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Performance Evaluation of Soil, Fly Ash, and Recycled Concrete Aggregate Geopolymer Mixtures for Pavement Base and Subbase Applications

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Abstract

In regions where suitable natural aggregates are scarce or expensive, soils are often treated with cement to produce pavement base and subbase materials. This study evaluated soil–RCA geopolymer mixtures as a sustainable alternative for these applications. Response surface methodology (RSM) was used to prepare mixtures containing soil, recycled concrete aggregate (RCA), Class F fly ash (FA), sodium hydroxide, and sodium silicate. The effects of FA, RCA, and liquid sodium silicate (Na_2SiO_3) in the alkaline activator solution on compressive strength (f_c), elastic modulus (E), and density were examined using regression analysis, Analysis Of Variance, and sensitivity analysis. Selected mixtures were further evaluated using wetting and drying, freeze and thaw, and scanning electron microscopy (SEM). Geopolymer stabilization increased strength and stiffness compared with untreated soil. FA improved both f_c and E, while RCA produced a nonlinear response, with 15% RCA providing favorable mechanical performance. Increasing Na_2SiO_3 reduced both responses under the tested conditions. The mixtures remained within the mass and volume change limits after 12 cycles. SEM observations showed geopolymer reaction products, particle coating, and matrix densification. The findings indicate that soil–RCA geopolymer mixtures can provide suitable performance for pavement base and subbase layers while reducing reliance on cement and virgin aggregates.

Keywords: soil stabilization; RCA; FA; geopolymer; pavement base and subbase; durability

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Academic Editor: Ching S. Chang

Received: 27 July 2026
Revised: 30 September 2026
Accepted: 6 October 2026
Published: 8 October 2026

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1. Introduction and Background

1.1. Introduction

Pavement base and subbase layers provide structural support by distributing traffic loads and reducing stresses within the pavement structure [1]. In regions where suitable natural aggregates are unavailable or expensive, locally available soils are commonly treated with Portland cement to produce soil–cement base and subbase layers [2]. This treatment improves the strength and stiffness of the material and provides a stable pavement foundation [3]. Portland cement is commonly used for this purpose because it can produce a stable and durable pavement foundation. However, cement production requires substantial energy and contributes to carbon dioxide emissions. Cement-treated base and subbase layers may also develop shrinkage cracks that can propagate through the asphalt surface and reduce pavement service life [4].

The environmental effects associated with cement production have encouraged the use of alternative binders derived from industrial byproducts [5]. One such material is FA, which is an abundant industrial byproduct rich in silica and alumina that supports the geopolymerization process [6]. In contrast with Class C FA, which mainly relies on CaO activation, Class F FA has limited self-cementing properties and typically requires alkaline activation to form binding products [7]. Sodium hydroxide (NaOH) acts as an activation agent and facilitates the dissolution of reactive silica and alumina present in FA, while sodium silicate (Na_2SiO_3) supplies soluble silicate for the reaction [8]. The resulting aluminosilicate products can bind soil and FA particles and form a more stable matrix. The behavior of FA-based geopolymer mixtures depends on the selected mixture composition and curing conditions. These factors include FA content, alkaline activator composition, alkali liquid-to-FA ratio, sodium silicate-to-sodium hydroxide ratio, curing temperature, and curing duration [9]. These variables must be carefully selected because changes in the activator composition can alter FA dissolution, gel formation, particle bonding, and micro/macro pore structure.

Recycled concrete aggregates (RCAs) can be used as a sustainable material in pavement construction [10]. RCA is obtained from demolished concrete and can partially replace virgin aggregate in pavement base and subbase layers [11]. Its use can reduce construction waste, conserve natural aggregate resources, and promote the reuse of construction and demolition materials [12]. FA-based geopolymer binders have been shown to improve the properties of RCA and other recycled aggregates when used in pavement base and subbase layers [13]. The combined use of soil, RCA, and FA-based geopolymer binders offers a potential alternative to conventional soil–cement-stabilized bases. The mixture consists of a soil matrix, a recycled granular component provided by RCA, and a binding phase formed by alkali-activated FA. Soil–RCA geopolymer mixtures provide a feasible material for pavement base and subbase applications. However, mixture performance depends on the proportions of FA and RCA and the composition of the alkaline activator. Further evaluation is needed to determine how these components collectively affect mechanical performance, durability, and microstructural development.

This study evaluates soil–RCA geopolymer mixtures prepared using soil, Class F FA, RCA, NaOH, and Na_2SiO_3. FA content, RCA content, and Na_2SiO_3 content were varied systematically to examine their effects on compressive strength (*fc*), elastic modulus (*E*), and density. Regression analysis, Analysis of Variance (ANOVA), and parametric sensitivity were conducted to determine the linear and nonlinear effects of the mixture variables. Selected mixtures were further evaluated for durability through wetting–drying and freeze–thaw tests. The microstructure and morphology of the developed mixtures were investigated using Scanning Electron Microscopy (SEM) analyses. This study connects mixture composition with mechanical, durability, and microstructural behavior to evaluate the suitability of soil–RCA geopolymer mixtures for pavement base and subbase applications.

1.2. Previous Research on Geopolymer-Stabilized Pavement Materials

1.2.1. Geopolymer Stabilization of Soils

FA-based geopolymers have been widely studied for stabilizing weak soils. Cristelo et al. [14] found that Class F FA activated with sodium-based solutions can produce strength comparable to cement-stabilized soil under suitable mixture and curing conditions. Rios et al. [15] also reported that alkali-activated soil FA mixtures can be used in pavement base and subbase layers, although strength development may continue over longer curing periods. Sukmak et al. [16] showed that FA content, sodium silicate-to-sodium hydroxide ratio,

liquid content, moisture condition, curing temperature, and curing duration significantly affect the strength of clay FA geopolymer mixtures.

Geopolymer stabilization has also been applied to lateritic and clay soils used in pavement construction. Phummiphan et al. [17] reported that FA and slag-based geopolymer stabilization improved the strength of lateritic soil and produced cementitious reaction products within the matrix. Adhikari et al. [18] found that selected soil FA geopolymer mixtures provided satisfactory mechanical performance and resistance to wetting and drying. Their study examined medium and high-plasticity soils using different FA contents, sodium silicate-to-sodium hydroxide ratios, and NaOH concentrations. The selected mixtures also showed satisfactory performance under static and dynamic loading, while SEM, XRD, and FTIR analyses confirmed the formation of geopolymer reaction products during curing. Turan et al. [19] further showed that alkaline activation improved particle bonding and reduced voids in FA-treated clay.

1.2.2. Geopolymer Stabilization of Recycled Aggregates

Geopolymer binders have also been used to stabilize RCA, Reclaimed Asphalt Pavement (RAP), and other construction and demolition materials. Poltue et al. [20] showed that RCA stabilized with FA and a rice husk ash-based geopolymer developed strength suitable for pavement base applications. Tiyasangthong et al. [21] found that the RCA-to-FA ratio, sodium silicate-to-sodium hydroxide ratio, and curing time influenced the strength and microstructure of geopolymer-stabilized RCA. Their Scanning Electron Microscopy (SEM) results showed geopolymer products coating and connecting RCA and FA particles. Doan et al. [22] also demonstrated that FA and slag-based geopolymers can stabilize RCA, RAP, and crushed brick, although the suitable activator and precursor contents varied among the recycled materials.

1.2.3. Soil–Recycled Aggregate Geopolymer Mixtures

The combined use of soil, recycled aggregates, and geopolymer binders has received limited attention. Adhikari et al. [23] evaluated soil–RAP geopolymer mixtures and reported that FA, RAP, and alkaline activator contents affected compressive strength and durability. Increasing FA and RAP contents generally improved the mechanical properties, with the mixture containing 25% FA and 25% RAP producing approximately seven times the compressive strength of untreated soil. The selected mixtures also showed mechanical and durability performance comparable to or better than conventional soil–cement mixtures. Abdulwahed et al. [24] evaluated clayey soil modified with RAP and a fly ash-based geopolymer for unpaved road applications. The study showed that the FA-based geopolymer improved mixture stiffness, while the effect of RAP depended on its proportion. Response surface methodology (RSM) was also used to evaluate the effects of FA and RAP and identify suitable mixture proportions.

