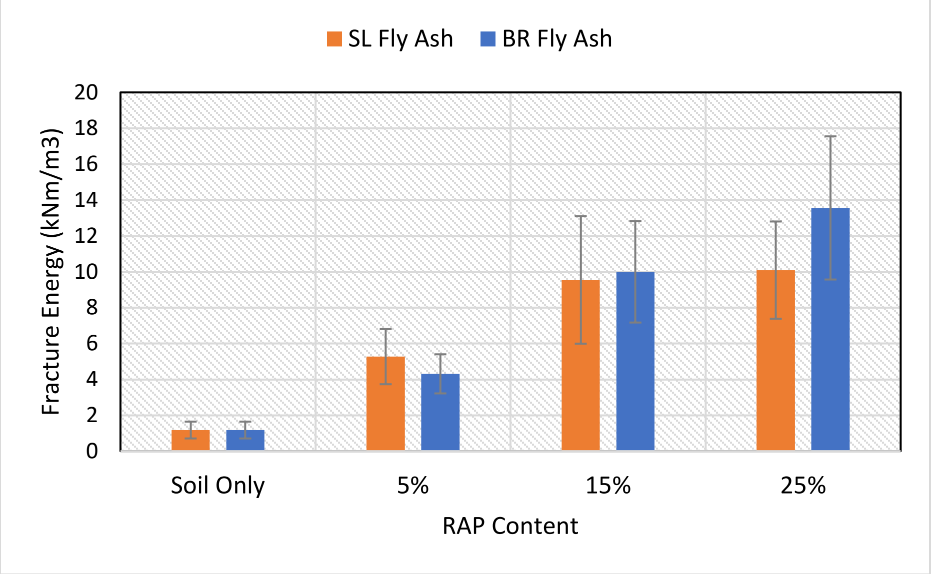


Figure 12. Effect of RAP content on the fracture energy of soil-RAP geopolymer.

5.3. Effect of Silicate Content

Surprisingly, as shown in Figures 13 and 14, the UCS and E values decreased significantly with increase in Na_2SiO_3 for the Soil RCA geopolymers particularly for the BR flyash. Interestingly, the highest values were shown to be at no Na_2SiO_3 content. It is suspected that the alkali hydroxide may be more important for strength development than alkali silicate at the optimum additional water content in order to obtain the maximum compressive strength. It is known that alkali hydroxide plays a role of leaching the Si and Al content from the reacting fly ash whereas alkali silicate aids in increasing the Si content in the system for geopolymerisation *(59)*. Sukmak et al. *(60)* reported that partial alkali hydroxide might be absorbed for soil cation exchange and therefore more alkali hydroxide was required than alkali silicate. For SL flyash, there was increase in the UCS and E values after 33% Na_2SiO_3 but the values of BR flyash based mixtures were more than that of SL for 0% and 33% Na_2SiO_3. The dissolution of silicate in the subsequent additions (50%) as in the case of BR flyash could be comparatively lower hence, the less UCS and E values. More availability of Aluminum in BR flyash could be a reason of increase in strength and stiffness at 0% Na_2SiO_3 as compared to SL flyash based mixtures. However, a microstructure analysis will give further insights into the nature of its kinematics at such effects.

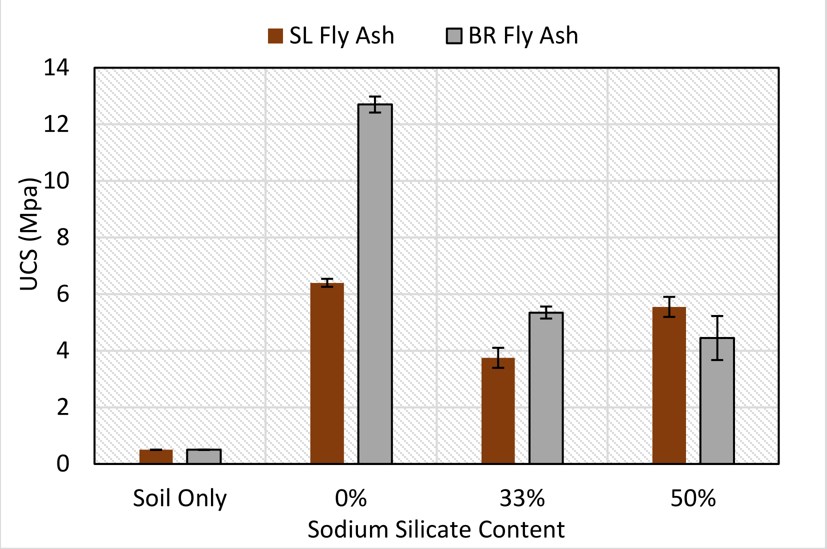


Figure 13. Effect of silicate content on UCS of soil-RCA geopolymer.

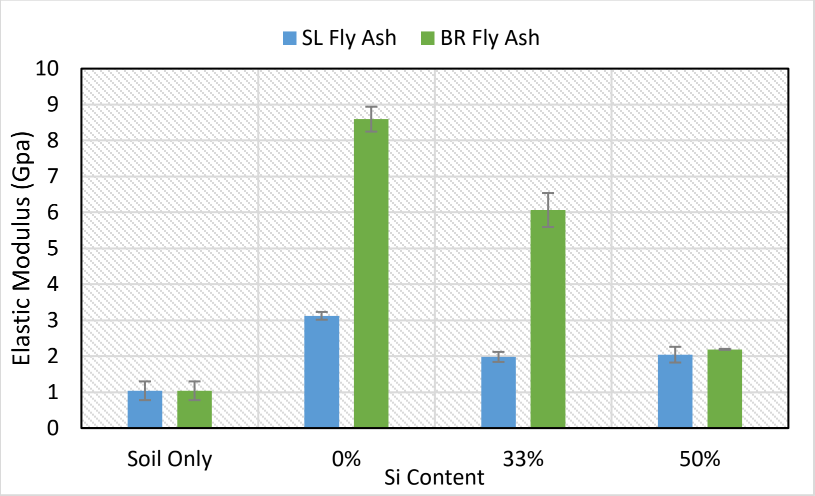


Figure 14. Effect of silicate content on elastic modulus of soil-RCA geopolymer.

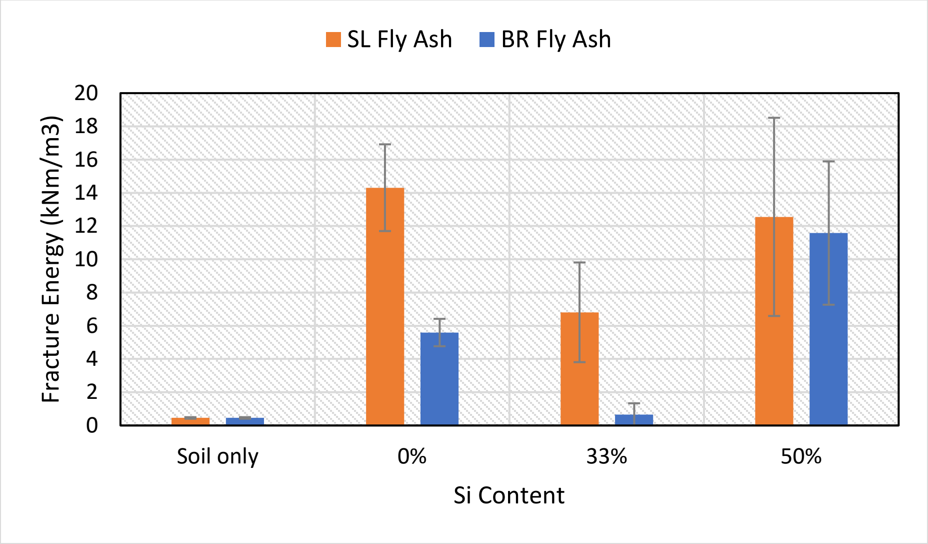


Figure 15. Effect of silicate on fracture energy soil-RCA geopolymer.

