Mechanical and Microstructural Characterization of a Nano-stabilized Sandy Soil

Jafari Kermanipour, Mojtaba, Bagheripour, Mohammad Hossein and Yaghoubi, Ehsan (2024) Mechanical and Microstructural Characterization of a Nano-stabilized Sandy Soil. Geotechnical and Geological Engineering, 42 (7). pp. 6131-6146. ISSN 0960-3182

Geotech Geol Eng (2024) 42:6131–6146
https://doi.org/10.1007/s10706-024-02890-6

ORIGINAL PAPER

Mechanical and Microstructural Characterization of a Nano-stabilized Sandy Soil

Mojtaba Jafari Kermanipour · **Mohammad Hossein Bagheripour** · **Ehsan Yaghoubi**

Received: 18 March 2024 / Accepted: 17 July 2024 / Published online: 30 July 2024

Abstract This research investigates the potential of using nanoparticles, Poly Aluminum Silicate and Poly Calcium Silicate, and industrial by-products, Recycled Glass Powder (RGP) and Ground Granulated Ballast Furnace Slag (GGBS) to enhance the durability and strength of a sandy soil, particularly in wet or saturated conditions where water table is close to building foundations. The study aims to determine the optimal content and concentration of additives and assess their influence on the compressive strength and the failure strain. The optimal content and concentration of dry additives and alkaline solutions were determined. Uniaxial compressive strength tests were conducted on various stabilized geopolymers, considering factors such as alkaline activator type, nanoparticle type and percentage, and degree of saturation. Scanning electron microscopy images were taken and analyzed to verify geomechanical testing outcomes. Mixtures with nanomaterials exhibited greater strength than untreated soil, with some exhibiting up to a tenfold increase. GGBS-based samples displayed a twofold increase in strength with nanomaterial addition, while RGP-based samples experienced reduced strength. However, both nanomaterials addressed the durability concerns in wet conditions. The addition of 2% nanomaterials to GGBS-based mixtures led to significant strength gains, with some showing a 20% increase after saturation. This research indicated the potential of nanoparticles and industrial by-products in resolving a major concern regarding geopolymers which is the lack of durability in wet or saturated conditions. These findings have implications for eco-friendly geoconstruction materials and practices.

Keywords Soil stabilization · Durability enhancement · Nanoparticles · Recycled Glass Powder · Moisture susceptibility

M. Jafari Kermanipour · M. H. Bagheripour
Department of Civil Engineering, Shahid Bahonar University of Kerman, Kerman, Iran
e-mail: M.jafari@eng.uk.ac.ir

M. H. Bagheripour
e-mail: bagheri@uk.ac.ir

E. Yaghoubi (✉)
College of Sport, Health and Engineering, Victoria University, Room D304, Ballarat Rd, Footscray, Melbourne VIC 3011, Australia
e-mail: Ehsan.Yaghoubi@vu.edu.au

E. Yaghoubi
Institute for Sustainable Industries & Liveable Cities, Victoria University, Room D304, Ballarat Rd, Footscray, Melbourne VIC 3011, Australia

1 Introduction

Stabilizing problematic soils is a common geotechnical practice and a sustainable, environmentally friendly process for building foundations and road subgrades (Lindh and Lemenkova 2023).

Traditionally, a popular technique of soil stabilization has been the use of Portland cement or lime, both of which are known to be non-environmentally friendly stabilizers (Yaghoubi et al. 2013; Al-Taie et al. 2023). There are environmental challenges associated with the production of these two additives, including high energy and natural resource consumption as well as greenhouse gas emissions. On the other hand, the annual global production of billions of tons of industrial waste such as Recycled Glass Powder (RGP), Ground Granulated Blast Furnace Slag (GGBS), and Fly Ash (FA) can provide a potential for developing eco-friendly materials in civil engineering projects. RGP is a recycled product made of one of the most commonly produced materials, glass, in several countries and GGBS is a waste byproduct of blast furnaces that are used to produce iron (Ashiq et al. 2022; Abushama et al. 2023).

Numerous studies conducted over the past few decades have demonstrated that geopolymers can be used as a suitable substitute for cement and can reduce greenhouse gas emissions during production by up to 80% when compared to cement. In addition, geopolymers have shown excellent resilience to heat and chemical attacks, as well as low natural resource consumption during production (Nabizadeh Mashizi et al. 2023). The drawback of geopolymers is known to be the lack of durability. However, adding nanomaterials to cementitious constituents is known to develop a blend with improved durability (Michálková et al. 2014; Bhojaraju et al. 2021). As a result, the mix design of cementitious materials based on nanotechnology used in construction projects has been the subject of extensive research in the last few years (Tong et al. 2016; Devi and Khan 2020; Laím et al. 2021). A variety of nanomaterials, including graphene-based nanomaterials (Gholampour et al. 2017),

Table 1 Classifications, and physical and compaction properties of the soil

Property	Result	Specification
Soil Classification (USCS)	SM	ASTM D422-63 (2007)
Effective size (D_{10})	0.042 mm	ASTM D422-63 (2007)
Coefficient of uniformity (C_u)	9.262	ASTM D422-63 (2007)
Coefficient of curvature (C_c)	1.939	ASTM D422-63 (2007)
OMC	13%	ASTM D698-07 (2007)
MDD	1.57 gr/cm^3	ASTM D698-07 (2007)
Specific gravity (Gs)	2.64	ASTM D 854 (2010)

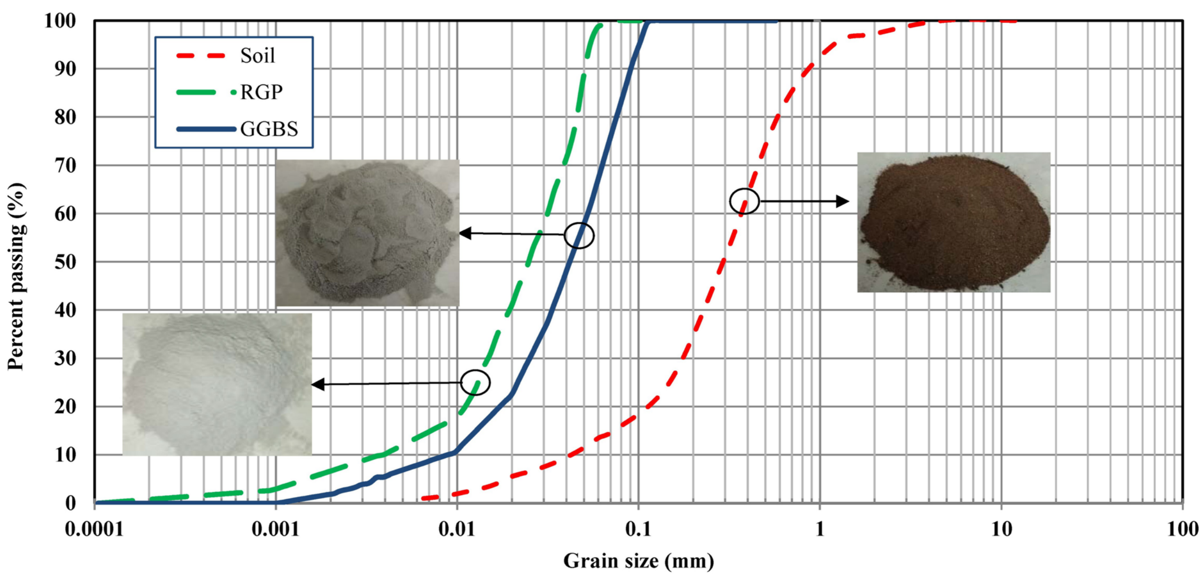


Fig. 1 The particle size distribution of the sand, Recycled Glass Powder, and Ground Gran-ulated Blast Furnace Flag used in this study

nano-silica (Qing et al. 2007; Indumathi et al. 2011) nano-aluminum (Sundaram et al. 2015; Broering et al. 2024), nano-titanium (Wongkornchaowalit and Lertchirakarn 2011), nano-kaolin (Kong et al. 2013), nano-clay, and carbon nanotubes (CNT) (Morsy et al. 2011; Meng et al. 2012; Kong et al. 2013), have been used in cementitious composites.