Xie et al. [25] investigated the stabilization of high-liquid-limit subgrade soil using a geopolymer derived from construction and demolition waste. The stabilized mixtures were evaluated through compressive strength, shear strength, resilient modulus, and permanent deformation, demonstrating the potential of recycled construction materials in geopolymer-based soil stabilization. Khattak and Odion [26] investigated soil–recycled aggregate geopolymer mixtures containing RCA and RAP for pavement base and subbase applications through a Tran-SET research project. The study evaluated mixture design, compaction characteristics, mechanical properties, wetting and drying durability, and microstructural characteristics. Regression analysis was also used to evaluate the effects of the mixture variables on f_c and support the selection of suitable mixtures.

Previous studies confirm that geopolymers can stabilize both soils and recycled aggregates. However, the effects of FA, RCA, and Na_2SiO_3 content are material-specific and may produce nonlinear changes in strength, stiffness, durability, and microstructure. The present study provides a detailed quantitative evaluation of these effects on soil–RCA geopolymer mixtures. Separate regression models and sensitivity analyses are used to evaluate compressive strength and elastic modulus, and the relationship between these two mechanical responses is established. Density, wetting and drying, freeze and thaw, and SEM results are also evaluated to relate mixture composition to mechanical, durability, and microstructural behavior.

1.3. Research Need, Scope, and Objectives

Previous studies have shown that geopolymer binders can improve both soil and recycled aggregates for pavement applications. However, the combined effects of FA content, RCA content, and Na_2SiO_3 on soil–RCA geopolymer mixtures require further evaluation. These variables can influence strength, stiffness, density, durability, and microstructural development. A better understanding of their individual and combined effects is needed to identify suitable mixtures for pavement base and subbase applications.

This study integrates the quantitative evaluation of the combined effects of FA, RCA, and alkaline activator composition on soil–RCA geopolymer mixtures for pavement base and subbase applications. Unlike studies that primarily examine soil geopolymer stabilization or recycled aggregates separately, this study evaluates how these three mixture variables influence compressive strength, elastic modulus, density, durability, and microstructural development within the same material system. Separate statistical models and sensitivity analyses are used to quantify the influence of each mixture variable on strength and stiffness, while the relationship between compressive strength and elastic modulus is established to characterize their coupled mechanical response. The mechanical and statistical findings are further related to durability performance and SEM observations to explain how changes in mixture composition are reflected in the developed matrix. This integrated approach provides new insight into the mixture parameters governing the performance of soil–RCA geopolymer materials and supports the selection of suitable compositions for pavement base and subbase applications.

The specific objectives of this study are as follows:

1. To evaluate the effects of FA, RCA, and Na_2SiO_3 and their corresponding selected levels on the compressive strength (f_c), elastic modulus (E), and density of soil–RCA geopolymer mixtures.
2. To develop statistical models and conduct sensitivity analysis to quantify the linear and nonlinear effects of the mixture components on E and f_c, and to establish the relationship between these two mechanical responses.
3. To assess the durability of selected mixtures under wetting and drying as well as freeze–thaw cycles.
4. To examine the microstructure of selected mixtures using SEM and relate the observed features to their mechanical and durability performance.

2. Materials and Methods

This study used laboratory testing and statistical analysis to evaluate soil–RCA geopolymer mixtures for pavement base and subbase applications. The main mixture variables were FA content, RCA content, and Na_2SiO_3. Mixture performance was evaluated using f_c, elastic modulus (E), density, durability, statistical modeling, sensitivity analysis, and SEM. The mechanical and statistical results were also used to select representative mixtures for durability and microstructural evaluation.

2.1. Materials

The materials used in this study included soil, RCA, Class F FA, NaOH, and Na_2SiO_3, which were characterized as part of the related experimental program [26]. The soil formed the primary mixture matrix, while RCA served as the recycled granular component. FA was used as the aluminosilicate precursor. NaOH and Na_2SiO_3 formed the alkaline activator system. The technical-grade Na_2SiO_3 solution contained 63% water and 37% solids, consisting of 28% SiO_2 and 9% Na_2O. The solution had a specific gravity of 1.39 and a pH of 11.3.

The physical properties and classification of the soil are presented in Table 1. The soil had a liquid limit of 32.2%, a plastic limit of 22.5%, and a plasticity index of 9.7. More than 90% of the soil passed through a No. 200 sieve with a 0.075 mm (75 μm) opening. The soil was dark brown and was classified as A-4 according to the American Association of State Highway and Transportation Officials (AASHTO) system [27] and as sandy lean clay according to the Unified Soil Classification System (USCS) [28].

Table 1. Physical properties and classification of soil.

Property	Value
Plastic limit, %	22.5
Liquid limit, %	32.2
Plasticity Index	9.7
USCS	Sandy lean clay
AASHTO classification	A-4
Passing 0.075 mm (No. 200) sieve, %	>90
Color	Dark brown

The chemical compositions of the FA, soil, and RCA are presented in Table 2. Energy-dispersive X-ray spectroscopy (EDS) was used to determine the elemental composition of the materials, and the results were expressed as oxide weight percentages (wt.%). The FA primarily contained silicon dioxide (SiO_2) and aluminum oxide (Al_2O_3), with contents of 69.39% and 21.70%, respectively. The soil contained 71.21% SiO_2, 13.86% iron oxide (Fe_2O_3), and 10.69% Al_2O_3. The RCA contained 54.88% SiO_2 and 33.96% calcium oxide (CaO). The high CaO content of the RCA was associated with the residual cement paste attached to the recycled concrete particles [29].

Table 2. Composition of BR FA, soil, and RCA determined by EDS (wt.%).

Compound	FA	Soil	RCA
Na_2O	0.91	0.18	0.00
MgO	0.00	0.38	0.42
Al_2O_3	21.70	10.69	5.67
SiO_2	69.39	71.21	54.88
SO_3	0.00	0.00	1.42
K_2O	1.35	2.77	0.71
CaO	1.69	0.91	33.96
$Fe2O_3$	4.96	13.86	2.95
Total	100.00	100.00	100.00

The RCA obtained from a local contractor was dried and sieved before mixing to obtain the required particle size distribution. Approximately 90% of the RCA passed through a 9.5 mm (3/8 in.) sieve, 45% passed through a 4.75 mm (No. 4) sieve, and 35% passed through a 0.425 mm (No. 40) sieve. The RCA therefore contained both coarse and fine particles that contributed to the granular structure of the mixtures. The soil, RCA, and

FA were proportioned according to the mixture design matrix. The alkaline activator was prepared using NaOH and Na_2SiO_3 at the required silicate ratio for each mixture. Together, these materials formed the soil–RCA geopolymer system that was evaluated in this study.

2.2. Mixture Design

A response surface methodology (RSM)-based experimental design was used to develop the mixture matrix [26]. The mixture matrix was used in this study to evaluate the effects of FA, RCA, and Na_2SiO_3 on the performance of soil–RCA geopolymer mixtures. The control mixture, M1, consisted of untreated soil without FA, RCA, or alkaline activator. The remaining mixtures contained FA contents ranging from 5% to 25%, RCA contents ranging from 5% to 25%, and Na_2SiO_3 contents ranging from 0% to 50% of the alkaline activator solution. The corresponding alkali ratio, defined as the Na_2SiO_3/NaOH solution ratio, is also presented in Table 3. The reported silicate contents and alkali ratios refer to the activator solution and not to the solid mixture composition.

Table 3. Experimental mixture design for soil–RCA geopolymer mixtures.

S. No	Mix ID	FA, %	Na_2SiO_3 (%)	Alkali Ratio	RCA (%)
1	M1	0	0	0	0
2	M2	5	33	0.5	15
3	M3	15	33	0.5	15
4	M4	25	33	0.5	15
5	M5	15	33	0.5	5
6	M6	15	33	0.5	25
7	M7	15	0	0	15
8	M8	15	50	1	15
9	M9	10	20	0.25	10
10	M10	20	43	0.75	20
11	M11	25	50	1	25

Note: Alkali ratio = Na_2SiO_3/NaOH solution ratio.

The measured f_c, E, and density values were used to compare mixture performance and develop statistical models. Representative mixtures were then selected for wetting and drying, freezing and thawing, and SEM analyses based on their mechanical performance and statistical response.