Figure 16 and 17 illustrate the impact of alkali ratio on the UCS and E of Soil-RAP-Geopolymer mixtures. It decreases with further increase of Na_2SiO_3/NaOH. It could be due to excess amount of alkali hydroxide within the sample as the ratio increases and this may be presented as salt precipitates which hinder the geopolymerisation thus resulting in strength reduction. Hence, it is suggested that an optimum amount of alkali hydroxide and alkali silicate could possibly obtain the maximum compressive strength. This condition is attainable when Na_2SiO_3/NaOH is 0. This is predicted to be a result of the constituents of the soil and the flyash in the material. For constant 15%FA and 15%RAP contents, the increase in Na_2SiO_3 content exhibited decrease in strength at 0.5 ratio. Comparatively, the decrease is more significant for RCA mixtures as compared to RAP ones. At alkali ratio of 1 the strength and modulus started to increase. At alkali ratio of 0 (no sodium silicate) the increases in strength and modulus for RCA mixture are 10 and 7 times the control mixtures, respectively. Similarly, the RAP mixtures at 0 alkali ratio exhibited improvements of about 10 and 16 times in strength and modulus, respectively.

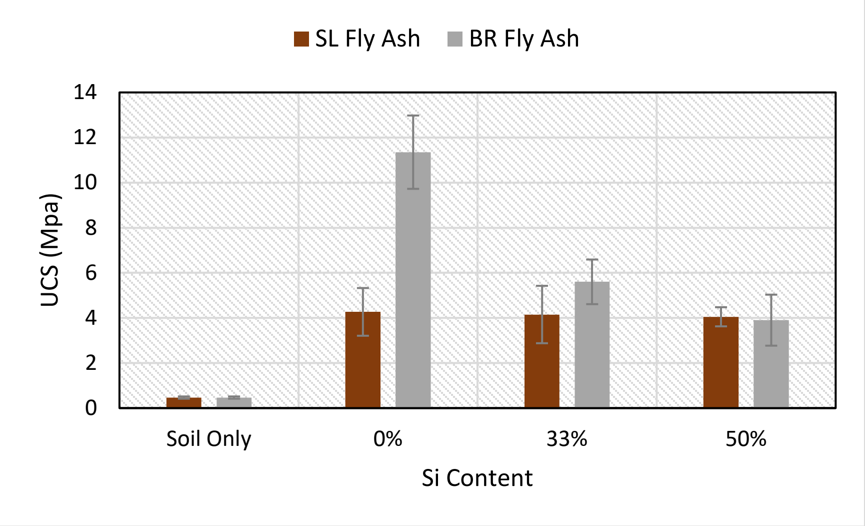


Figure 16. Effect of silicate content on UCS of soil-RAP geopolymer.

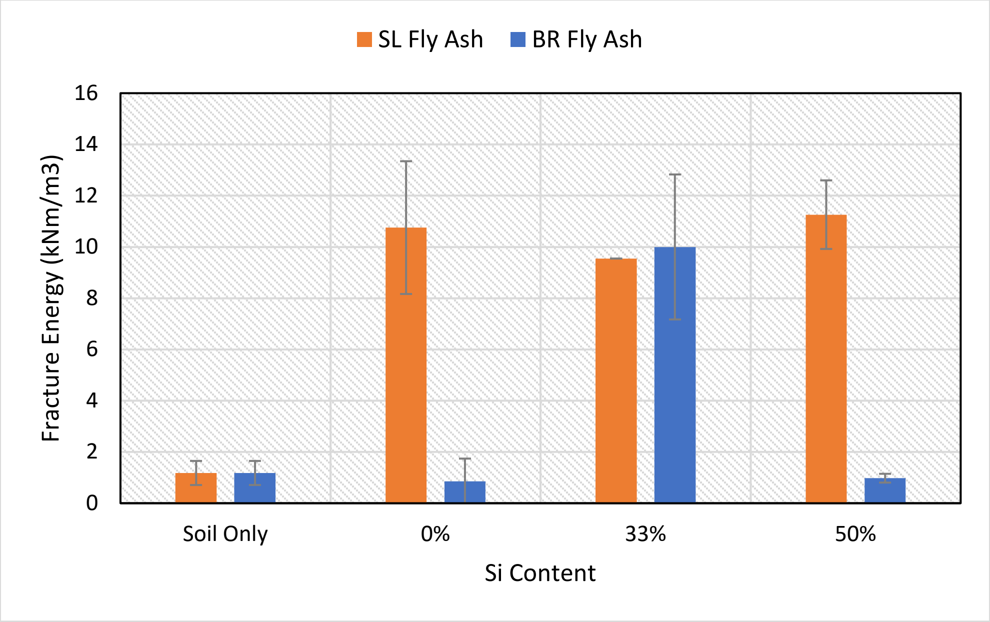


Figure 17. Effect of silicate content on fracture energy of soil-RAP geopolymer.

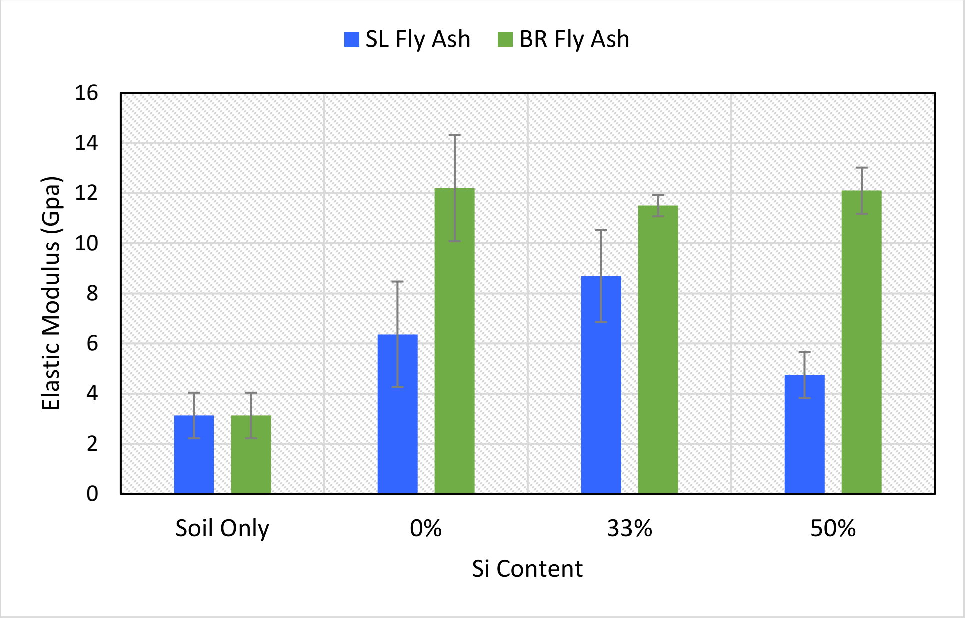


Figure 18. Effect of silicate content on elastic modulus of soil-RAP geopolymer.