A new technology that has recently drawn the interest of the construction industry is, in fact, the creation of geopolymers from glass waste. According to published studies, unlike typical geopolymers, a high synthesis temperature is not necessary to produce geopolymer from a mixture of glass powder (Pascual et al. 2014). The excellent performance of glass powder both as a precursor in geopolymer production and as an alkaline solution is due to the presence of silicate and due to its alkaline properties, respectively. In fact, the RGP contains almost 13% sodium oxide (Na_2O). The high Na content of RGP could allow a reduction in the concentration of the sodium hydroxide (NaOH) solution used as an activator (Cyr et al. 2012; Solanki et al. 2020).

GGBS has been widely investigated as a supplementary cementitious material but has rarely been considered as a potential additive for nano-modified cement pastes. Bhojaraju et al. used GGBS to improve the fresh properties of cementitious materials subjected to modification with graphene and graphene oxide (Bhojaraju et al. 2021). They also investigated the influence of GGBS on the service life characteristics of these modified materials and showed that GGBS improved the durability of stabilized samples.

Table 2 The oxide compositions of the materials

Component Oxides (%)	GGBS	RGP
SiO_2	36.5	73.77
Al_2O_3	13	1.9
Fe_2O_3	0.3	0.031
CaO	38.9	8.87
MgO	8.7	2.1
Na_2O	0.11	11.5
K_2O	0.31	0.281
P_2O_5	0.11	0
SO_3	1.76	0.78
TiO_2	0.01	0
Mn_2O_3	0.3	0
LoI	1.0	0.22

Noolu et al. observed that the addition of 40% GGBS and 8 M of NaOH led to obtaining a higher UCS for stabilized Black Catton soil (a highly expansive soil) and the durability test revealed only 9.2% reduction of the UCS after 12 wetting–drying cycles (Noolu et al. 2021). Replacing GGBS is a useful method to enhance sediment properties. It increases strength, reduces sediment alkalinity, and enhances the capacity to immobilize Fe, Ni, and Zn. The release of metals (Al, Mn, Cu, As, Ba, and Pb) is closely linked to the interaction of physicochemical factors. Different metals respond differently to curing temperature, curing duration, and pH levels (Zhang et al. 2020).

This study endeavors to close the current research gap by addressing the following queries: 1) how effective are RGP and GGBS in improving the mechanical properties of the cement paste containing nanomaterials?, 2) to what extent do the PAS and PCS influence the strength properties of cement paste?, and 3) what are the effects of nanomaterials on the service life of cementitious materials with RGP or GGBS? An extensive experimental program was planned to investigate the issues raised above. The present study evaluates the effect of various parameters, including (a) the optimum concentration of the alkaline solution, (b) the optimum percentage of adhesive, (c) the optimum percentages of PAS and PCS nanomaterials on the stabilized soil, and (d) durability of stabilized samples in saturated conditions. This study addresses the previous lack of thorough investigations focused on soil mixtures containing PAS and PCS, thereby filling this research gap. Moreover, the effect of dissolved Water Glass (Na_2SiO_3) in combination with sodium hydroxide, as the alkaline solution on the strength of stabilized soil was investigated. Finally, a durability investigation is carried out as another objective of the study to quantify the impact

Table 3 physical and chemical properties of nanomaterials

Property	PAS	PCS
SiO_2	54.33 (%)	54.1 (%)
Al_2O_3	14.73 (%)	–
CaO	–	18.5 (%)
Moisture	1%	1%
Bulk Density	0.5 g/cm^3	0.5 g/cm^3
Average particle size	60 nm	50 nm

of saturation on the durability of cement mixed with PAS and PCS.

2 Materials and Methods

2.1 The Natural Soil

The soil examined in this study was collected from the subgrade of a highway located in the southern areas of Kerman City in Iran. The soil was classified as silty sand by conducting particle size analysis according to the ASTM-D422 (ASTM D422-63 2007), as shown in Fig. 1. To ensure consistency in the preparation of specimens, the collected sand was sieved through a No.4 sieve (4.75 mm) to remove gravel-sized particles (< 1%). The physical properties of the soil, including the Maximum Dry Density (MDD) and the Optimum Moisture Content (OMC), are summarized in Table 1 using the standard Proctor method ASTM D698-07 (ASTM D698-07 2007). Minor changes in the Optimum Moisture Content (OMC) due to the geopolymer-based additives were anticipated and found to be up to a 2.3% variation through experimental investigations. However, in this study, all samples including treated or untreated soil, were compacted with the same OMC (Table 1) for comparison purposes.

2.2 Geopolymer Binders

To ensure purity, the recycled glass powder (RGP) as a precursor for the geopolymer was initially sieved through sieve No. 200, and particles finer than 75 microns were used for mixing with soil. The particle size distribution of the glass powder was determined using the laser method and presented in Fig. 1. Additionally, the chemical composition of the RGP was analyzed through the XRF test, and the results are summarized in Table 2. As presented in Table 2, the RGP is a rich source of silica (SiO_2 = 73.77%), indicating that RGP components have a great potential for the formation of geopolymer gel (Burciaga-Díaz et al. 2020).

Table 4 The composition of the materials and mixtures used in this study

Samples	Mixture type	Water Content (%)	Sand	GGBS Content (%)	RGP Content (%)	Nanomaterial's content (%)		Alkaline activator
						PCS	PAS	
Natural soil (NS)	–	13	100	0	0	0	0	NaOH 7MOL
GGBS	–	13	80	20	0	0	0	
RGP	–	13	80	0	20	0	0	
A1G	GGBS-based mixture	13	80	19.5	0	0	0.5	
A2G		13	80	19	0	0	1	
A3G		13	80	18.5	0	0	1.5	
A4G		13	80	18	0	0	2	
C1G		13	80	19.5	0	0.5	0	
C2G		13	80	19	0	1	0	
C3G		13	80	18.5	0	1.5	0	
C4G		13	80	18	0	2	0	
A1R	RGP-based mixture	13	80	0	19.5	0	0.5	
A2R		13	80	0	19	0	1	
A3R		13	80	0	18.5	0	1.5	
A4R		13	80	0	18	0	2	
C1R		13	80	0	19.5	0.5	0	
C2R		13	80	0	19	1	0	
C3R		13	80	0	18.5	1.5	0	
C4R		13	80	0	18	2	0	
A4RW		13	80	0	18	0	2	%50NaOH + %50WG

Fig. 2 Curing of samples in the oven

A laser analyzer was used to determine the PSD of the Ground Granulated Blast Furnace Slag (GGBS) as depicted in Fig. 1. The chemical composition of the GGBS was analyzed using an X-ray fluorescence spectrometer, and the results are presented in Table 2. A significant proportion of Calcium Oxide (CaO = 38.9%) indicates that the GGBS has the potential to react with pozzolanic materials and produce a cementitious material. Additionally, GGBS is a source of silica (SiO2 = 36.5%) making it suitable for developing geopolymers (Kampala et al. 2014). The particle size distribution of GGBS indicates that 80% of its particles are finer than 75 µm.

2.3 Alkaline Activators

The sodium hydroxide (NaOH) powder with 99% purity and pH = 14 was used as the most common alkaline activator for the geopolymer production process. Granular NaOH is mainly produced through the chlor-alkali electrolytic process. NaOH can also be obtained by mixing pure sodium metal (Na) with water (H_2O). The by-products are hydrogen gas (H_2) and heat, which often lead to flames. The chemical formula related to this production process is presented in Eq. (1). Moreover, to compare the effect of adding SiO_2 in the powder form (RGP) or the solution form (Sodium silicate), which is known as Water Glass (WG), the combination of WG and NaOH by an equal ratio was used in samples containing RGP. The WG used in this research was viscous, and slightly yellow.

$$2Na + 2H_2O \rightarrow 2NaOH + H_2 \tag{1}$$

2.4 Nanomaterials

As presented in Table 3 the physical and chemical characteristics and the percentage of Nano Calcium Polysilicate (PCS) and Nano Aluminum Polysilicate (PAS) constituent elements, based on the information obtained from the manufacturing company, the maximum size of PCS particles was 50 nm and PAS's maximum particle size was 100 nm. The presence of silicate (SiO2 = 54.1%) and lime (CaO = 18.5%) in the constituent elements of PCS in combination with geopolymers can effectively contribute to the geopolymerization process and pozzolanic reactions. However, it is expected that the presence of aluminum oxide (Al2O3 = 14.73%) along with silicate (SiO2 = 54.3%) in the constituent elements of PAS in combination with geopolymers can play a more significant role in producing a larger amount of geopolymer gel.