2.3. Compaction Characteristics

The compaction characteristics of the control soil and three representative soil–FA–RCA blends were determined using the modified Proctor method in accordance with ASTM D1557 [30]. The tests were conducted using the liquid alkaline activator to determine the maximum dry density (MDD) and optimum liquid alkaline content (OAC) associated with the selected material proportions. The measured MDD and OAC values used in this study are presented in Table 4 [26]. These values were used as reference points for calculating the MDD and OAC of the remaining mixtures.

Table 4. Compaction characteristics of selected soil–FA–RCA blends.

S. No	Mix ID	FA, %	RCA (%)	MDD, kg/m^3	OAC, %
1	M1	0	0	1900	13.80
2	M3/M7	15	15	1870	11.50
3	M11	25	25	1810	11.00

Note: MDD—maximum dry density; OAC—optimum liquid alkaline content.

2.4. Specimen Preparation and Curing

The required quantities of soil, RCA, and FA were measured according to the mixture design. The dry materials were mixed until a uniform blend was obtained. The alkaline activator was then added and mixing continued until the materials were evenly distributed.

Cylindrical specimens measuring 72 mm in diameter and 144 mm in height were prepared for compression testing. The required quantity of soil was oven-dried for 24 h at 110 ± 5 °C and then mixed with FA and RCA until a uniform dry blend was obtained. The alkaline solution was added based on the optimum moisture content. Each mixture was placed in a cylindrical mold in three equal layers. Each layer was rodded 25 times to settle the particles followed by further compaction using a 6-ton press to achieve the target maximum dry density. The specimens were then extruded, trimmed, sealed in high-temperature-resistant zip lock bags to minimize moisture loss, and cured for 72 h at 60 °C [26]. The sealed condition was maintained to minimize moisture loss during curing. Triplicate specimens were prepared for each mixture and tested.

A preliminary curing evaluation was conducted to determine an appropriate curing duration. The specimens were cured at 60 °C, and f_c was measured at selected curing times. As shown in Figure 1, strength increased rapidly between 24 and 72 h, followed by no additional improvement. Therefore, a curing period of 72 h at 60 °C was adopted for the main experimental program to accelerate the geopolymer reaction and strength development within a shorter laboratory curing period. Although elevated-temperature curing requires additional energy, the selected condition provided a consistent basis for comparing the mixtures under controlled conditions. It also allowed the effects of the mixture parameters to be evaluated under consistent curing conditions.

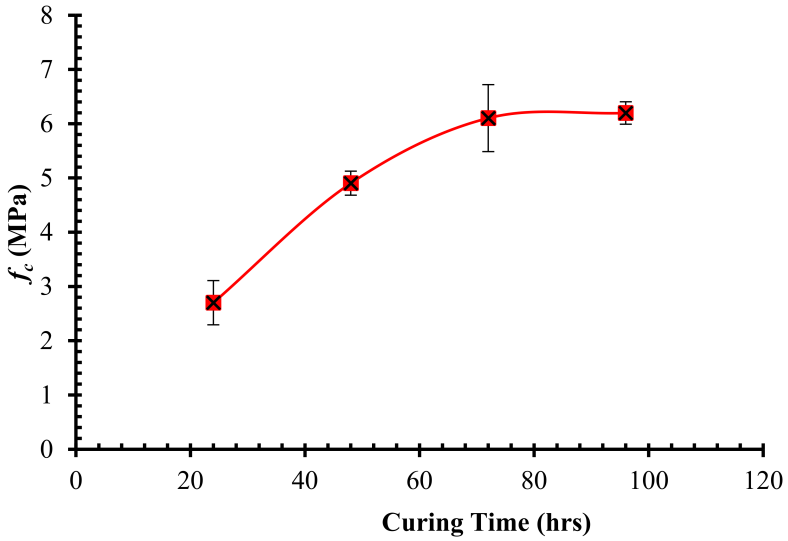


Figure 1. Typical curve showing effect of curing time on f_c at 60 °C for soil–RCA geopolymer mixture.

2.5. Compressive Strength, Elastic Modulus, and Density

After curing, the specimens were tested under axial compression according to ASTM D2166 [31]. The cylindrical specimens were loaded to failure at a constant loading rate of 5 mm/min. Load and axial deformation were recorded throughout the test.

Compressive strength was calculated using Equation (1):

$$f_c = \frac{P}{A} \quad (1)$$

where f_c is the compressive strength in MPa, P is the maximum load at failure, and A is the cross-sectional area of the specimen.

The elastic modulus was determined from the slope of the initial linear portion of the stress–strain curve. The selected linear region extended to approximately one-third of the peak f_c. The elastic modulus was calculated as follows:

$$E = \frac{\Delta\sigma}{\Delta\varepsilon} \tag{2}$$

where E is the elastic modulus, $\Delta\sigma$ is the change in compressive stress, and $\Delta\varepsilon$ is the corresponding change in axial strain. The modulus values were reported in GPa. Specimen density was also calculated from the measured mass and volume after curing.

2.6. Statistical and Sensitivity Analysis

Separate regression models were developed to quantify the effects of FA, S, and RCA on f_c and E. Linear, quadratic, and interaction terms were initially considered to capture both individual and combined effects. The general second order model was expressed as follows:

$$\begin{gathered} Y = \beta_0 + (\beta_1 \times FA) + (\beta_2 \times S) + (\beta_3 \times RCA) + (\beta_4 \times FA^2) + (\beta_5 \times S^2) \\ +(\beta_6 \times RCA^2) + \{\beta_7 \times (FA \times S)\} + \{\beta_8 \times (FA \times RCA)\} + \{\beta_9 \times (S \times RCA)\} \end{gathered} \tag{3}$$

where Y represents either predicted f_c or E, and β_0 to β_9 are regression coefficients. The final models retained the terms that provided meaningful contributions to model fit and variable significance.

Analysis of Variance (ANOVA) was used to evaluate model adequacy and determine the statistical significance of the mixture variables. Model performance was assessed using the coefficient of determination (R^2), adjusted R^2, standard error, F statistic, and p values. Sensitivity analysis was then conducted by varying one mixture variable across its experimental range while keeping the remaining variables constant. This procedure was used to examine the independent effects of FA, RCA, and Na_2SiO_3 and to support the selection of mixtures for durability and SEM testing.

2.7. Durability Testing

Selected mixtures were evaluated using wetting and drying and freeze and thaw tests. The mixtures were selected based on their mechanical properties, regression results, and sensitivity trends. Durability was evaluated using percentage mass change and percentage volume change after 12 cycles.

For the wetting and drying test, each cycle consisted of 5 h of immersion in water at room temperature, followed by 43 h of oven drying at 71 ± 3 °C. The procedure was repeated for 12 cycles. Specimen mass and dimensions were measured to determine changes caused by repeated moisture exposure and drying. For the freeze and thaw test, each cycle consisted of 24 h of freezing followed by 23 h of thawing in a moist environment. The procedure was repeated for 12 cycles. Final specimen mass and volume were compared with the initial measurements. The following equations were used for mass and volume changes.

$$\text{Mass change}(\%) = \frac{M_i - M_f}{M_i} \times 100 \tag{4}$$

$$\text{Volume change}(\%) = \frac{V_f - V_i}{V_i} \times 100 \tag{5}$$

where M_i and M_f are the initial and final specimen masses, respectively, and V_i and V_f are the initial and final specimen volumes, respectively.

2.8. Scanning Electron Microscopy (SEM) Analysis

Scanning Electron Microscopy (SEM) was used to examine the microstructure and fracture morphology of selected soil–RCA geopolymer mixtures. A ThermoScientific Scios 2 Dual Beam scanning electron microscope located at the UL Lafayette Microscopy Center, Billeaud Hall, University of Louisiana at Lafayette, Lafayette, LA, USA, was used for this study. Small, fractured pieces were collected from tested specimens. The samples were mounted on aluminum stubs using conductive carbon tape and coated with a thin layer of gold to improve electrical conductivity and image quality [32].

The selected mixtures represented systems activated with NaOH alone and with a combination of NaOH and Na_2SiO_3. The SEM images were examined to identify geopolymer gel formation, particle coating, particle bonding, unreacted or partially reacted FA particles, and visible pore spaces. The observations were used to compare the microstructural characteristics of the selected mixtures and support the interpretation of their mechanical and durability behavior.