5.4. Regression Analysis and Selected Mixtures

Regression analyses were conducted for UCS predictions for Soil-RAG-GP mixtures using the following generalized model:

$$y = \beta_o + \beta_1 x_{i1} + \beta_2 x_{i2} + \beta_3 x_{j1} + \beta_4 x_{i1}^2 + \beta_5 x_{i2}^2 + \beta_6 x_{i1} x_{i2} \qquad [7]$$

x_{i1}=0, 5, 10, 15, 20, and 25, x_{i2}=0, 5, 10, 15, 20, and 25, x_{j1}=0, 0.5, and 1

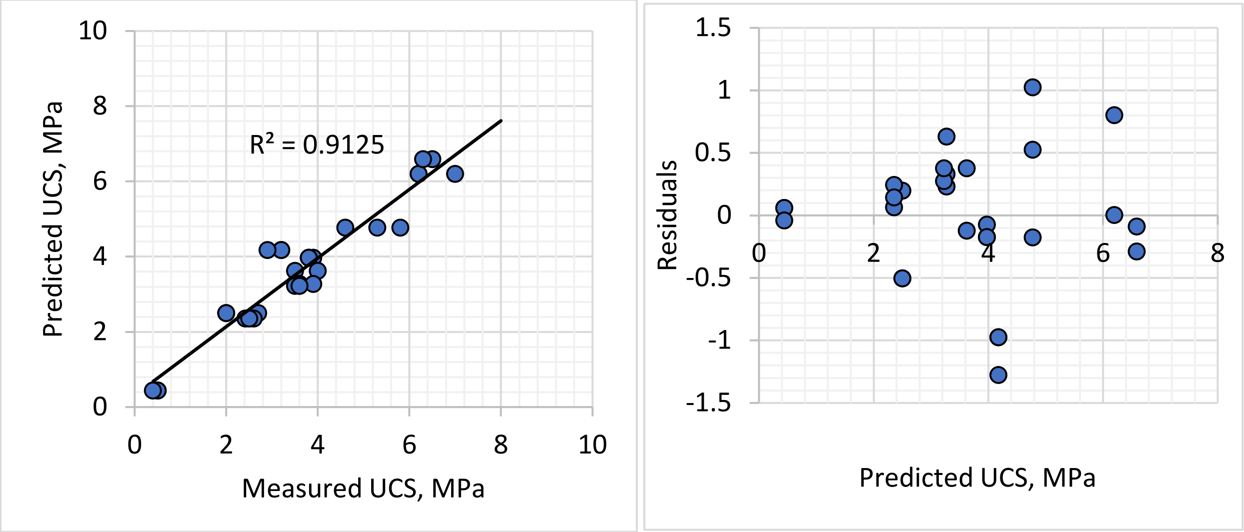
where:
y = UCS of specimen;
x_{i1}, $x_{i2,}$ and x_{j1} = mixed variables of flyash, RAG and Na_2SiO_3 content (Si) in alkaline solution of NaOH and Na_2SiO_3; and
β_o, β_1, β_2,…… β_6 = coefficients of the prediction model.

The UCS response for soil-RCA geopolymer, SL and BR flyashes based on the model above is as shown below in equation 8 and 9, respectively.

$$UCS = 0.4386 + 1.7720(FA) + 0.3359(RCA) - 0.8474(Si) + 0.0032(Si)^2 + 0.0073(RCA)^2 - 0.1205(FA)(RCA) + 0.0436(RCA)(Si) \quad [8]$$

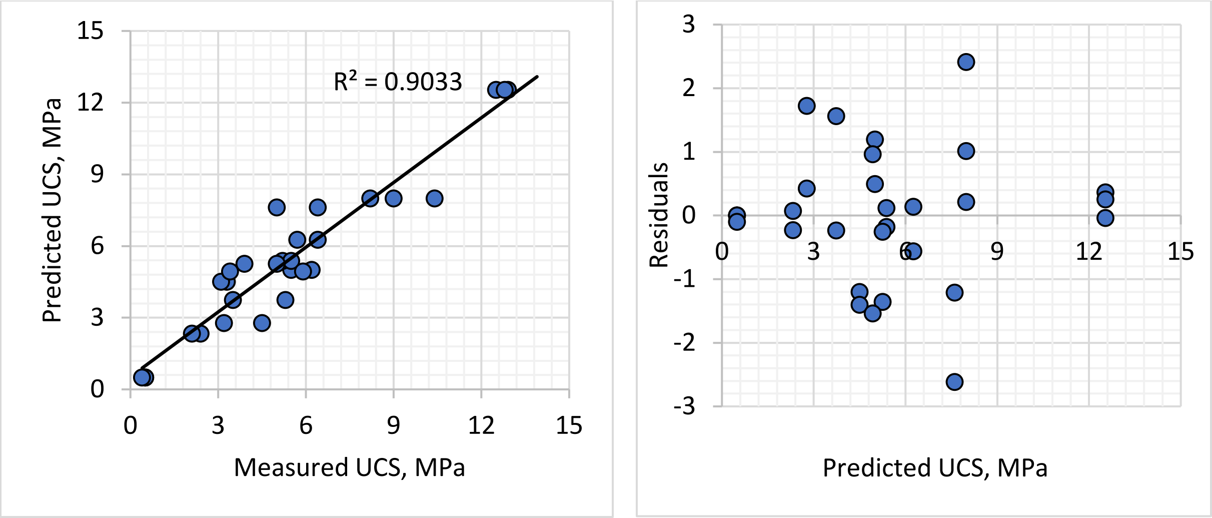
$$UCS = 0.5001 + 0.2606(FA) + 0.5419(RCA) - 0.0688(Si) + 0.0042(Si)^2 - 0.0191(RCA)(Si) \quad [9]$$

Thus, from the analysis, the parameters namely the percentage of flyash, RCA and Na_2SiO_3 in the one-way interaction and the combination of factor, namely percentage of flyash/RCA content in the two-way interaction is statistically significant indicating their major effects on the strength of Soil-RCA geopolymer (Table 6 and Table 7). This response was observed in both flyash types. Predicted versus measured values and distribution of residuals for the models are shown in Figures 19 and 20.



(a) (b)

Figure 19. (a) Predicted vs. measured UCS and (b) Residuals distribution for Soil-RCA geopolymers (SL flyash).



(a) (b)

Figure 20. (a) Predicted vs. measured UCS and (b) Residuals distribution for Soil-RCA geopolymers (BR flyash).

Table 6. Summary of statistical analysis for Soil-RCA Geopolymers mixtures (SL fly ash): (a) Regression statistics, (b) ANOVA summary, and (c) ANOVA results.

(a)

Regression Statistic	Value
Multiple R	0.955
R Square	0.913
Adjusted R Square	0.883
Standard Error	0.588
Observations	29

(b)

	df	SS	MS	F	Significance F
Regression	7	75.73	10.818	31.303	9.90E-10
Residual	21	7.26	0.346	-	-
Total	28	82.99	-	-	-

(c)

	Coefficients	Standard Error	t-Stat	P-value	Lower 95%	Upper 95%
Intercept	0.4386	0.3358	1.3062	0.2056	-0.2597	1.1368
FA	1.7720	0.4634	3.8242	0.0010	0.8084	2.7357
RCA	0.3359	0.0653	5.1446	0.0000	0.2001	0.4717
Si	-0.8474	0.2198	-3.856	0.0009	-1.3044	-0.3904
Si^2	0.0032	0.0006	5.5536	0.0000	0.0020	0.0043
RCA^2	0.0073	0.0032	2.2458	0.0356	0.0005	0.0140
(FA)(RCA)	-0.1205	0.0302	-3.986	0.0007	-0.1833	-0.0576
(RCA)(Si)	0.0436	0.0144	3.0330	0.0063	0.0137	0.0734

Table 7. Summary of statistical analysis for Soil-RCA Geopolymers mixtures (BR fly ash): (a) Regression statistics, (b) ANOVA summary, and (c) ANOVA results.