2.5 Sample Preparation, Curing and UCS Tests

Samples were produced using a split cylindrical steel mold, having a diameter of 37 mm and a height of 75 mm. First, the sandy soil was dried in an industrial oven at 35 ± 1 °C for three days. The selected temperature of 35 ± 1 °C was to simulate a common temperature condition for soil stabilization projects in Kerman Province or areas with similar climates. To achieve a uniform mixture for preparing the specimens, first, based on the weight percentage of the materials mentioned in Table 4, sand and precursor materials were dry-mixed for 5 min. Subsequently, this mixture was combined with the predetermined amount of alkaline activator which was determined as the optimum amount in Sect. 3.1

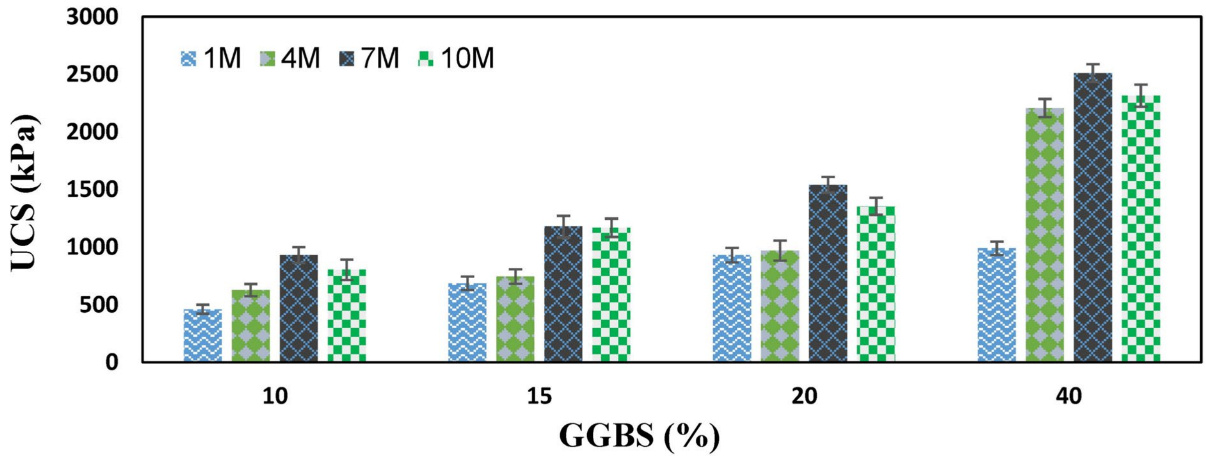


Fig. 3 UCS results at different precursor and alkaline activator contents

(7 M) and mixed for 10 min (Rios et al. 2016; Raza et al. 2024). The resulting mixture was then divided into three equal parts by weight and poured into three layers, using the Undercompaction method with zero percent reduction (Ladd 1978). In the Undercompaction method, successive layers of sand are compacted to a predefined density, resulting in increased density in the underlying layers due to the overlying compaction. This technique leverages the densification effect to produce a uniformly dense sandy soil specimen. In addition, a metal shaft, sized to match the diameter of the sample and, the inner diameter of the mold, was employed to compact each layer. Before pouring the mixture into the mold, a plastic film was used as a liner for sealing and preventing moisture loss from the external surface of the samples. The sample was next placed inside plastic bags having two zippers which were vacuumed. Then the samples were placed in an oven at a temperature of 35 ± 1 °C for 7 days as demonstrated in Fig. 2. It should be noted that samples might experience higher temperatures inside the plastic bags compared to the oven set at 35 ± 1 °C, which may potentially enhance the polymerization process. At the completion of the curing time, the samples were taken out of the zipped plastic bags and were prepared for testing.

The UCS test was performed on the samples according to the ASTM D2166-87 (ASTM D 2166 2013). The displacement rate of the compression

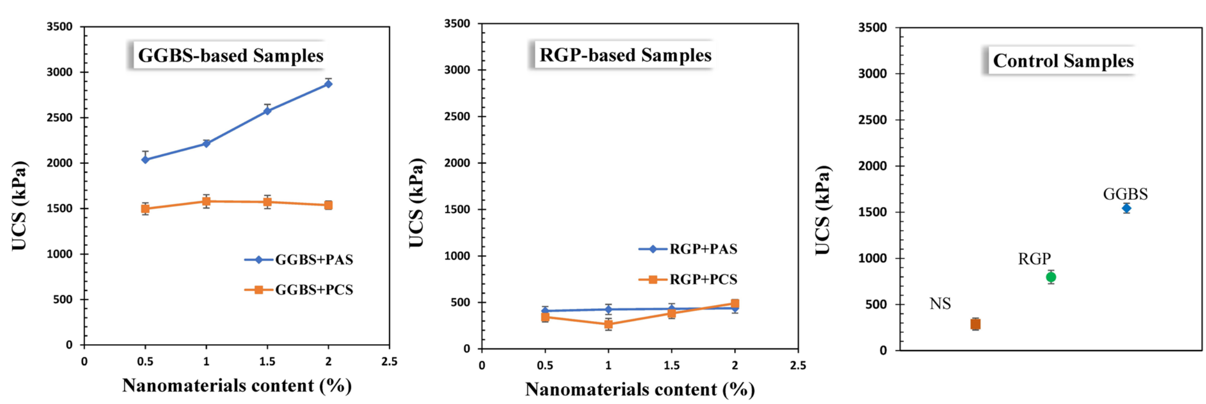


Fig. 4 UCS values of samples versus various nanomaterial contents mixed with different base precursors and comparison with control samples

machine was set to 1 mm/min and the stress–strain behavior of samples was monitored during tests. A total of 60 cylindrical Geopolymer specimens were prepared with different Nano contents and different Nano types. To increase the accuracy of the results, for each series of samples, 3 replicates were prepared and the average compressive strength was reported.

Table 4 shows the mixture proportions, alkali activator types, and nano types as well as their percentages in different mixtures of this study. The water content was 13% of the total dry weight of the mixture of the soil, Geopolymer, and nanomaterials. The dry nano content, as a powder, was added to the mixture at 0.5%, 1%, 1.5%, and 2% of the total dry weight of the sample.

2.6 FE-SEM and EDX Tests

In order to evaluate the underlying mechanisms of the effect of additives on the soil, energy dispersive spectroscopy (EDX) analysis and field emission scanning electron microscope (FE-SEM) examination were performed (Alyamani and Lemine 2012). Stabilized and unstabilized soils images were magnified 5000 times using a field emission scanning electron microscope. The SEM and EDX tests were carried out on pieces collected from cylindrical samples fractured during the UCS test.

3 Results and Discussion

In this section, the effects of two different nano-sized additives, being PAS and PCS, in five general mix designs on the strength and properties of Geopolymer concrete (GPC), the binding materials (industrial waste such as fly ash, GGBS, and RGP) with high silica and alumina content, are discussed. Also, the effect of different saturation conditions to simulate the rise in the groundwater table is evaluated.

3.1 Compressive Strength

In order to determine the optimal contents of the alkaline activator and precursor, samples cured for 7 days were prepared with different percentages of GGBS-based geopolymer and different molarities of alkaline sodium hydroxide solution. The adopted weight percentages of GGBS were 10, 15, 20, and 40 percent according to the optimal moisture content of 13%. Alkaline sodium hydroxide solution with molarities of 1, 4, 7, and 10 was also added to the samples. The average of three UCS values of each sample is presented in Fig. 3. The results indicated that samples with 7 M alkaline solution concentration had the highest strength, which was achieved with 40% precursors. However, in construction projects, replacing 40% of in-situ soil volume with geopolymer is not considered economical and feasible. Hence, taking into account operational and economic considerations, the precursor content of 20% was selected. Therefore, in all of the specimens, the overall quantity