3. Results and Discussion

3.1. Physical Properties

The present study also examined the density of the cured soil–RCA geopolymer mixtures, with the results presented in Table 5. The control mixture, M1, had the highest density of 1870 kg/m^3. At a constant RCA content of 15% and Na_2SiO_3 of 33%, increasing FA content reduced the density from 1854 kg/m^3 for M2 to 1746 kg/m^3 for M3 and 1709 kg/m^3 for M4. This reduction may be associated with the lower specific gravity and finer particle characteristics of FA compared with the soil and RCA.

Table 5. Density of soil–RCA geopolymer mixtures.

S. No	Mix ID	FA, %	Na_2SiO_3 (%)	RCA (%)	Density, kg/m^3	SD
1	M1	0	0	0	1870	4
2	M2	5	33	15	1854	11
3	M3	15	33	15	1746	64
4	M4	25	33	15	1709	3
5	M5	15	33	5	1759	7
6	M6	15	33	25	1741	1
7	M7	15	0	15	1716	13
8	M8	15	50	15	1742	7
9	M9	10	20	10	1774	50
10	M10	20	43	20	1756	21
11	M11	25	50	25	1737	20

Note: SD = standard deviation.

At a constant FA content of 15% and Na_2SiO_3 of 33%, increasing RCA content produced a smaller change in density. The density decreased from 1759 kg/m^3 for M5 with 5% RCA to 1746 kg/m^3 for M3 with 15% RCA and 1741 kg/m^3 for M6 with 25% RCA. The results show that FA content had a more noticeable effect on density than RCA content within the tested mixture range. The measured standard deviations were generally low, indicating consistent density values among the replicate specimens.

However, the reduction in density did not correspond directly to a reduction in mechanical performance. For example, M4 had a density of 1709 kg/m^3 compared with 1854 kg/m^3 for M2, representing a reduction of approximately 8%. Despite this lower density, the compressive strength increased from 2.93 MPa to 7.91 MPa, while the elastic modulus increased from 1.09 GPa to 5.52 GPa. This indicates that density alone did not control the response of the stabilized mixtures and that geopolymer bonding and

particle interactions also played an important role in the development of strength and stiffness. The contrasting density and mechanical responses suggest that the formation and continuity of the binding matrix had a greater influence on mechanical performance than the bulk density of the mixture. Thus, a lower density did not necessarily indicate a weaker stabilized material within the evaluated mixture range.

3.2. Mechanical Characteristics

The mechanical testing of the soil–RCA geopolymer mixtures was conducted as part of the earlier experimental program [26]. The complete f_c and E of the soil–RCA geopolymer mixtures are presented in Table 6. The control mixture, M1, had the lowest f_c and E values of 0.71 MPa and 0.55 GPa, respectively. All geopolymer-stabilized mixtures showed higher strength and stiffness than the untreated soil. At a constant RCA content of 15% and Na_2SiO_3 of 33%, increasing FA content from 5% to 25% substantially increased f_c from 2.93 MPa for M2 to 7.91 MPa for M4. The corresponding E also exhibited about 5 times increase from 1.09 GPa to 5.52 GPa. This trend shows that higher FA content improved the mechanical response of the mixtures within the tested range. The greater proportional increase in elastic modulus indicates that stiffness was more sensitive to FA content than compressive strength.

Table 6. Measured compressive strength and elastic modulus values of soil–RCA geopolymer mixtures.

S. No	Mix ID	FA, %	S, %	RCA (%)	f_c (Mpa)	SD (Mpa)	E (GPa)	SD (GPa)
1	M1	0	0	0	0.71	0.01	0.55	0.05
2	M2	5	33	15	2.93	0.09	1.09	0.07
3	M3	15	33	15	6.13	0.09	4.19	0.09
4	M4	25	33	15	7.91	0.04	5.52	0.48
5	M5	15	33	5	3.93	0.04	3.45	0.05
6	M6	15	33	25	3.80	0.02	3.36	0.06
7	M7	15	0	15	13.95	0.15	9.78	0.02
8	M8	15	50	15	4.79	0.10	1.90	0.01
9	M9	10	20	10	3.42	0.10	1.89	0.02
10	M10	20	43	20	3.05	0.15	1.11	0.04
11	M11	25	50	25	2.58	0.10	0.89	0.05

Note: SD = standard deviation.

The complete measured f_c and E values for all mixtures are further compared in Figure 2. The figure provides a direct comparison of the strength and stiffness responses across the eleven mixture compositions.

The effect of RCA content was nonlinear. At 15% FA and 33% Na_2SiO_3, M3 with 15% RCA produced higher f_c and E values than mixtures containing 5% or 25% RCA. Na_2SiO_3 also had a strong effect. M7, containing 15% FA, 15% RCA, and 0% Na_2SiO_3, produced the highest f_c and E values of 13.95 MPa and 9.78 GPa, respectively. Increasing Na_2SiO_3 to 33% and 50% reduced both responses. This indicates that the activator composition strongly influenced matrix development under the tested conditions. The low standard deviations reported for most mixtures indicate good consistency among the replicate specimens.

The observed mechanical response reflects the different roles of the mixture constituents. Increasing FA content provided more reactive aluminosilicate material for the development of the binding phase, which improved particle bonding and matrix stiffness. RCA contributed to the granular structure of the mixture, while the peak response near 15% RCA suggests that a moderate RCA content provided favorable particle interaction while maintaining sufficient geopolymer binder to coat and connect the particles. At higher RCA contents, the increased aggregate surface area may have reduced the amount of binding

phase available for effective particle bonding. The decrease in f_c and E with increasing Na_2SiO_3 further indicates that the balance of the alkaline activator influenced matrix development under the tested curing conditions. The results therefore suggest that mechanical performance depended on the combined balance of FA, RCA, and activator composition rather than on any single component.

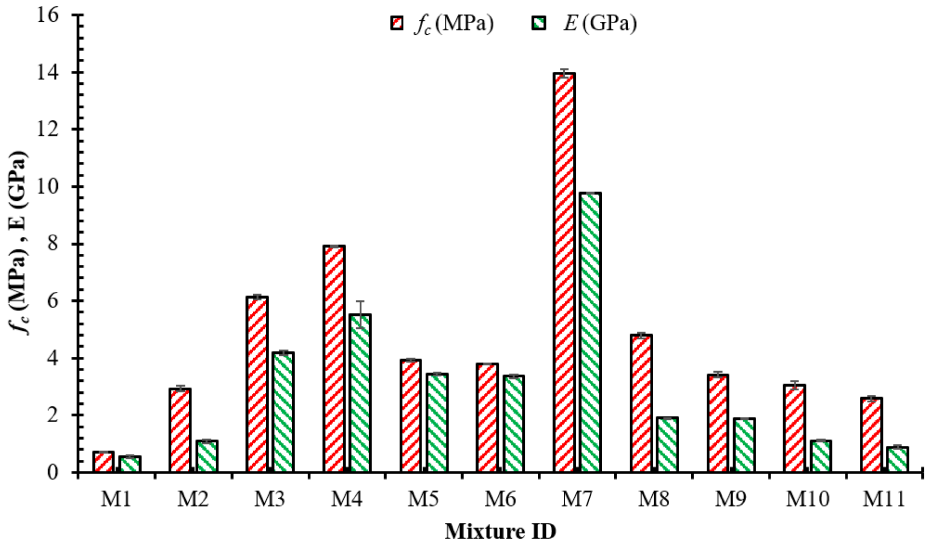


Figure 2. Compressive strength and elastic modulus of soil–RCA geopolymer mixtures.

The present study further examined the relationship between E and f_c to quantitatively evaluate the relative development of stiffness and strength in the soil–RCA geopolymer mixtures. As shown in Figure 3, a strong linear relationship was observed between the two mechanical parameters. The fitted relationship was $E = 667.91\ f_c$, with an R^2 value of 0.97, where both E and f_c are expressed in MPa. This result indicates that mixture stiffness generally increased in proportion to compressive strength, although some variation was observed among mixtures with varying FA, RCA, and Na_2SiO_3. The strong relationship indicates that stiffness and strength developed concurrently across the evaluated mixtures, while the observed scatter suggests that mixture composition also influenced the stiffness-to-strength response. This strong relationship suggests that the mechanisms contributing to strength development also contributed to matrix stiffness.

3.3. Statistical Modeling

Regression models were developed separately for f_c and E using FA content, Na_2SiO_3, and RCA content as explanatory variables. Linear and quadratic terms were retained based on statistical significance and model performance. Interaction terms were initially considered but were not included in the final models because they did not provide a meaningful improvement in model fit.