(a)

Regression Statistic	Value
Multiple R	0.950
R Square	0.903
Adjusted R Square	0.882
Standard Error	1.175
Observations	29

(b)

	df	SS	MS	F	Significance F
Regression	5	296.7	59.33	42.97	6.403E-11
Residual	23	31.8	1.38	-	-
Total	28	328.4	-	-	-

(c)

	Coefficients	Standard Error	t-Stat	P-value	Lower 95%	Upper 95%
Intercept	0.5001	0.6631	0.7541	0.4584	-0.8717	1.8719
FA	0.2606	0.0391	6.6642	0.0000	0.1797	0.3415
RCA	0.5419	0.0703	7.7111	0.0000	0.3965	0.6873
Si	-0.0688	0.0440	-1.5643	0.1314	-0.1598	0.0222
Si^2	0.0042	0.0010	4.0340	0.0005	0.0020	0.0063
RCA^2	-0.0191	0.0023	-8.4545	0.0000	-0.0238	-0.0144
(FA)(RCA)	0.5001	0.6631	0.7541	0.4584	-0.8717	1.8719
(RCA)(Si)	0.2606	0.0391	6.6642	0.0000	0.1797	0.3415

The UCS response for soil-RAP geopolymer, SL and BR flyashes based on the model above is as shown below in Equation 10 and 11 respectively. The summaries of statistical analysis are detailed in Tables 8 and 9.

$$UCS = -6.0747 + 0.7063(FA) - 0.4257(RCA) + 0.3579(Si) + 0.3579(Si)^2 + 0.02941(FA)(RCA) - 0.03021(FA)(Si) \qquad [10]$$

$$UCS = -6.0569 + 1.2187(FA) - 0.5524(RCA) + 0.4011(Si) + 0.0074(RCA)^2 + 0.0012(Si)^2 + 0.0257(FA)(RCA) - 0.0416(FA)(Si) \qquad [11]$$

The two models above showed that the significance of the two-way interaction was more obvious in the FA/Si combination unlike the soil-RCA geopolymers. This further explained the difference in the chemical reaction of RCA and RAP with the other constituent variables. While flyash is showing more affinity for RCA in soil-RCA geopolymers, it is attracted more to silicate in soil-RAP geopolymer. This phenomenon could be as a result of RAP being more deficient in silicate content as shown in the chemical composition in Table 2. Nevertheless both models showed good relationship between predicted versus measured values and even scatter of residuals (Figures 21 and 22).

Table 8. Summary of statistical analysis for Soil-RAP Geopolymers (SL fly ash): (a) Regression statistics, (b) ANOVA summary, and (c) ANOVA results.

(a)

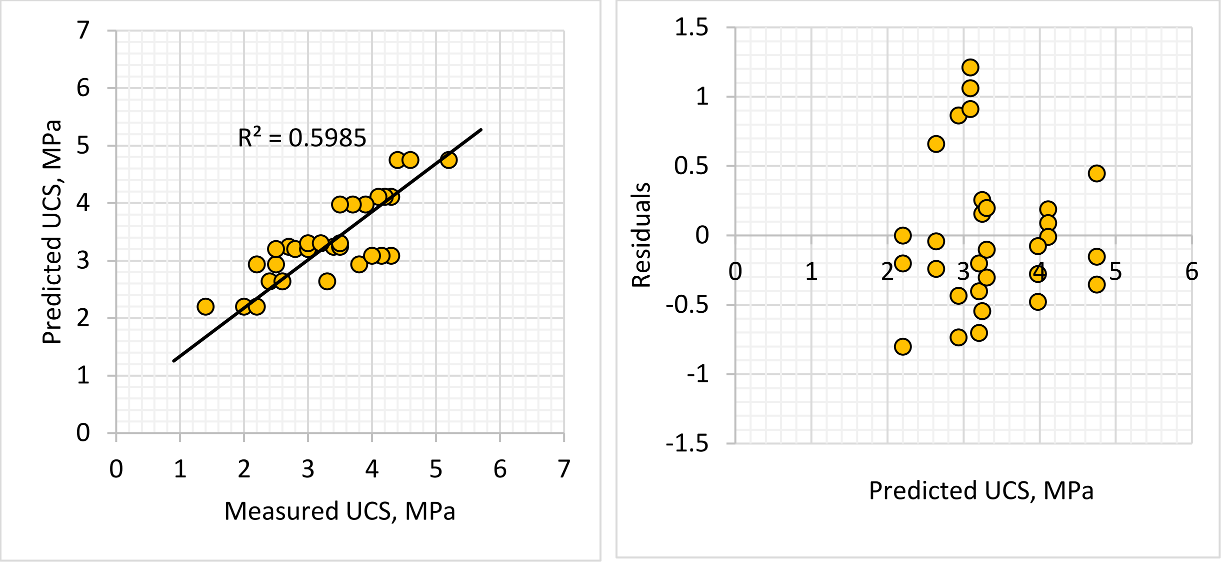
Regression Statistic	Value
Multiple R	0.809
R Square	0.654
Adjusted R Square	0.564
Standard Error	0.590
Observations	30

(b)

	df	SS	MS	F	Significance F
Regression	6	15.112	2.519	7.242	0.000197
Residual	23	7.999	0.348	-	-
Total	29	23.112	-	-	-

(c)

	Coefficients	Standard Error	t-Stat	P-value	Lower 95%	Upper 95%
Intercept	-6.0747	2.6201	-2.3185	0.0297	-11.4948	-0.6546
FA	0.7063	0.1616	4.3713	0.0002	0.3720	1.0405
RCA	-0.4257	0.2359	-1.8046	0.0842	-0.9137	0.0623
Si	0.3579	0.1587	2.2550	0.0340	0.0296	0.6862
Si^2	0.0022	0.0005	4.2012	0.0003	0.0011	0.0033
RCA^2	0.0294	0.0162	1.8207	0.0817	-0.0040	0.0628
(FA)(RCA)	-0.0321	0.0109	-2.9451	0.0073	-0.0546	-0.0095
(RCA)(Si)	-6.0747	2.6201	-2.3185	0.0297	-11.4948	-0.6546



(a) (b)

Figure 21. (a) Predicted vs. measured UCS and (b) Residuals distribution for Soil-RAP geopolymers (SL flyash).

Table 9. Summary of statistical analysis for Soil-RAP Geopolymers (BR fly ash): (a) Regression statistics, (b) ANOVA summary, and (c) ANOVA results.

(a)

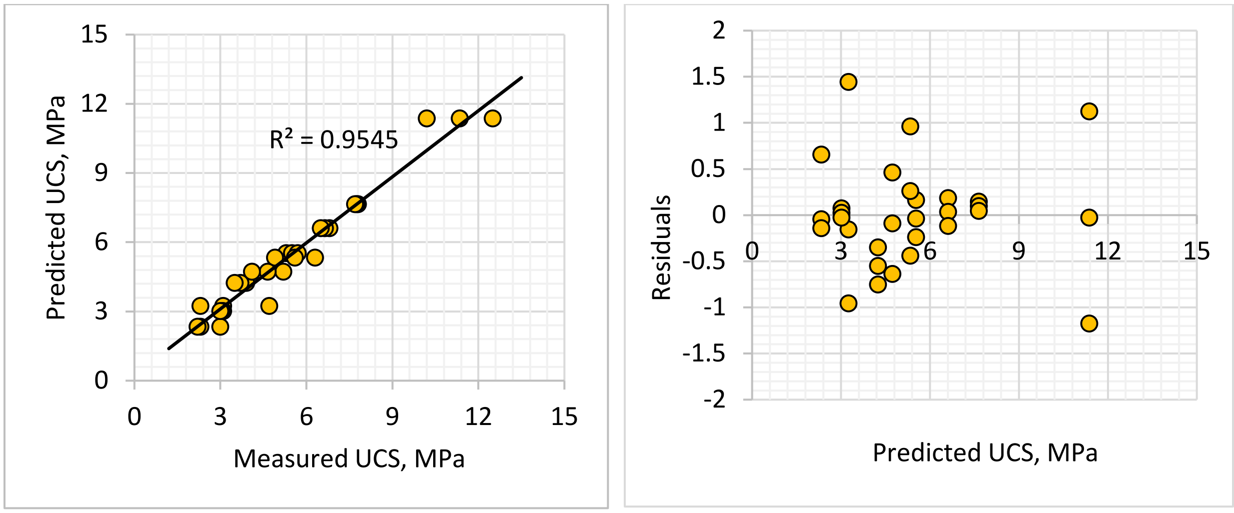
Regression Statistic	Value
Multiple R	0.977
R Square	0.954
Adjusted R Square	0.940
Standard Error	0.643
Observations	30