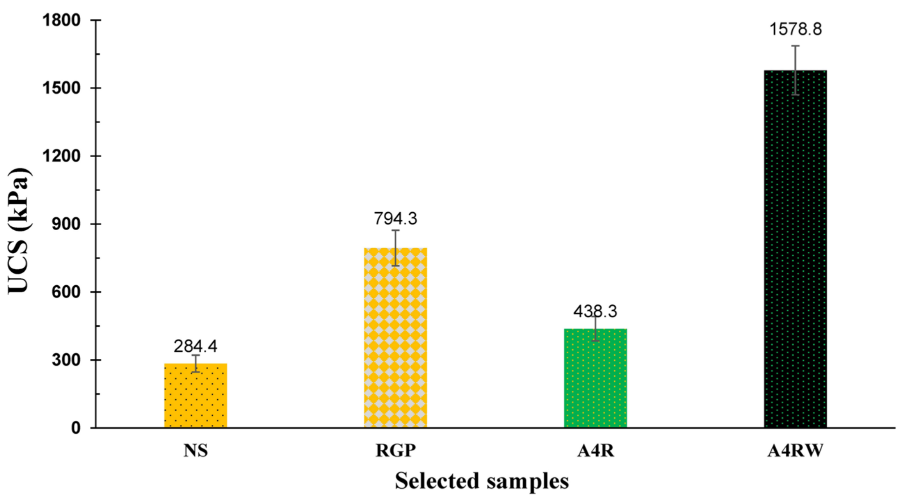


Fig. 5 The UCS results of samples prepared with and without WG

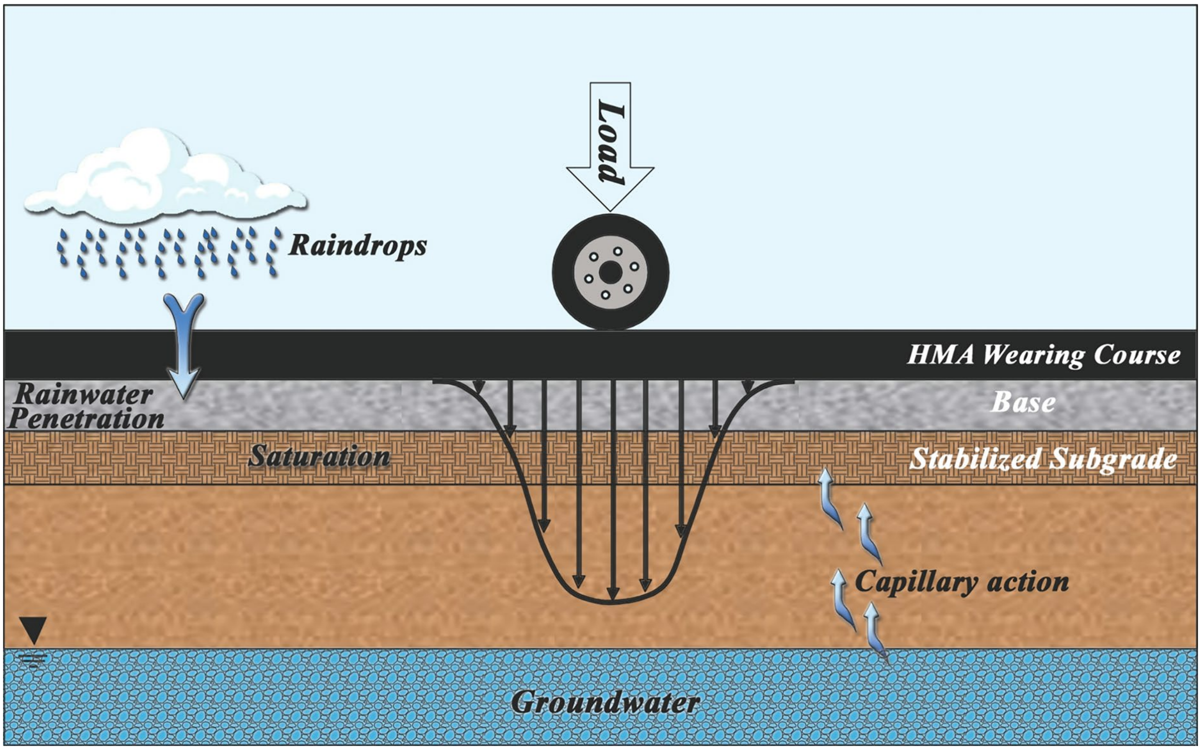
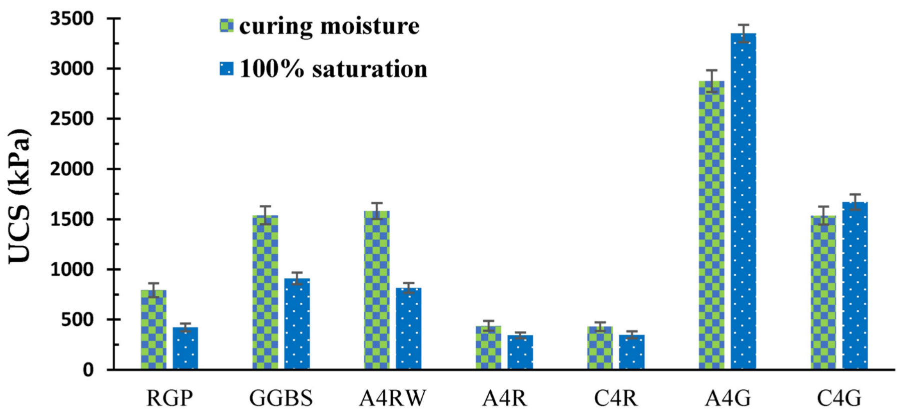


Fig. 6 Schematic elevation view of the potential for the saturation of the stabilized subgrade through capillary phenomena and surface water penetration

of precursor substance and nanomaterial was set at 20%, while the alkali activator concentration was fixed at 7 M.

The UCS test results at different PAS, and PCS contents of 0, 0.5, 1, 1.5, and 2% for the GGBS-based samples are demonstrated in Fig. 4. The performance of PAS in GGBS-based samples exhibited variation, whereby an increase in PAS resulted in a corresponding increase in UCS. The strength of the samples demonstrated a remarkable improvement, reaching up to twice the strength of the sample without PAS and up to tenfold the strength of the natural sand sample. In contrast, the uniaxial compressive strength of the samples was not increased by the addition of PCS, and the strength of the

Fig. 7 Comparison of UCS of selected samples at two different moisture conditions



soil stabilized with GGBS particles was almost unchanged.

Following the results achieved and presented in Fig. 4, an analysis was conducted to determine the impact of PAS, and PCS contents (0, 0.5, 1, 1.5, and 2%) in conjunction with RGP (20, 19.5, 19, 18.5, and 18%) on the UCS results, which are shown in Fig. 4. The same concentration of sodium hydroxide (7 M) as RGP-based samples was used. Based on the UCS test results, the inclusion of PAS in the RGP-based samples not only failed to lead to a favorable effect on the compressive strength but also reduced the UCS by half, although the increase in strength was directly related to the increase in PAS. Subsequently, as the proportion of PCS particles increased, the UCS test results showed that despite an increased strength, the compressive strength of these samples was generally lower than that of the stabilized RGP sample. The strength of the sample containing 0.5% of PCS, was reduced by a factor of 2.8 compared with the RGP samples. Thus the detrimental effects of PCS in combination with glass powder on stabilized soil strength was evident.

In the course of this study, it was noted that the UCS values of samples containing PAS were much higher than non-stabilized sandy soil samples. However, the higher strength values of GGBS-based concrete compared to RGP-based concrete could be attributed to the presence of a high percentage of calcium oxide and a high rate of pozzolanic reaction in GGBS-based samples.

3.2 Effect of Adding Sodium Silicate Solution

To study and compare the effect of silicate in dry and solution states, new samples were prepared by using, Water Glass (WG), as an alkaline activator. Previous studies on the effects of adding WG to an alkali solution on the compressive strength of GPC have shown that the addition of WG had a significant influence on the compressive strength of the samples, with an optimal value of 50 percent of alkaline solution (Sarah Kareem Mohammed et al. 2023). Therefore, the