The regression and Analysis of Variance (ANOVA) results for f_c are presented in Table 7. The model produced a multiple correlation coefficient of 0.95, a coefficient of determination (R^2) of 0.90, and an adjusted R^2 of 0.87. The model was statistically significant, with an F statistic of 38.28 and a significance level below 0.001. These results indicate that the retained mixture variables explained approximately 90% of the variation in f_c.

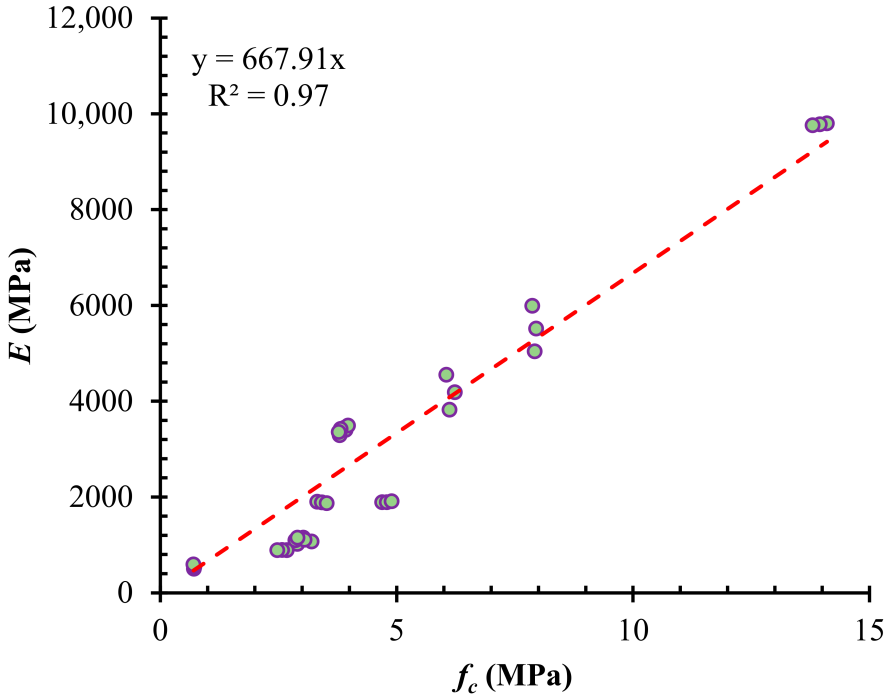


Figure 3. Relationship between elastic modulus and compressive strength of soil–RCA geopolymer mixtures.

Table 7. Regression and ANOVA results for f_c of soil–RCA geopolymer mixtures.

Regression Statistics							
Multiple R							0.95
R Square							0.90
Adjusted R Square							0.87
Standard Error							1.22
Observations							33
ANOVA							
		df	SS	MS	F	Significance F	
Regression		6	342.65	57.11	38.28	0.0000	
Residual		26	38.79	1.49			
Total		32	381.44				
	Coefficients	Standard Error	t Stat	*p*-Value	Lower 95%	Upper 95%	Lower 95.0%	Upper 95.0%
Intercept	0.8165	0.68	1.20	0.24	−0.58	2.22	−0.58	2.22
F	0.6046	0.13	4.81	0.00	0.35	0.86	0.35	0.86
S	−0.3219	0.04	−7.28	0.00	−0.41	−0.23	−0.41	−0.23
R	0.8160	0.13	6.49	0.00	0.56	1.07	0.56	1.07
F^2	−0.0117	0.00	−2.85	0.01	−0.02	0.00	−0.02	0.00
S^2	0.0028	0.00	3.20	0.00	0.00	0.00	0.00	0.00
R^2	−0.0273	0.00	−6.64	0.00	−0.04	−0.02	−0.04	−0.02

The final f_c model was expressed as follows:

$$f_c = 0.8165 + 0.6046\,(FA) - 0.3219(S) + 0.8160\,(R) - 0.0117\,(FA)^2 + 0.0028\,(S)^2 - 0.0273\,(R)^2 \quad (6)$$

The positive linear coefficients for FA and RCA indicate that increasing these components initially increased f_c. The negative quadratic coefficients show that the rate of improvement decreased at higher FA and RCA contents. The negative linear coefficient for Na_2SiO_3 indicates that increasing Na_2SiO_3 reduced f_c within the tested range. The positive quadratic term for Na_2SiO_3 indicates curvature in the Na_2SiO_3 response rather

than a constant rate of reduction. These results show that the strength response was controlled by a balance among precursor content, recycled aggregate proportion, and activator composition rather than by a single mixture component.

In the present study, a separate regression model was developed for E to quantify the influence of FA, Na_2SiO_3, and RCA contents on mixture stiffness. The regression and ANOVA results for E are presented in Table 8. The model had a multiple correlation coefficient of 0.920, an R^2 of 0.846, and an adjusted R^2 of 0.817. The model was statistically significant, with an F statistic of 29.65 and a significance level below 0.001. The retained variables therefore explained approximately 85% of the variation in E.

Table 8. Regression and ANOVA results for elastic modulus (E) of soil–RCA geopolymer mixtures.

Regression Statistics								
Multiple R								0.92
R Square								0.85
Adjusted R Square								0.82
Standard Error								1.13
Observations								33
ANOVA								
		df	SS	MS	F	Significance F		
Regression		5	188.79	37.76	29.65	0.0000		
Residual		27	34.38	1.27				
Total		32	223.18					
	Coefficients	Standard Error	t Stat	*p*-Value	Lower 95%	Upper 95%	Lower 95.0%	Upper 95.0%
Intercept	0.5581	0.62	0.90	0.38	−0.72	1.83	−0.72	1.83
F	0.5843	0.12	5.08	0.00	0.35	0.82	0.35	0.82
S	−0.1590	0.02	−9.97	0.00	−0.19	−0.13	−0.19	−0.13
R	0.3292	0.12	2.86	0.01	0.09	0.57	0.09	0.57
F2	−0.0119	0.00	−3.20	0.00	−0.02	0.00	−0.02	0.00
R2	−0.0110	0.00	−2.94	0.01	−0.02	0.00	−0.02	0.00

The final E model is expressed as follows:

$$E = 0.5581 + 0.5843\ (FA) - 0.1590\ (S) + 0.3292\ (R) - 0.0119\ (FA)^2 - 0.0110\ (R)^2 \quad (7)$$

For the elastic modulus model, FA and RCA produced the greatest stiffness gains at lower to moderate contents. Their effects became less pronounced as the proportions increased, as reflected by the negative quadratic terms. In contrast, Na_2SiO_3 was negatively associated with E, indicating that higher Na_2SiO_3 reduced mixture stiffness within the experimental range. The similar influence of FA, RCA, and Na_2SiO_3 on both f_c and E indicates that the same mixture parameters governed strength and stiffness development. However, differences in the coefficient magnitudes show that the two mechanical responses were not equally sensitive to changes in mixture composition.

The regression models developed in the present study were further evaluated using measured versus predicted responses and residual analysis. Figure 4 presents the model validation results. Figure 4a compares the measured and predicted values of f_c and E. Most observations were located near the line of equality, indicating reasonable agreement between the experimental and predicted responses. This agreement supports the ability of the models to represent the main mechanical trends within the investigated mixture ranges. Figure 4b presents the residuals against the predicted values. The residuals were distributed around zero without a clear increasing or decreasing pattern, indicating that the models did not show a strong systematic prediction bias [33]. Therefore, the models

provide a useful basis for interpreting the relative effects of FA, RCA, and Na_2SiO_3 and for the subsequent sensitivity analysis.