(b)

	df	SS	MS	F	Significance F
Regression	7	190.877	27.26810	65.9103	2.71662E-13
Residual	22	9.102	0.41372	-	-
Total	29	199.978	-	-	-

(c)

	Coefficients	Standard Error	t-Stat	P-value	Lower 95%	Upper 95%
Intercept	-6.0569	2.8768	-2.1054	0.0469	-12.0230	-0.0907
FA	1.2187	0.1900	6.4145	0.0000	0.8247	1.6128
RCA	-0.5524	0.2831	-1.9515	0.0638	-1.1395	0.0346
Si	0.4011	0.1756	2.2844	0.0324	0.0370	0.7653
Si^2	0.0074	0.0033	2.2313	0.0362	0.0005	0.0142
RCA^2	0.0012	0.0006	1.9472	0.0644	-0.0001	0.0025
(FA)(RCA)	0.0257	0.0177	1.4534	0.1602	-0.0110	0.0623
(RCA)(Si)	-0.0416	0.0122	-3.4120	0.0025	-0.0669	-0.0163



(a) (b)

Figure 22. (a) Predicted vs measured UCS, (b) Residuals distribution for Soil-RAP geopolymers (BR flyash).

The cost effectiveness was determined according to requirement for alkali, and RAG addition. For instance, the mixtures with 15% RAG or greater and 33% Si or less are most preferred because they optimize the usage of RAG which is the central theme of this research with less focus or dependence on flyash. Apparently, using more recycled aggregates not only reduce the entire life cycle cost of the project, it makes more sustainable. Based on the model prediction and sensitivity, measured values, and cost effectiveness, the following geopolymer mixtures were selected for further testing as shown in Table 10.

Table 10. Selected mixtures for Soil-RAG geopolymers.

	SL 1	SL 2	BR 1	BR 2
RCA	15%FA25%RCA33%Si	15%FA15%RCA0%Si	15%FA15%RCA0%Si	25%FA15%RCA33%Si
RAP	15%FA15%RAP33%Si	15%FA15%RAP0%Si	15%FA15%RAP0%Si	15%FA25%RAP33%Si

5.5. Mechanical Characteristics of Selected Soil-cement and Soil-RAG-GP Mixtures

5.5.1. Unconfined Compressive Strength (UCS) and Elastic Modulus (E)

The UCS and E values for the soil RCA geopolymers confirm the importance of RCA content addition in geopolymers. It is evident from the results as shown in figure 23 that the UCS of selected mixtures of BR flyash have the higher UCS as compared to both soil cement and SL fly ash. The highest which is BR1 has twice as much strength as soil cement and this can be attributed to the fly ash chemical content because the said mix (BR1) has no silicate content in its mix. On the other hand, the 7 and 28-day strengths of soil cement are quite higher than that of the selected mixtures because of quick strength attainment of soil cement at 7 days in addition to soil-RCA geopolymer having slower pozzolanic reaction at the earliest stage of curing.

Ultimately, all selected mixtures for both fly ash types are stiffer than 28-day soil cement in similar pattern to UCS, which further infer the linear relationship between UCS and elastic modulus of any material.

Comparing the 72h oven curing Soil-RAP geopolymers with 28-day soil cement UCS, it stemmed from the chart in figure that the soil cement mixtures have higher UCS than non-silicate selected mixture for fly ash but surprisingly, a lower elastic modulus. However, comparing with BR fly ash, both selected mixtures demonstrated higher strength and elastic modulus as indicated in figure 25. As expected, the 7 and 28-day strengths are much lower than the soil cement mixtures.

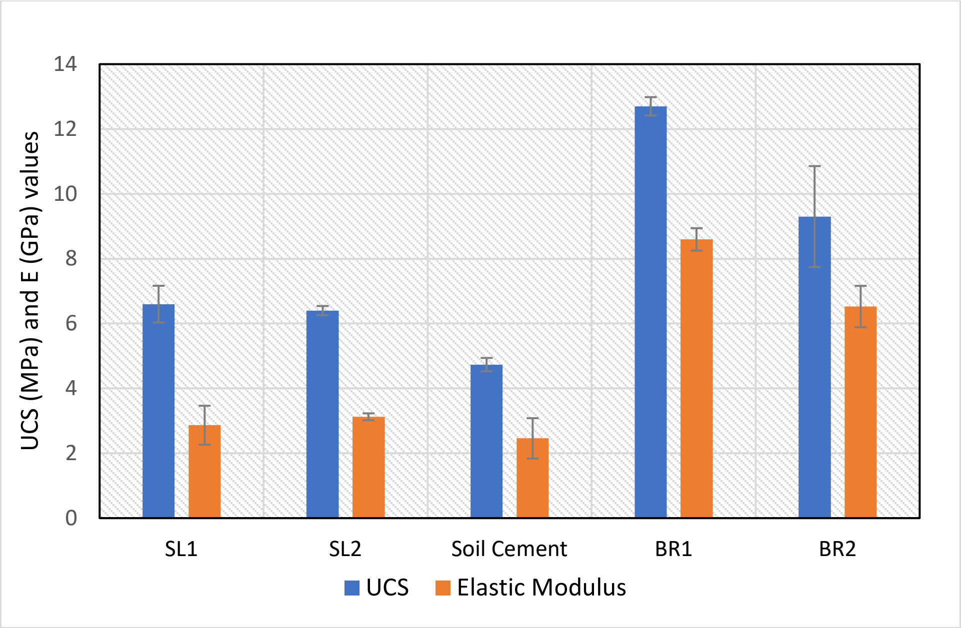


Figure 23. UCS and elastic moduli of soil-RCA geopolymers and soil cement.

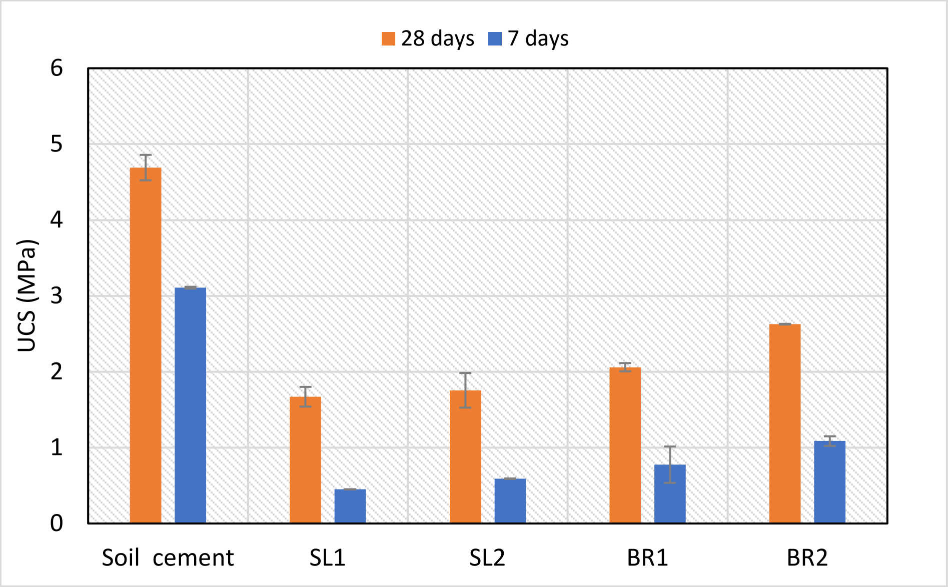


Figure 24. Room temperature curing for soil-RCA geopolymers and soil cement.