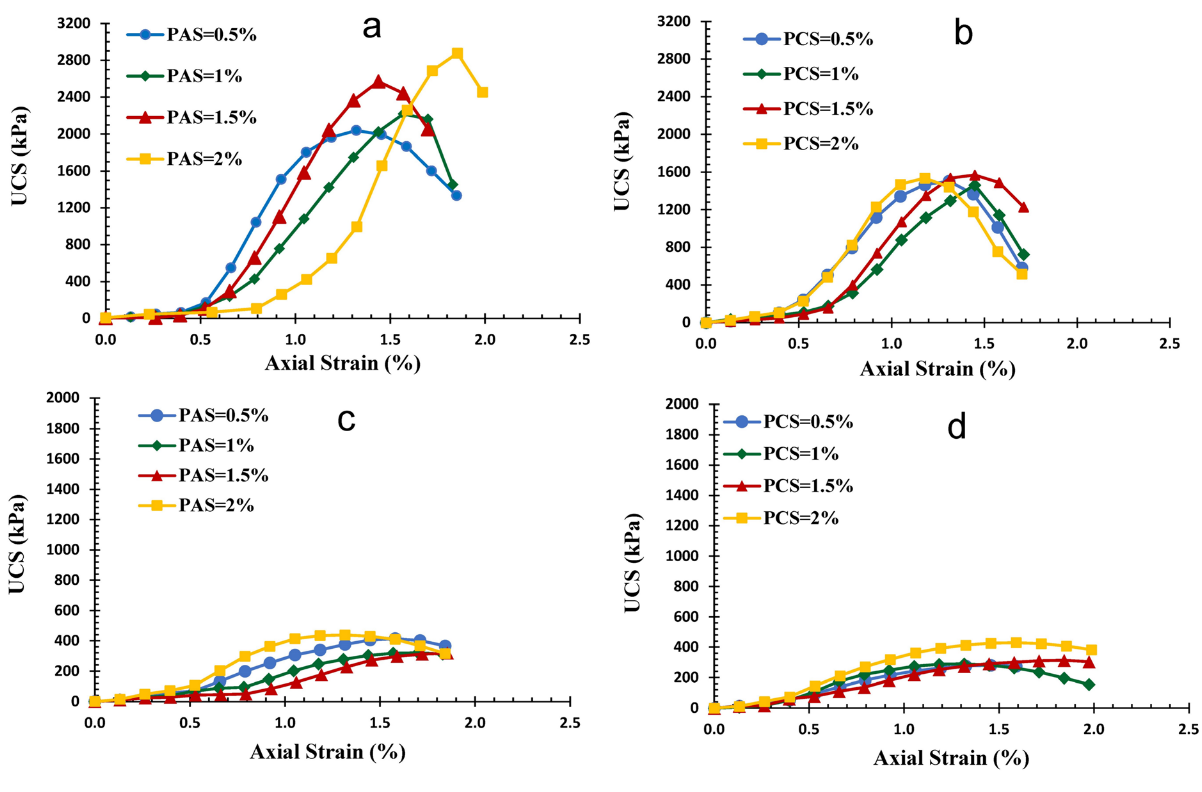


Fig. 8 Stress–strain plots of GGBS-based samples with **a** PCS, and **b** PAS, and RGP-based sam-ples with **c** PCS and **d** PAS

Table 5 The percentage of strength increment/decrement of samples with PAS and PCS

Mixture ID	% PAS	percentage of increased/decreased strength compared to 0.5% PAS	Mixture ID	% PCS	percentage of increased/ decreased strength compared to 0.5% PCS
A1G	0.5	0	C1G	0.5	0
A2G	1	9	C2G	1	−3
A3G	1.5	26	C3G	1.5	4
A4G	2	41	C4G	2	3
A1R	0.5	0	C1R	0.5	0
A2R	1	−21	C2R	1	3
A3R	1.5	−24	C3R	1.5	10
A4R	2	7	C4R	2	52

samples were prepared with 18% RGP and 2% PAS. However, the difference was that the alkaline solution for activating the precursors was made of a combination of 50% sodium silicate (WG) and 50% sodium hydroxide. Figure 5 shows that A4RW with the composition presented in Table 4 has a strength about 2 times higher than the corresponding RGP sample, almost 4 times that of the corresponding sample of A4R, and more than 5 times the natural soil (NS). As shown in Table 4, the only difference between samples A4R and A4RW is that 50% of the alkaline sodium hydroxide solution is replaced with sodium silicate solution. Therefore, the addition of silicate minerals in the form of WG solution can play a more efficient role in improving the strength of geopolymer samples than the type of RGP powder. This was also observed in studies carried out by other researchers (Feng et al. 2022).

3.3 Investigation of the Moisture Susceptibility

Stabilizing the subgrade or the building foundation with geopolymer may yield challenges. An important challenge, especially in areas where the groundwater table is close to the surface, is the performance of the stabilized soil in wet or saturated conditions that may not be acceptable (Pourabbas Bilondi et al. 2018a; Arrieta Baldovino et al. 2020). In the case of road subgrades for instance, as schematically shown in Fig. 6, the stabilized subgrade can potentially get saturated by the intrusion of surface water and also by the upward movement of groundwater through capillarity.

To evaluate the durability and performance of the samples under saturated conditions, a selection of samples presented in Table 4 was adopted. The selection of samples was based on the highest UCS value in each group of samples along with the control samples. The selected samples were prepared under the same conditions as before. After 7 days of curing, the samples were immersed in water for 48 h. The saturation of the samples was ensured by maintaining a constant weight of the wet sample. That is the sample did not absorb any more water and thus, no weight gain was observed indicating a saturated state. Uniaxial compressive strength tests were then carried out on the samples in a fully saturated state. The results presented in Fig. 7 show that five mixtures, being RGP, GGBS, A4RW, A4R, and C4R experienced a decrease in strength after 48 h of saturation. It should be noted that the unstabilized sand sample disintegrated after 5 h of saturation. In contrast, samples A4G, and C4G, with the combination of nanoparticles and GGBS resulted in an unexpected increase in uniaxial compressive strength after 48 h of saturation. This result suggested that the proposed mixing approach for stabilizing sandy soils has successfully addressed the main challenge associated with geopolymer stabilization, namely limited durability under saturated conditions. As illustrated in Fig. 7, the UCS of soil samples treated with RGP and GGBS dramatically decreased after saturation and the addition of PCS, PAS, and WG could not prevent the decrease in the strength of RGP-based samples. However, the addition of nanoparticles to GGBS was so helpful in saving the durability of treated samples on saturation conditions.