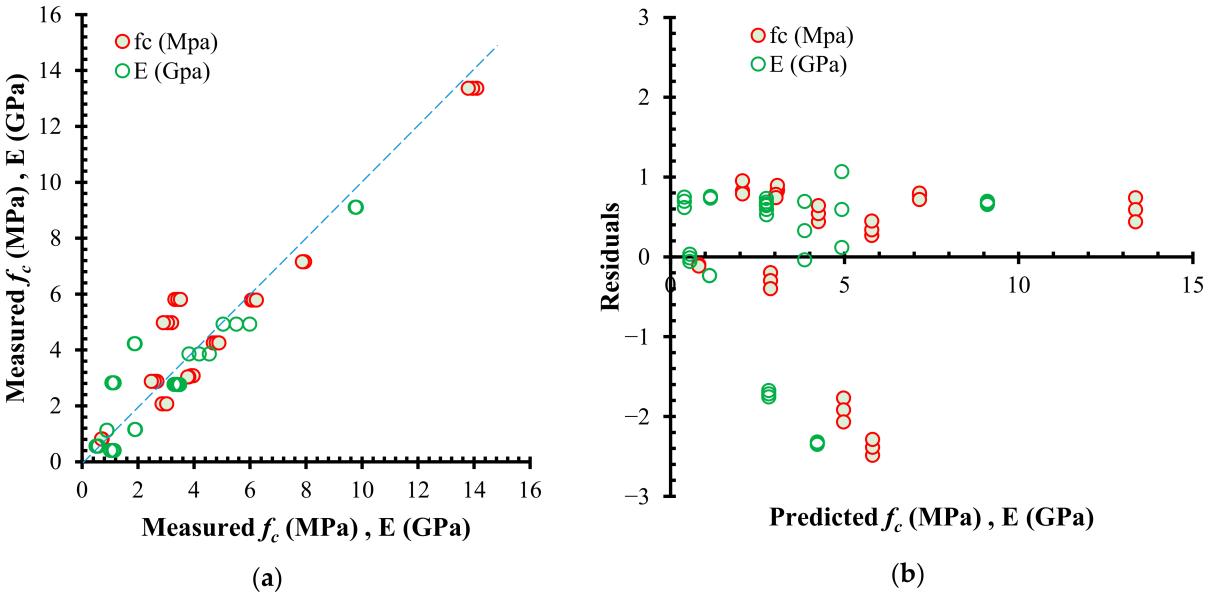


Figure 4. Model validation for soil–RCA geopolymer mixtures: (**a**) measured versus predicted values for f_c and E, and (**b**) residuals versus predicted values.

3.4. Sensitivity Analysis

In the present study, sensitivity analysis was conducted using f_c and E regression models to separately evaluate the individual effects of FA, RCA, and Na_2SiO_3 on f_c and E. One mixture variable was varied across its experimental range while the remaining variables were held at selected values. The results are presented in Figure 5.

Figure 5a,b illustrate that increasing FA content increased both f_c and E under the conditions used in the analysis. The response increased rapidly at lower FA contents and became more gradual at higher contents. The observed rate of increase in strength and modulus was minimal after 15% FA content. This trend indicates that FA contributed positively to matrix development, although the benefit became less pronounced beyond the intermediate FA range. This response suggests a diminishing mechanical benefit from additional FA rather than a proportional increase in performance with FA content.

Figure 5c,d display that the effects of RCA on f_c and E were nonlinear. Both responses increased as RCA content approached approximately 15%, showed an optimum value and then decreased at higher RCA contents. This trend indicates that moderate RCA content provided a favorable balance between the granular structure and the available geopolymer binder. At lower RCA contents, the granular contribution was limited, whereas at higher RCA contents the available binder may have been insufficient to effectively coat and connect the particles. Figure 5e,f show that increasing Na_2SiO_3 reduced both f_c and E at all evaluated FA levels. The highest predicted responses occurred at low Na_2SiO_3, particularly when the FA content was high. These results demonstrate that the additional Na_2SiO_3 did not improve the mechanical response under the mixture and curing conditions used in this study. The sensitivity trends show three distinct responses: increasing FA produced diminishing improvements, RCA exhibited an intermediate favorable level, and increasing Na_2SiO_3 reduced mechanical performance. This demonstrates that the mixture components affected the soil–RCA geopolymer system through different response patterns.

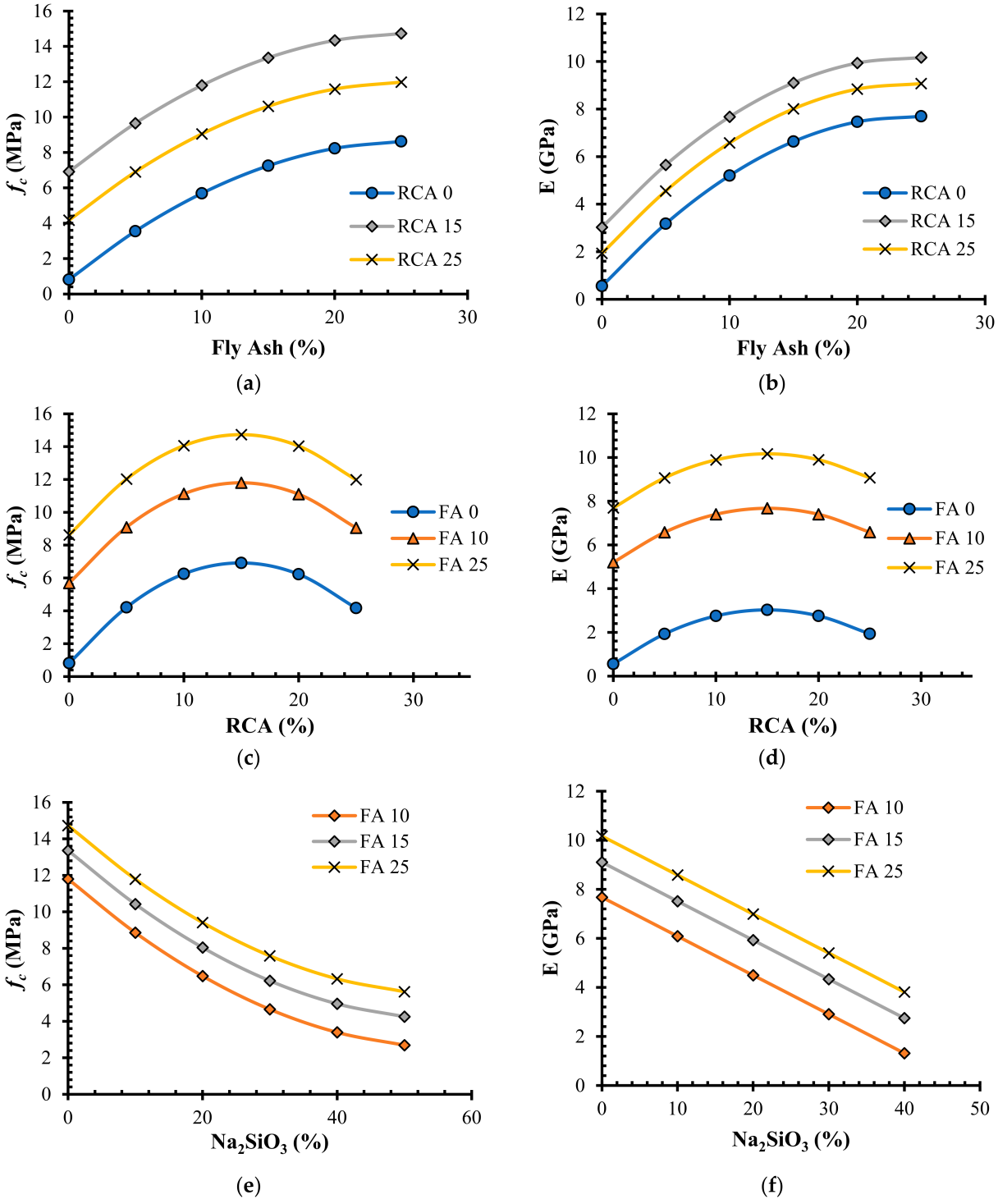


Figure 5. Sensitivity analysis of soil–RCA geopolymer mixtures: (**a**) effect of fly ash content on f_c, (**b**) effect of fly ash content on E, (**c**) effect of RCA content on f_c, (**d**) effect of RCA content on E, (**e**) effect of Na_2SiO_3 on f_c, and (**f**) effect of Na_2SiO_3 on E.

3.5. Selected Mixtures for Further Evaluation

Based on the mechanical test results, regression models, and sensitivity analysis, two mixtures were selected for durability and microstructural evaluation, which are shown in Table 9. The selected mixtures were M7, containing 15% FA, 15% RCA, and 0% S, and M4, containing 25% FA, 15% RCA, and 33% S.

Table 9. Selected soil–RCA geopolymer mixtures for durability and SEM evaluation.