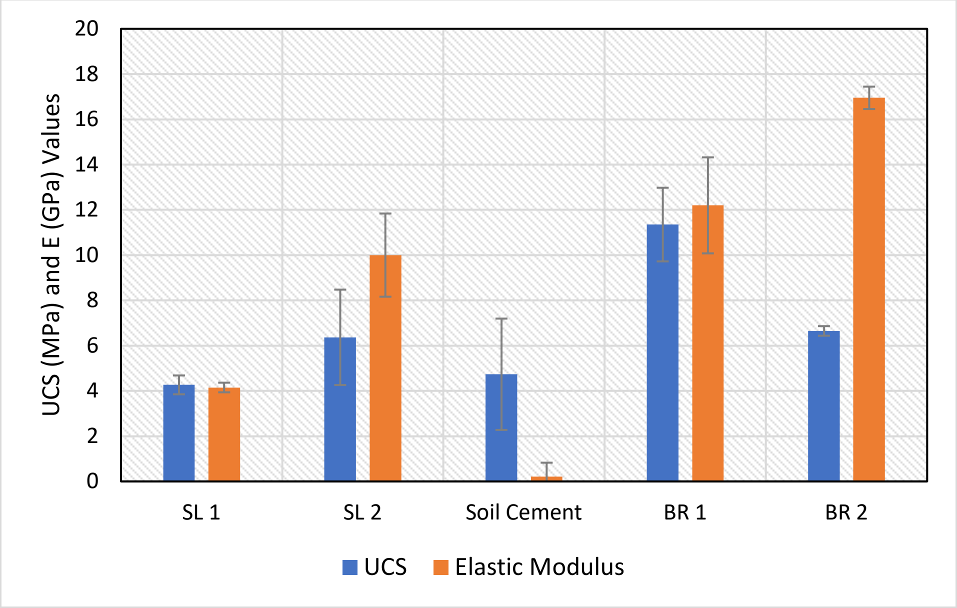


Figure 25. UCS and elastic moduli of soil-RAP geopolymer and soil cement.

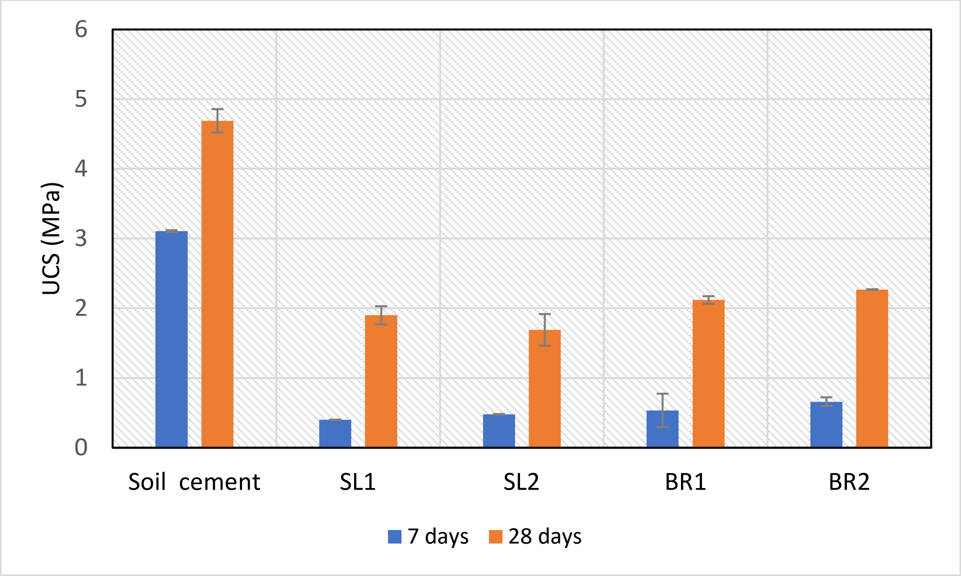


Figure 26. Room temperature curing for soil-RAP geopolymers.

5.5.2. Resilient Modulus and Permanent Deformation

The resilience modulus of the selected soil-geopolymer and soil cement-mixtures at different are shown in Figure 27. It can be seen that selected Soil-RCA-Geopolymer mixture exhibited comparable resilient modulus to that of soil-cement mixture. However, Soil-RAP-Geopolymer mixture showed about 30% lower values than the soil-cement mixtures. Similar trend was observed for permanent deformation characteristics as illustrated in Figure 27 and 28. It was found that the permanent deformation as well as the rate of its accumulation under repeated load were not much different than the soil-cement mixtures.

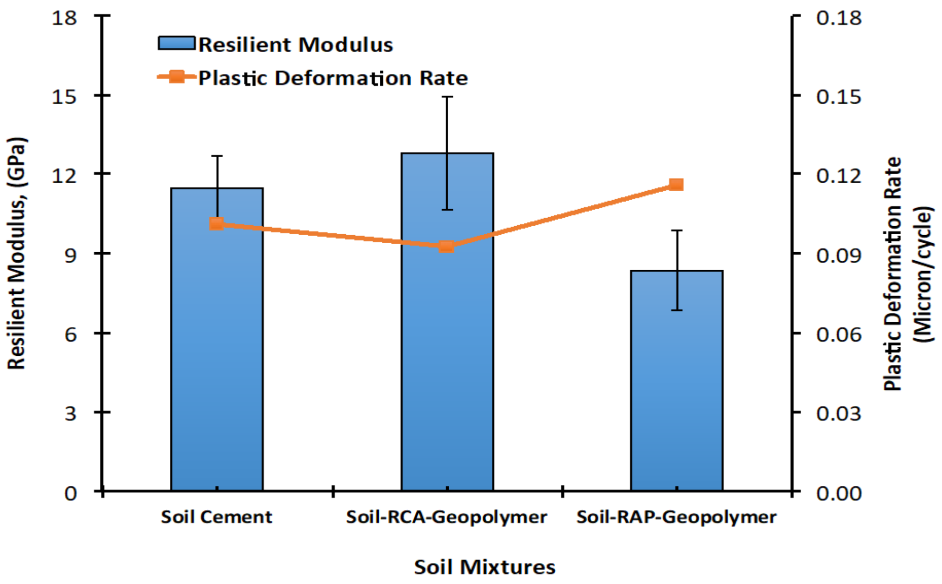


Figure 27. Resilient Modulus and plastic deformation of soil RAG geopolymers and soil cement.

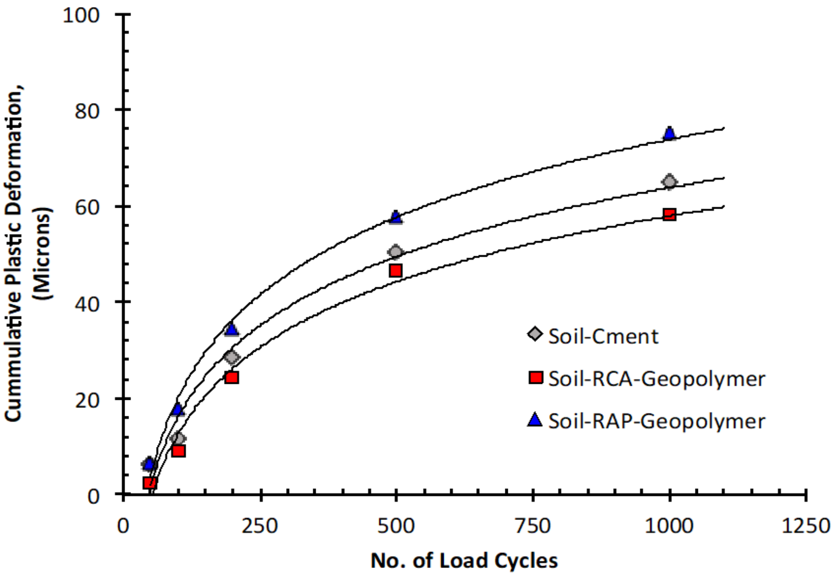


Figure 28. Cumulative plastic deformation of soil-RAG geopolymers and soil cement.