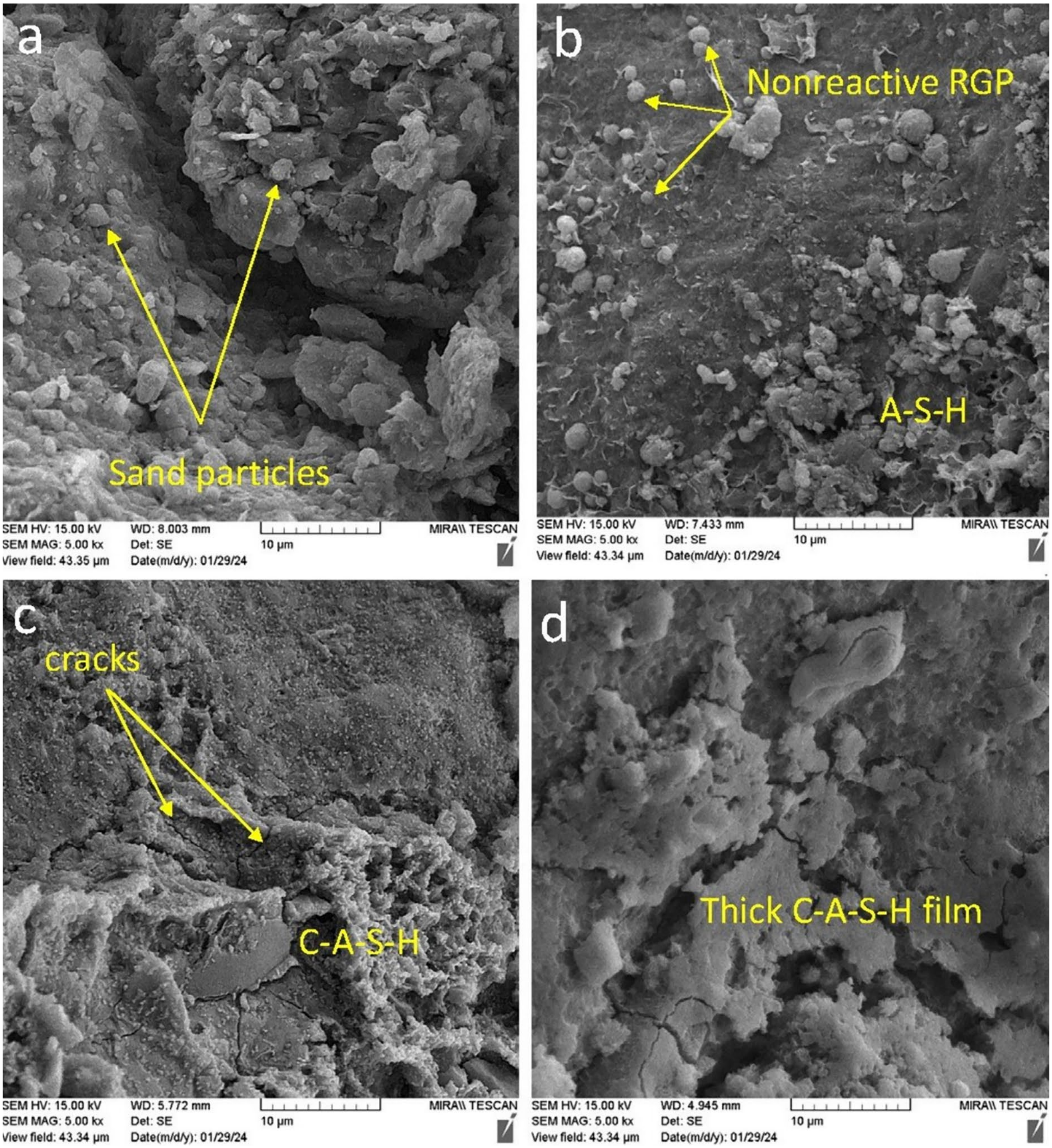
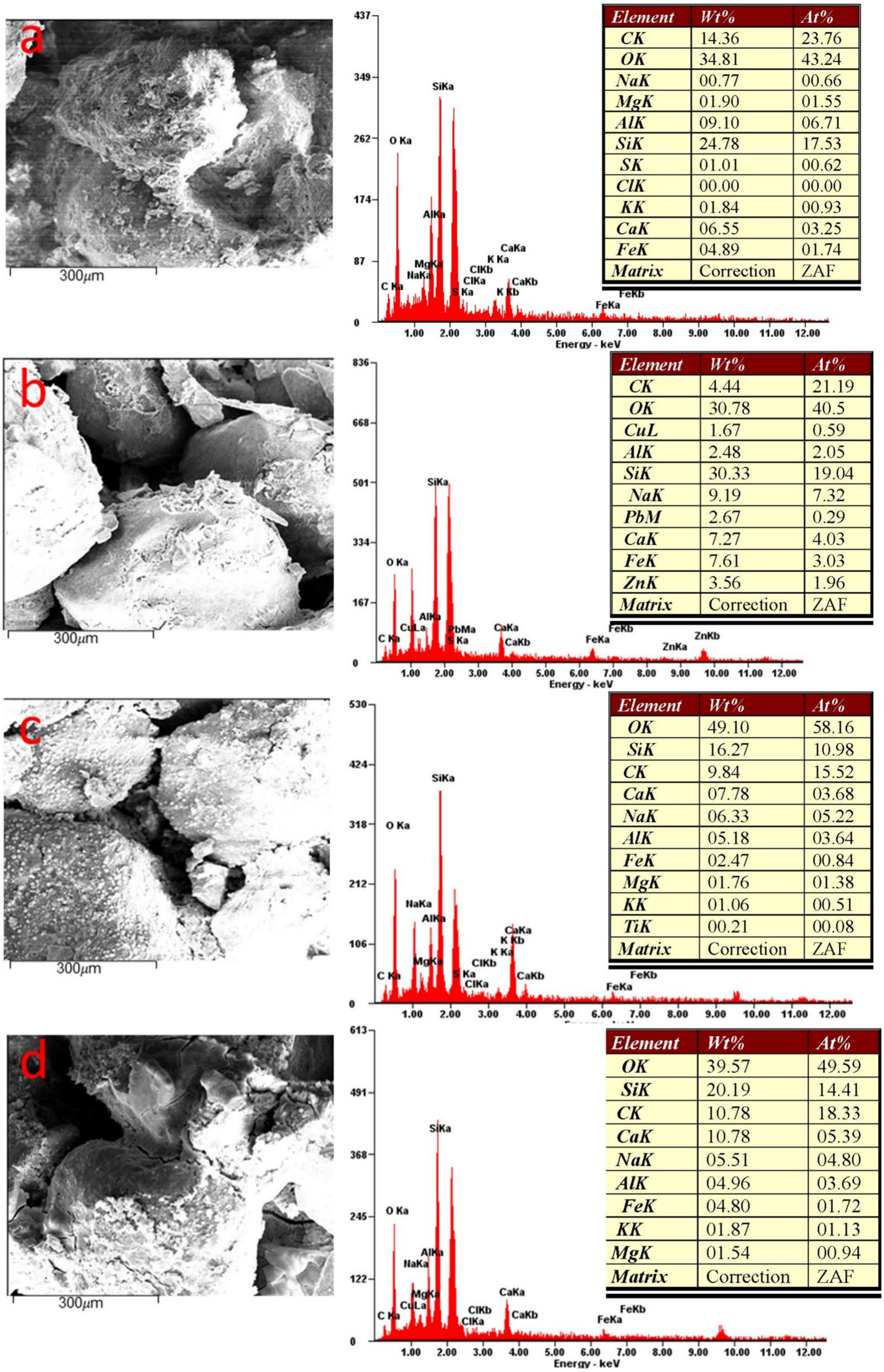


Fig. 9 FE-SEM images of selected specimens, **a** Soil; **b** RGP; **c** GGBS and **d** A4G

3.4 Stress–Strain Behavior

The stress–strain curves of tests drawn for samples stabilized using RGP and GGBS with 0.5–2% nano-aluminum silicate and nano-calcium silicate are shown in Fig. 8. A comparison of the stress–strain curves of the specimens shows that the failure stress for RGP-based specimens is lower than those of GGBS-based samples. This could be attributed to the presence of Cao minerals in GGBS and to the combination with nanoparticles that play an effective role in increasing the strength of samples compared to RGP.



(a)

Element	Wt%	At%
CK	14.36	23.76
OK	34.81	43.24
NaK	00.77	00.66
MgK	01.90	01.55
AlK	09.10	06.71
SiK	24.78	17.53
SK	01.01	00.62
ClK	00.00	00.00
KK	01.84	00.93
CaK	06.55	03.25
FeK	04.89	01.74
Matrix	Correction	ZAF

(b)

Element	Wt%	At%
CK	4.44	21.19
OK	30.78	40.5
CuL	1.67	0.59
AlK	2.48	2.05
SiK	30.33	19.04
NaK	9.19	7.32
PbM	2.67	0.29
CaK	7.27	4.03
FeK	7.61	3.03
ZnK	3.56	1.96
Matrix	Correction	ZAF

(c)

Element	Wt%	At%
OK	49.10	58.16
SiK	16.27	10.98
CK	9.84	15.52
CaK	07.78	03.68
NaK	06.33	05.22
AlK	05.18	03.64
FeK	02.47	00.84
MgK	01.76	01.38
KK	01.06	00.51
TiK	00.21	00.08
Matrix	Correction	ZAF

(d)

Element	Wt%	At%
OK	39.57	49.59
SiK	20.19	14.41
CK	10.78	18.33
CaK	10.78	05.39
NaK	05.51	04.80
AlK	04.96	03.69
FeK	04.80	01.72
KK	01.87	01.13
MgK	01.54	00.94
Matrix	Correction	ZAF

◂**Fig. 10** SEM/EDX images of selected specimens, **a** Soil; **b** RGP; **c** GGBS and **d** A4G

As shown in Fig. 8a and b, the specimens containing GGBS behave as brittle materials similar to cement concretes. This behavior is clearly visible in the sample containing GGBS with 2% PAS. Toufigh et al. stated that by raising the ratio of GGBS to binder, key factors such as compressive strength, energy absorption, and modulus of elasticity rise, while ductility decreases (Toufigh et al. 2021). In contrast, the RGP-based specimens shown in Fig. 8c and d behave as a ductile composite, which can be attributed to the non-linear strain softening behavior model. The ductility behavior of RGP-based samples was also observed by a previous study, which showed that increasing the RGP content leads to an increase in strain and thus an increase in ductility (Pourabbas Bilondi et al. 2018b). For a better investigation of RGP and GGBS-based sample behavior, Table 5 was prepared which shows that the increase in PAS contents leads to a steady upward trend of UCS in RGP-based samples. However, the effect of increasing PCS content was not consistent, in which the UCS decreased with 1 and 1.5% PCS and increased with 2% PCS. The reason why a small amount of stress is observed in the strain-strain graphs up to 0.5% strain may be due to the incomplete contact of the upper plate of the UCS device with the top of the stabilized samples at the start of the test (Duan and Zhang 2019; Samantasinghar and Singh 2021).