Mix ID	FA, %	S, %	RCA, %
M7	15	0	15
M4	25	33	15

M7 was selected because it produced the highest measured f_c and E values among the evaluated mixtures. This mixture represented activation with NaOH without the addition of Na_2SiO_3. M4 was selected because it produced relatively high strength and stiffness while representing a higher FA content and a moderate Na_2SiO_3 level. Both mixtures contained 15% RCA, which was identified as the favorable RCA content through the experimental and sensitivity results.

3.6. Durability Performance

The selected mixtures were evaluated under wetting and drying as well as freeze and thaw conditions. Durability was assessed using percentage mass change and percentage volume change after 12 cycles. The adopted durability criteria were a maximum volume change of 2% and a maximum mass change of 10% [34,35]. These limits correspond to commonly used soil cement durability criteria for A-4 soils, for which the maximum allowable weight loss is 10% and the maximum volume change is 2%.

3.6.1. Wetting and Drying Durability

The wetting and drying results from the experimental program are presented in Figure 6 [26]. After 12 cycles, M7 showed a volume change of 1.39% and a mass change of 4.43%. Similarly, volume and mass changes for M4 mixtures were 1.27% and 4.40%, respectively.

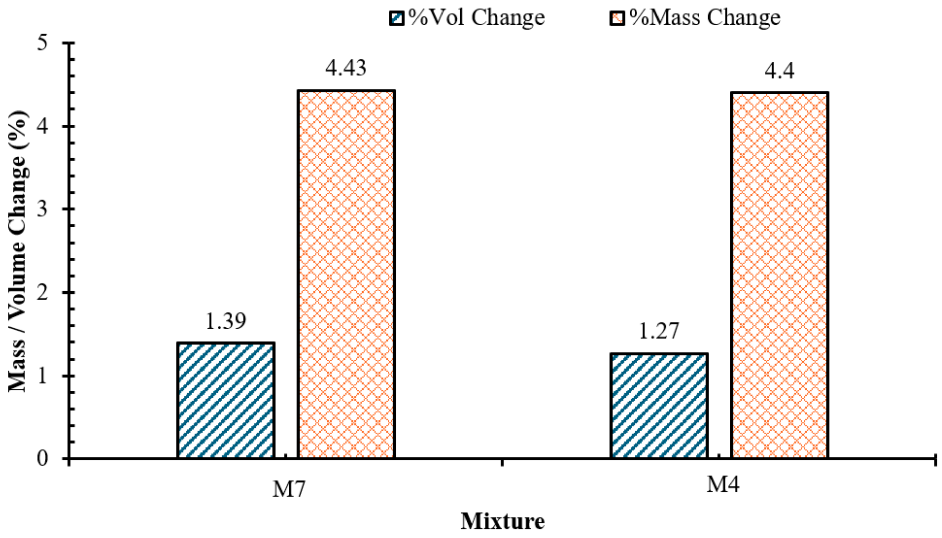


Figure 6. Mass and volume changes of selected soil–RCA geopolymer mixtures after 12 wetting and drying cycles.

Both mixtures remained below the accepted limits for mass and volume change of 2% and 10%, respectively. M4 produced a slightly lower volume change than M7, while the mass changes were nearly identical. The limited mass and volume changes indicate that both mixtures maintained stable performance during repeated wetting and drying cycles. This response suggests that the developed binding matrix was sufficient to limit substantial particle loss and dimensional change during repeated moisture exposure and drying. The similar durability responses of M7 and M4, despite their differences in strength

and stiffness, indicate that resistance to wetting and drying was not directly proportional to mechanical performance.

3.6.2. Freeze–Thaw Durability

As an additional durability evaluation in the present study, the selected mixtures were subjected to freeze and thaw testing. The freeze and thaw results are presented in Figure 7. After 12 cycles, M7 showed a volume change of 0.75% and a mass change of 2.23%. M4 showed a volume change of 0.73% and a mass change of 2.16%.

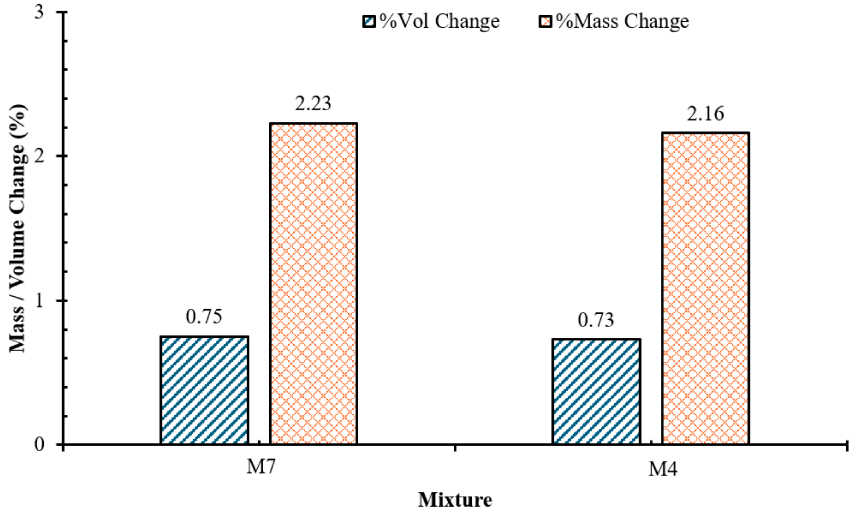


Figure 7. Mass and volume changes of selected soil–RCA geopolymer mixtures after 12 freeze and thaw.

Both mixtures remained below the adopted durability limits under freeze and thaw exposure. The measured mass and volume changes were lower than those recorded during wetting and drying. This result indicates that the selected mixtures experienced less physical change under freeze and thaw exposure than under wetting and drying. The greater changes observed during wetting and drying suggest that repeated moisture exposure and drying produced greater physical disturbance than the applied freeze and thaw cycles under the tested laboratory conditions. The similar responses of M7 and M4 also indicate that both mixtures maintained dimensional stability despite their differences in mechanical strength and stiffness.

3.7. Microstructure and Morphology

The SEM micrographs obtained for the selected soil–RCA geopolymer mixtures [26] were further examined in the present study in relation to the mechanical response of the mixtures. Figure 8a,b represent mixture M7, containing 15% FA, 15% RCA, and 0% S. The micrographs depict irregular soil and RCA particles surrounded by fine reaction products. Several FA particles were coated by the binding phase, while the spaces between adjacent particles were partially filled. This morphology indicates the formation of a connected geopolymer matrix that improved particle contacts and reduced discontinuities within the mixture. The more continuous matrix can facilitate stress transfer among the soil, RCA, and reacted FA particles, which is consistent with the relatively high mechanical response of M7. The filling of spaces between adjacent particles also indicates that the reaction products contributed to greater continuity of the solid matrix rather than acting only as coatings on individual particles. The mixture produced an f_c of 13.95 MPa and an elastic modulus of 9.78 GPa. Some spherical and partially reacted FA particles remained visible, indicating that the reaction was not complete throughout the matrix. The presence of partially reacted

FA also suggests that complete consumption of the precursor was not required to develop the relatively high mechanical performance observed for M7.