5.5.3. Indirect Tensile Strength (ITS)

Figure 29 shows the graphical representation for soil-RAG geopolymers samples at 72-hour oven curing as compared with soil cement after 28 day curing periods. In the case of indirect tensile strength for RCA samples, a very similar trend to that of compressive strength is observed, where it increases with the addition of RCA contents (see figure 29) and the effect of oven curing was however, found to improve the tensile strength of geopolymers containing RCA by about 11–21% as compared with the soil cement mixtures. A higher tensile strength for the geopolymer mixtures also indicates a stronger cracking resistance as compared with the soil cement mixture. This expectedly can be attributed to the presence of more Aluminum ions in the flyash particularly the BR 1, which strengthens the bonding between the soil and RCA aggregate hence, tensile strength is very high. In addition, the results also indicate that tensile strength increases as the flyash content increases. Notably, selected mixtures of both flyash can tolerate higher tensile strain prior to failure and more likely to resist cracking than soil-cement mixtures. For the soil RAP geopolymers, one of the selected mixtures had a lower ITS than soil cement as seen in the UCS values. While the selected mixture with silicate content demonstrated higher strength for SL flyash, the non-silicate mixture had the higher for BR flyash and expectedly the highest in the results. Also, less cracks than the soil-RCA geopolymers were observed after the completion of the durability procedures. In overall, soil-RCA geopolymers showed the highest ITS among the mixtures.

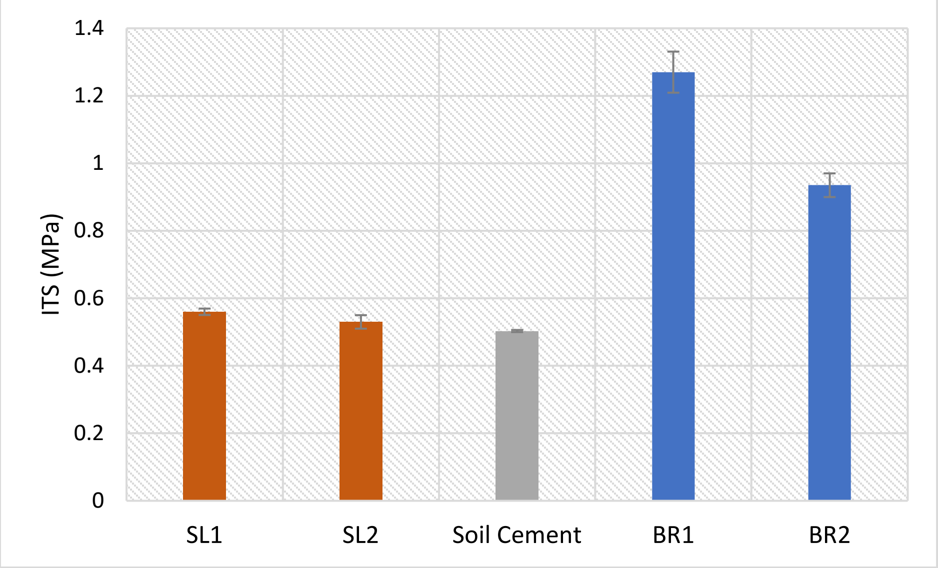


Figure 29. Indirect tensile stress for soil-RCA geopolymers and soil cement.

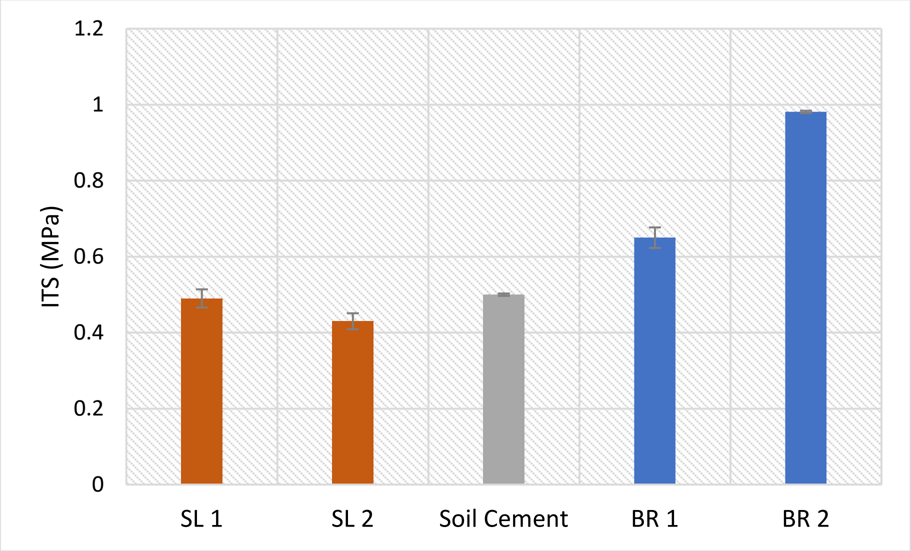


Figure 30. Indirect tensile stress for Soil-RAP geopolymers and soil cement.

5.5.4. Durability

The wet and dry durability test results for soil RAG geopolymers are summarized in Table 11. The data in the table depicts that the 10% soil-cement mixtures and soil geopolymer mixtures passed the durability tests criteria. The ASTM standard requires that the durability specimen cannot exceed a change in volume of 2% or a change in mass of 10%. The worst volume change was recorded for soil cement mixture at 6.25%. This could be due to more shrinkage and swelling tendency than other mixtures. On the other hand, the soil-cement mixtures and soil geopolymer mixtures experienced less than 1.5% weight loss.

Since all geopolymer specimens were cured at 7 days room temperature, it is thought that the voids and porosity in the specimens should be free of water at the beginning of the test. Therefore, the weight gain of the soil-RAG-based geopolymer samples can be related to the saturation of the empty or partially filled voids and pores. The visual appearance of the soil geopolymers sample showed visible sign of cracking, leaching, and deterioration after 10 cycles particularly in soil cement and soil-RCA specimens which in the absence of any visible damage, explains the weight gain as related to the penetration of the water into the voids and pores of these specimens.

Table 11. Durability results for Soil-RAG geopolymers.

	Soil RAP Geopolymer		**Soil RCA Geopolymer**	
	Vol. Change (%)	**Mass Change (%)**	**Vol. Change (%)**	**Mass Change (%)**
SL 1	1.65	5.8	1.00	4.25
SL 2	1.72	6.4	1.41	4.36
BR 1	1.48	5.5	1.39	4.43
BR 2	1.33	5.2	1.27	4.40
Soil Cement	1.50	6.3	1.50	6.30

5.5.5. Microstructure and Fracture Morphology of Soil-RAG-Geopolymer Mixture

Figure 31(a, b, c, d) represents the SEM micrograph of soil-geopolymer mixture with RCA containing different proportion of Na_2SiO_3 and NaOH as alkali activator. Figure 31(a, b) depicts the SEM image of mixture containing 15% FA 15% RCA and Na_2SiO_3: NaOH as a ratio of 0:1; so Na_2SiO_3 is not present in the mixture and only NaOH is acting as alkali activator. This micrograph is significantly describing the bonding behavior in the absence of Na_2SiO_3 while only NaOH is accelerating the geopolymerization reaction. Figure 31(a) shows that spherical flyash and flaky soil and RCA particles are bonded together (Zone A, B) with geopolymer gel which is an indication of strong bonding *(51, 61, 62).* From Figure 31(b) it can be observed that some flyash particles are still in unreacted (Zone C) and partially reacted (Zone D) *(61, 62)* condition, indicating that the geopolymerization reaction is still in progress and might continue. The UCS reported for this particular mixture was around 6.4 MPa.

Figure 31(c, d) represents SEM micrograph of Na_2SiO_3 and NaOH activated soil-geopolymer mixture with RCA. This mixture contains Na_2SiO_3 and NaOH as a ratio of 1:2. This micrograph explains bonding behavior when both Na_2SiO_3 and NaOH are present in the geopolymerization process. From these images; it can be observed that a fairly different microstructure is formed due to the addition of Na_2SiO_3 to the mixture. Although moderate geopolymerization seems to be happened but lots of unreacted (Zone E, F) and some partially reacted (zone G) *(61, 62)* flyash are also visible in the SEM image which provides the indication of weak bonding in the structure and possible explanations for the overall low strength of 3.7 MPa relative to the mixture without Na_2SiO_3.