3.5 FE-SEM and EDX Analysis

The microstructural analysis of selected samples, being RGP, GGBS, A4G, and the natural soil, was characterized at X5000 magnification. The FE-SEM images for four 7-day samples of NS, RGP, GGBS, and A4G (GGBS + PAS) are shown in Fig. 9a–d, respectively. Images of all four samples were taken from the failure surface after the UCS test. FE-SEM images show the formation of geopolymer gel in the stabilized samples (RGP, GGBS, A4G). Also, the analysis of the images in Fig. 9b and 9c show that the stabilized samples have a denser environment and a homogeneous structure with less porosity than those of non-stabilized samples. As shown in Fig. 9d, nanoparticles contribute to the formation of geopolymer product (C-A-S-H) leading to the creation of a thick layer covering the surface of soil particles, which played an effective role in the improvement of the mechanical properties and durability of the sample (Part et al. 2017).

As shown in Fig. 10a–d, According to the Energy Dispersive X-ray (EDX) examination, the main components were Si, Al, Na, O, and C. The ratios of silicon to aluminum (Si/Al) and sodium to aluminum (Na/Al) are significant factors affecting the strength and permeability of geopolymer samples (Lingyu et al. 2021). A previous study based on the alkali leaching test revealed that the most effective molar ratios (Si/Al = 3.5–4) demonstrated the highest compressive strength (Dinh et al. 2024). The increase in Si/AL value from 2.83 to 3.14 in Fig. 10a–c is a sign of the continuation of the geopolymerization process during the curing time. Moreover, it is demonstrated that the elevated mechanical characteristics of Na-Geopolymer pastes and mortars can be promptly attained during the initial stage and would marginally escalate as the duration of the curing process prolongs (Hou et al. 2019). Thus, a rise in the Na/AL value from 0.13 to 3.7 and 1.22 in Fig. 10a–c, respectively, exhibits an improvement in the UCS values. Subsequently, an augmentation of the Si/AL ratio was observed from 3.14 to 4.1 in Fig. 10c and d, resulting in an enhanced mechanical performance of the stabilized soil.

4 Conclusion

In this research, the effect of two types of nanoparticles namely nano-aluminum silicate and calcium silicate on the compressive strength of soils stabilized by geopolymers including RGP and GGBS was investigated and compared. Also, the durability of the stabilized soils in saturated conditions was evaluated. The following results are drawn from the current study:

- The optimal concentration of sodium hydroxide alkaline activator was 7 M, while the optimal percentage of GGBS additive was 20%. Therefore, the 20% dry additive in a 7 M alkali activator was adopted to prepare all of the samples.
- It was generally observed that the uniaxial compressive strength of all stabilized samples showed an increase in strength compared to untreated soil (control sample).

- Investigating the effect of using nano-aluminum silicate in combination with RGP contents showed that adding this nanoparticle up to 2% (A4R) increased the strength of stabilized soil up to 2 times compared to the untreated soil. However, compared to the sample with only RGP, their strength was reduced by half.
- The effect of a combination of nano-aluminum silicate with GGBS was very positive as it increased the strength of the samples up to 2 times compared to the GGBS sample and up to 10 times compared to the untreated soil.
- The performance of nano-calcium silicate in combination with RGP contents had a negative effect as the strength of the samples was halved compared to the RGP control sample. However, compared to the untreated soil, the strength was almost doubled. When these nanoparticles were combined with GGBS, they did not make a considerable change in the strength compared to the GGBS control samples.
- Combination of sodium silicate (water glass) with sodium hydroxide in an equal percentage content makes a new alkaline solution which when further combined with RGP and PAS (A4RW) could enhance the strength of soil when compared to the RGP, A4R, and NS samples by 2, 4 and 5.5 times, respectively.
- Examination of the durability of the typically selected samples that were submerged for 48 h revealed that the strength of almost all of the samples decreased after saturation. However, compared to the unstabilized soil, which disintegrated after 5 h of saturation, they could have acceptable stability and strength. Regarding the compressive strength of samples A4G and C4G, it was observed that after 48 h of saturation, their unconfined compressive strength increased by 20%. That was due to the continuation of chemical reactions at the end of 7 days of curing, which increased humidity and also helped to increase strength.
- A major drawback of geopolymers has been reported as their weakness and strength reduction in wet conditions which was addressed in this study by the addition of nanomaterials. However, it is proposed here that due to the enhanced durability of samples A4G and C4G in saturated conditions, complementary studies be conducted for optimizing the mix design of such treated soils for use in construction projects.

The outcomes of this study help the builidng, geotechnical and construction industry by the provision of more sustainable approaches for stabilizing soils and improving their strength and durability under typical and saturated conditions.

Author Contributions Conceptualization: Mohammad Hossein Bagheripour & Ehsan Yaghoubi; Methodology: Mohammad Hossein Bagheripour & Mojtaba Jafari Kermanipour; Formal analysis and investigation: Mojtaba Jafari Kermanipour & Ehsan Yaghoubi; Writing—original draft preparation: Mojtaba Jafari Kermanipour; Writing—review and editing: Mohammad Hossein Bagheripour & Ehsan Yaghoubi; Resources: Mohammad Hossein Bagheripour; Supervision: Mohammad Hossein Bagheripour & Ehsan Yaghoubi.

Funding Open Access funding enabled and organized by CAUL and its Member Institutions. The authors declare that no funds, grants, or other support were received during the preparation of this manuscript.

Data Availability The datasets generated during and/or analyzed during the current study are available within the manuscript. Further details can be provided upon request.

Declarations

Conflict of interest The authors have no relevant financial or non-financial interests to disclose.

References

Abushama WJ, Tamimi AK, Tabsh SW et al (2023) Influence of optimum particle packing on the macro and micro properties of sustainable concrete. Sustain 15:14331. https://doi.org/10.3390/su151914331

Al-Taie A, Yaghoubi E, Wasantha PLP et al (2023) Mechanical and physical properties and cyclic swell-shrink behaviour of expansive clay improved by recycled glass. Int J Pavement Eng 24:2204436. https://doi.org/10.1080/10298436.2023.2204436

Alyamani A, Lemine OM (2012) FE-SEM characterization of some nanomaterial. In: Scanning Electron Microscopy. IntechOpen, London. https://doi.org/10.5772/34361

de Arrieta Baldovino J, dos Santos Izzo RL, da Silva ÉR, Lundgren Rose J (2020) Sustainable use of recycled-glass powder in soil stabilization. J Mater Civ Eng 32:4020080. https://doi.org/10.1061/(asce)mt.1943-5533.0003081

Ashiq SZ, Akbar A, Farooq K, Mujtaba H (2022) Sustainable improvement in engineering behavior of Siwalik Clay using industrial waste glass powder as additive. Case Stud Constr Mater 16:e00883. https://doi.org/10.1016/j.cscm.2022.e00883

ASTM D 2166 (2013) Standard test method for unconfined compressive strength of cohesive soil. ASTM Int 1–7

ASTM D 854 (2010) D854—Standard test methods for specific gravity of soil solids by water pycnometer. ASTM Stand Guid 2458000:1–7

ASTM D422–63 (2007) Standard test method for particle-size analysis of soils. ASTM Stand Guid D422–63:1–8

ASTM D698–07 (2007) Standard test methods for laboratory compaction characteristics of soil using standard effort. ASTM Int 12:1–13

Bhojaraju C, Mousavi SS, Brial V et al (2021) Fresh and hardened properties of GGBS-contained cementitious composites using graphene and graphene oxide. Constr Build Mater 300:123902. https://doi.org/10.1016/j.conbuildmat.2021.123902

Broering WB, De Melo JVS, Manfro AL (2024) Modification of the asphalt binder with nano-aluminum oxide: an alternative to improve the thermal conductivity and the rheological properties of the asphalt matrix. J Test Eval 52:1109–1128. https://doi.org/10.1520/JTE20230402

Burciaga-Díaz O, Durón-Sifuentes M, Díaz-Guillén JA, Escalante-García JI (2020) Effect of waste glass incorporation on the properties of geopolymers formulated with low purity metakaolin. Cem Concr Compos 107:103492. https://doi.org/10.1016/j.cemconcomp.2019.103492

Cyr M, Idir R, Poinot T (2012) Properties of inorganic polymer (geopolymer) mortars made of glass cullet. J Mater Sci 47:2782–2797. https://doi.org/10.1007/s10853-011-6107-2