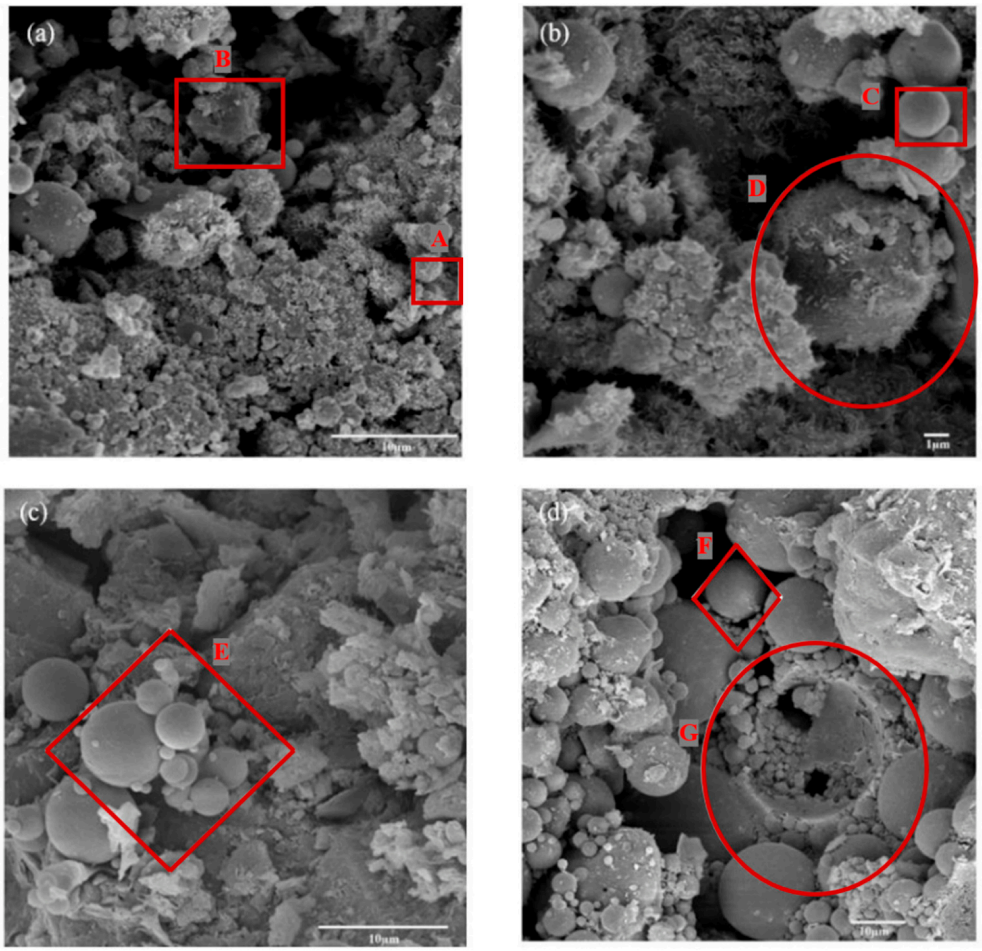


Figure 8. SEM micrographs of selected soil–RCA geopolymer mixtures: (**a**,**b**) M7 containing 15% FA, 15% RCA, and 0% S, and (**c**,**d**) M4 containing 25% FA, 15% RCA, and 33% S [26]. Zones A and B indicate bonded particles with geopolymer gel; Zone C indicates unreacted FA; Zone D indicates partially reacted FA; Zones E and F indicate unreacted FA; and Zone G indicates partially reacted FA.

Figure 8c,d represent mixture M4, containing 25% FA, 15% RCA, and 33% S. The micrographs represent clusters of unreacted or partially reacted FA particles, visible voids, and less continuous bonding in some regions. Although reaction products were present around the soil, RCA, and FA particles, the matrix appeared less uniform than that of M7. The observed morphology indicates that the activator composition affected gel development and particle bonding. The visible voids and discontinuities can interrupt load transfer through the matrix and create localized regions of stress concentration. This response is consistent with the lower f_c and elastic modulus of M4, which were 7.91 MPa and 5.52 GPa, respectively. Although M4 contains a higher FA content, its less continuous matrix indicates that increasing the amount of precursor alone did not ensure greater matrix development. The effectiveness of FA therefore depended on the activator condition and the resulting reaction within the mixture. The comparison between M7 and M4 therefore shows that a denser and more continuous reaction matrix was associated with higher strength and stiffness, while greater void content and unreacted FA were associated with a lower mechanical response. These observations provide a microstructural basis for the mechanical results and show that mixture composition influenced both the continuity of the developed binding matrix and the resulting strength and stiffness.

4. Conclusions and Recommendations

This study evaluated soil–RCA geopolymer mixtures for pavement base and subbase applications. FA, RCA, and Na_2SiO_3 were varied to examine their effects on density, f_c, E, durability, and microstructural development. The following conclusions were drawn:

1. Geopolymer stabilization improved the mechanical properties of the soil. The untreated soil produced an f_c of 0.71 MPa and an E of 0.55 GPa, while all stabilized mixtures exhibited improved strength and modulus values. This improvement indicates that the alkali-activated fly ash formed binding products that strengthened the soil and RCA matrix.
2. Increasing FA content improved f_c and E when RCA and Na_2SiO_3 were held constant. The observed improvements in strength and modulus values were about 2.5 and 5 times, respectively. The higher FA content provided additional aluminosilicate material for the geopolymer reaction, which improved particle bonding and matrix stiffness.
3. RCA content produced a nonlinear response. Mixtures containing 15% RCA exhibited higher strength and modulus than mixtures containing 5% or 25% RCA under comparable conditions. The 15% RCA content likely provided a favorable balance between particle packing, aggregate interlock, and the amount of geopolymer binder available to coat the particles. Higher RCA contents may have reduced the binder available for effective bonding.
4. Increasing Na_2SiO_3 reduced the mechanical response within the tested range. The mixture containing 15% FA, 15% RCA, and 0% Na_2SiO_3 produced the highest f_c and E values of 13.95 MPa and 9.78 GPa, respectively. This finding indicates that NaOH activation without additional Na_2SiO_3 produced a more favorable activator balance for the materials and curing conditions evaluated. The addition of Na_2SiO_3 may have reduced reaction uniformity and effective particle bonding.
5. FA and RCA reduced the density of the mixtures compared with the untreated soil. The effect of FA was more pronounced, while changes in RCA content produced smaller differences in density. The reduction in density was mainly associated with the lower specific gravity and finer particle characteristics of FA compared with the original soil and RCA.
6. The regression models provided strong agreement with the experimental results. The f_c model produced an R^2 of 0.90 while the E model generated an R^2 of 0.85. These results confirm that FA, RCA, and Na_2SiO_3 explained most of the observed variation in strength and stiffness. The models can support preliminary mixture selection within the experimental ranges evaluated in this study.
7. The selected mixtures satisfied the adopted durability criteria after 12 wetting and drying and freeze and thaw cycles. Mass changes remained below 4.5%, and volume changes remained below 1.4%. Lower mass and volume changes were recorded under freeze and thaw exposure than under wetting and drying exposure. This response indicates that repeated wetting and oven drying produced greater physical changes than the applied freeze and thaw cycles, although both mixtures maintained acceptable dimensional and mass stability.
8. Scanning Electron Microscopy (SEM) showed geopolymer reaction products coating and connecting soil, RCA, and FA particles. The mixture containing 15% FA, 15% RCA, and 0% Na_2SiO_3 showed a more continuous and compact matrix. The Na_2SiO_3-containing mixture showed more visible voids and unreacted or partially reacted FA particles. The denser microstructure of the mixture without Na_2SiO_3 was consistent with its higher strength and stiffness, while the remaining voids and unreacted particles in the Na_2SiO_3-containing mixture indicated less complete matrix development.

The results of the testing reflect that soil–RCA geopolymer mixtures can provide suitable mechanical and durability performance for pavement base and subbase applications. A mixture containing high FA, moderate RCA, and low Na_2SiO_3 contents produced the most favorable response among the evaluated mixtures. For preliminary mixture selection, FA, RCA, and activator composition should be considered together rather than independently. Within the investigated ranges, an RCA content near 15% provided favorable mechanical performance, while increasing FA generally improved strength and stiffness, and additional Na_2SiO_3 was not beneficial under the tested conditions. The regression and sensitivity results can be used to screen candidate mixtures within the experimental ranges, followed by mechanical and durability verification. However, the current results are based on accelerated curing at 60 °C for 72 h, which may not directly represent field conditions. Further testing under ambient or room-temperature curing is needed to evaluate long-term strength development, durability, and the practical feasibility of these mixtures for pavement applications.

Author Contributions: Research conception and design: A.K., D.O. and M.J.K.; laboratory testing and experimentation: A.K., D.O. and M.J.K.; microscopy and interpretation of results: A.K., A.A., S.K., D.O. and M.J.K.; data analysis and writing: A.K., A.A., S.K., D.O. and M.J.K. All authors have read and agreed to the published version of the manuscript.

Funding: This project was funded by the Tran-SET (Project No: 18GTLSU10) and the National Science Foundation (NSF) under Grant No: 1757786.

Institutional Review Board Statement: Not applicable.

Informed Consent Statement: Not applicable.

Data Availability Statement: All data generated or analyzed during this study are included in this article. Additional supporting data are available from the corresponding author upon reasonable request.

Acknowledgments: The authors gratefully acknowledge the Transportation Consortium of South Central States (Tran-SET) and the National Science Foundation (NSF) for providing financial support for this research. The authors also thank the University of Louisiana at Lafayette for providing the facilities and institutional support needed to conduct this research.

Conflicts of Interest: The authors declare no conflicts of interest.

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