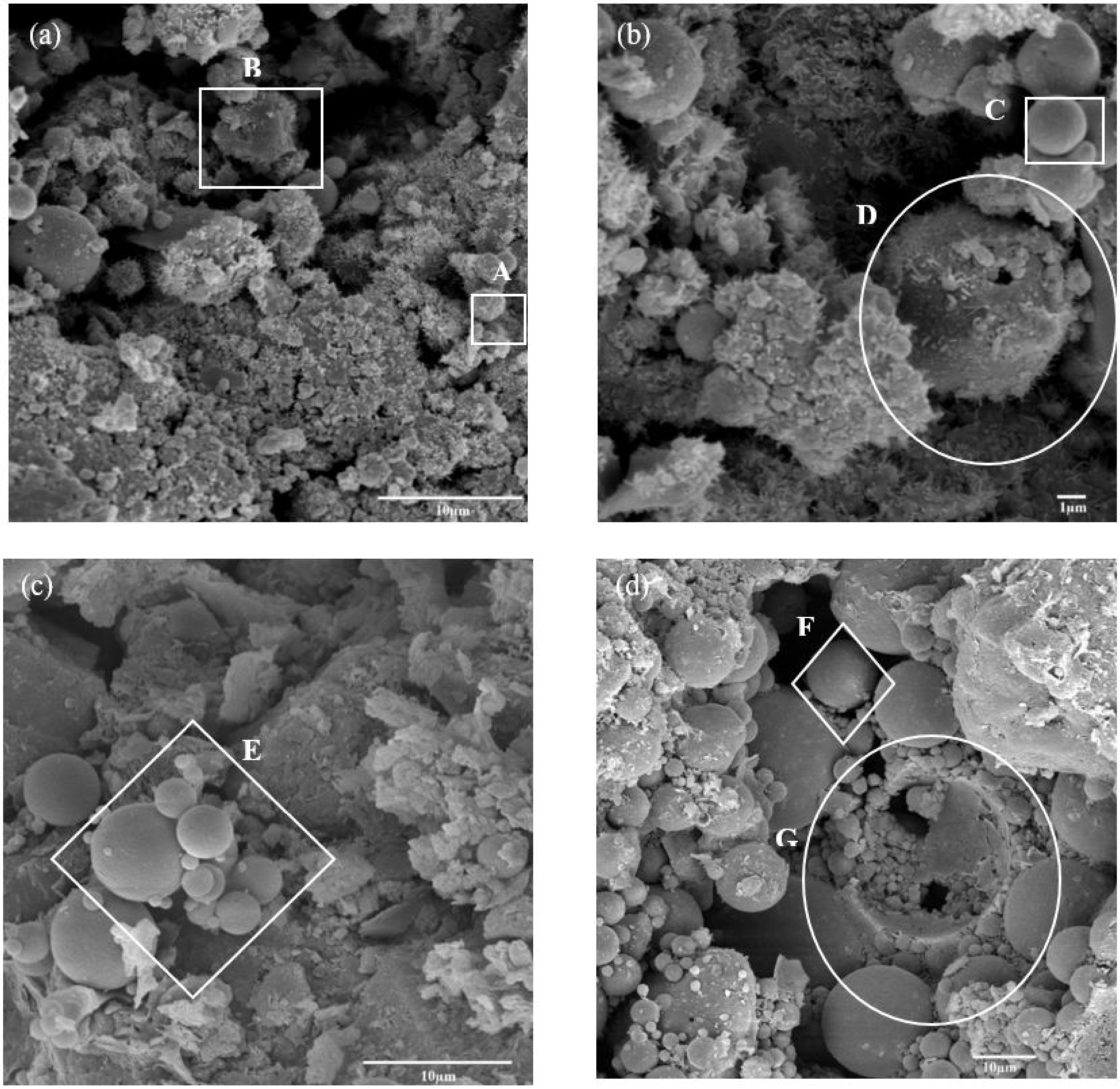


Figure 31. SEM analysis, the microstructure and morphology of soil-geopolymer with RCA (a, b) only NaOH, (c, d) Na_2SiO_3: NaOH as 1:2.

5.6. Cost Analysis

In order to conduct cost analysis, the following assumptions and calculations were made:

- The durability and shrinkage characteristics of the developed RCA/RAP Geopolymer base materials are better than the soil-cement mixtures. Even though it is difficult to quantify the actual field performance from laboratory data, it is expected that such improvements may lead to the service life extension of about 25%.

- It is assumed that the cost of developed RCA/RAP geopolymer mixture is the same as the conventional cement stabilized (CSD) mixtures.
- Hot-mix asphalt (HMA) application of 3.5” over 8” to 10” soil-cement base is used in this comparison.
- Added cost savings and benefits due to energy saving and environment impact are not considered in this analysis.

The following calculations were made:

- Cost of 3.5” HMA over soil-cement base/lane-mile = $350,000;
- Service life of such HMA soil-cement pavement = 15 yr;
- Service life of Geopolymer pavement (25% increase) = (1.25*15) = 18.75 yr;
- Cost /lane-mile/year for soil-cement base pavement = ($350,000/15) = $23,333;
- Cost /lane-mile/year for Geopolymer base pavement = ($350,000/18.75) = $18,666;
- Cost Reduction/lane-mile/year = ($23,333-$18,666) = $4,667; and
- % Cost Reduction/lane-mile/year = ($4,667/$23,333)*100 = 20%.

6. CONCLUSIONS

This research study focused on the development and evaluation of sustainable Soil-Recycled Aggregate-Geopolymer (Soil-RAG-GP) mixtures for road base and subbase layers in order to develop an alternate green material with a high recycled content and less carbon footprint as supported by U.S green Building Council under their LEED program. It was an attempt to find an alternative solution to the traditional soil-cement mixture used for pavement base and subbase layers. Based on the results and discussion, the following conclusions and recommendations were drawn:

1. For Soil-RAP-Geopolymer mixtures the strength and moduli increased with the increase in FA content and exhibited an optimum value. Similar trend was observed with increasing RAP dosage. On the other hand, increasing alkali ratio exhibited only slight improvement.
2. An increase in FA had no effect on the UCS and E of the Soil-RCA-Geopolymer mixture. An increase in RCA dosage has a positive effect on the UCS of the mixture. However, increase in sodium silicate had a decreasing then increasing effect on the UCS and E values.
3. The UCS, E, and ITS of the selected geopolymer mixtures at 72-h curing (60ºC) were considerably higher than the 28-day room temperature cured soil-cement mixture. The BR flyash-based geopolymer mixtures exhibited the highest values. On other hand, the 7-day room temperature curing of Soil-RCA geopolymer mixtures yielded much lower values than the soil-cement mixtures. This indicated that Soil-RCA geopolymer needed extra time to cure and gain strength at room temperature.
4. The resilient moduli, permanent deformation, and durability characteristics of selected Soil-RAG-Geopoymer mixtures (72 h oven-cured) were either similar or higher than the conventional soil-cement mixture (28-day room temperature curing).
5. Microstructure and morphological analysis of selected Soil-RAG-Geopolymer mixture established the geopolymerisation process in the mixtures, which facilitated in the improvement of the durability and mechanical characteristics of the mixture.

This study has shown that this developed “green” Geopolymer-based soil base/subbase materials will exhibit durability, high performance, and environment-friendly characteristics. However, with further testing using different mixtures, varying types of flyash and chemical composition, the conclusions of this study can be strengthened. Other variable to be considered in future research are molarity of alkali activator, curing temperature, curing conditions, early strength development at room temperature and as well as ambient conditions, and gradation of RAG. These would be useful parameters to optimize for the practical application of this technology in the field.

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