Devi SC, Khan RA (2020) Effect of graphene oxide on mechanical and durability performance of concrete. J Build Eng 27:101007. https://doi.org/10.1016/j.jobe.2019.101007

Dinh HL, Liu J, Doh JH, Ong DEL (2024) Influence of Si/Al molar ratio and ca content on the performance of fly ash-based geopolymer incorporating waste glass and GGBFS. Constr Build Mater 411:134741. https://doi.org/10.1016/j.conbuildmat.2023.134741

Duan XL, Zhang JS (2019) Mechanical properties, failure mode, and microstructure of soil-cement modified with fly ash and polypropylene fiber. Adv Mater Sci Eng 2019:9561794. https://doi.org/10.1155/2019/9561794

Feng H, Liang J, Pang Y et al (2022) Effects of the fly ash and water glass on the mechanical properties and water stability of the high ductile magnesium phosphate cement-based composite. Constr Build Mater 333:127395. https://doi.org/10.1016/j.conbuildmat.2022.127395

Gholampour A, Valizadeh Kiamahalleh M, Tran DNH et al (2017) From graphene oxide to reduced graphene oxide: impact on the physiochemical and mechanical properties of graphene-cement composites. ACS Appl Mater Interfaces 9:43275–43286. https://doi.org/10.1021/acsami.7b16736

Hou L, Li J, Lu ZY (2019) Effect of Na/Al on formation, structures and properties of metakaolin based Na-geopolymer. Constr Build Mater 226:250–258. https://doi.org/10.1016/j.conbuildmat.2019.07.171

Indumathi P, Shabhudeen SP, Saraswathy CP (2011) Synthesis and characterization of nano silica from the pods of Delonix Regia ash. Int J Adv Eng Technol 2:421–426

Kampala A, Horpibulsuk S, Prongmanee N, Chinkulkijniwat A (2014) Influence of wet-dry cycles on compressive strength of calcium carbide residue-fly ash stabilized clay. J Mater Civ Eng 26:633–643. https://doi.org/10.1061/(asce)mt.1943-5533.0000853

Kong X, Zhang Y, Hou S (2013) Study on the rheological properties of Portland cement pastes with polycarboxylate superplasticizers. Rheol Acta 52:707–718. https://doi.org/10.1007/s00397-013-0713-7

Ladd R (1978) Preparing test specimens using undercompaction. Geotech Test J 1:16–23. https://doi.org/10.1520/gtj10364j

Laím L, Caetano H, Santiago A (2021) Review: effects of nanoparticles in cementitious construction materials at ambient and high temperatures. J Build Eng 35:102008. https://doi.org/10.1016/j.jobe.2020.102008

Lindh P, Lemenkova P (2023) Geotechnical properties of soil stabilized with blended binders for sustainable road base applications. Constr Mater 3:110–126. https://doi.org/10.3390/constrmater3010008

Lingyu T, Dongpo H, Jianing Z, Hongguang W (2021) Durability of geopolymers and geopolymer concretes: a review. Rev Adv Mater Sci 60:1–14. https://doi.org/10.1515/rams-2021-0002

Meng T, Yu Y, Qian X et al (2012) Effect of nano-TiO 2 on the mechanical properties of cement mortar. Constr Build Mater 29:241–245. https://doi.org/10.1016/j.conbuildmat.2011.10.047

Michálková Z, Komárek M, Šillerová H et al (2014) Evaluating the potential of three Fe- and Mn-(nano)oxides for the stabilization of Cd, Cu and Pb in contaminated soils. J Environ Manage 146:226–234. https://doi.org/10.1016/j.jenvman.2014.08.004

Morsy MS, Alsayed SH, Aqel M (2011) Hybrid effect of carbon nanotube and nano-clay on physico-mechanical properties of cement mortar. Constr Build Mater 25:145–149. https://doi.org/10.1016/j.conbuildmat.2010.06.046

Nabizadeh Mashizi M, Bagheripour MH, Jafari MM, Yaghoubi E (2023) Mechanical and microstructural properties of a stabilized sand using geopolymer made of wastes and

a natural pozzolan. Sustain 15:2966. https://doi.org/10.3390/su15042966
Noolu V, Mallikarjuna Rao G, Sudheer Kumar Reddy B, Chavali RVP (2021) Strength and durability characteristics of GGBS geopolymer stabilized black cotton soil. Mater Today Proc 43:2373–2376. https://doi.org/10.1016/j.matpr.2021.01.939
Part WK, Ramli M, Cheah CB (2017) An overview on the influence of various factors on the properties of geopolymer concrete derived from industrial byproducts. Handb Low Carbon Concr 77:263–334. https://doi.org/10.1016/B978-0-12-804524-4.00011-7
Pascual AB, Tognonvi MT, Tagnit-Hamou A (2014) Waste glass powder-based alkali-activated mortar. Int J Res Eng Technol 3:32–36
Pourabbas Bilondi M, Toufigh MM, Toufigh V (2018a) Experimental investigation of using a recycled glass powder-based geopolymer to improve the mechanical behavior of clay soils. Constr Build Mater 170:302–313. https://doi.org/10.1016/j.conbuildmat.2018.03.049
Pourabbas Bilondi M, Toufigh MM, Toufigh V (2018b) Using calcium carbide residue as an alkaline activator for glass powder–clay geopolymer. Constr Build Mater 183:417–428. https://doi.org/10.1016/j.conbuildmat.2018.06.190
Qing Y, Zenan Z, Deyu K, Rongshen C (2007) Influence of nano-SiO2 addition on properties of hardened cement paste as compared with silica fume. Constr Build Mater 21:539–545. https://doi.org/10.1016/j.conbuildmat.2005.09.001
Raza MH, Khan M, Zhong RY (2024) Strength, porosity and life cycle analysis of geopolymer and hybrid cement mortars for sustainable construction. Sci Total Environ 907:167839. https://doi.org/10.1016/j.scitotenv.2023.167839
Rios S, Cristelo N, Viana da Fonseca A, Ferreira C (2016) Structural performance of alkali-activated soil ash versus soil cement. J Mater Civ Eng 28:4015125. https://doi.org/10.1061/(asce)mt.1943-5533.0001398
Samantasinghar S, Singh SP (2021) Strength and durability of granular soil stabilized with FA-GGBS geopolymer. J Mater Civ Eng 33:6021003. https://doi.org/10.1061/(asce)mt.1943-5533.0003736
Sarah Kareem Mohammed AS, Géber R, Simon A et al (2023) Comparative study of metakaolin-based geopolymer characteristics utilizing different dosages of water glass in the activator solution. Results Eng 20:101469. https://doi.org/10.1016/j.rineng.2023.101469
Solanki P, Bierma T, Jin G (2020) Properties of flowable fill produced by substituting fly ash with recycled glass powder. Constr Build Mater 265:120330. https://doi.org/10.1016/j.conbuildmat.2020.120330
Sundaram DS, Yang V, Zarko VE (2015) Combustion of nano aluminum particles (Review). Combust Explos Shock Waves 51:173–196. https://doi.org/10.1134/S0010508215020045
Tong T, Fan Z, Liu Q et al (2016) Investigation of the effects of graphene and graphene oxide nanoplatelets on the micro- and macro-properties of cementitious materials. Constr Build Mater 106:102–114. https://doi.org/10.1016/j.conbuildmat.2015.12.092
Toufigh V, Karamian MH, Ghasemalizadeh S (2021) Study of stress–strain and volume change behavior of fly ash-GBFS based geopolymer rammed earth. Bull Eng Geol Environ 80:6749–6767. https://doi.org/10.1007/s10064-021-02292-5
Wongkornchaowalit N, Lertchirakarn V (2011) Setting time and flowability of accelerated portland cement mixed with polycarboxylate superplasticizer. J Endod 37:387–389. https://doi.org/10.1016/j.joen.2010.11.039
Yaghoubi E, Azadegan O, Li J (2013) Effect of surface layer thickness on the performance of lime and cement treated aggregate surfaced roads. Electron J Geotech Eng 18:1081–1094
ZhangZhao WLLY, McCabe BA et al (2020) Dredged marine sediments stabilized/solidified with cement and GGBS: factors affecting mechanical behaviour and leachability. Sci Total Environ 733:138551. https://doi.org/10.1016/j.scitotenv.2020.138551