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ABSTRACT
This research studied the feasibility of using waste glass powder, Portland cement, and sodium chloride to stabilise and geopolymerization clayey soil. The chemical composition and microstructure of the materials were determined by X-ray fluorescence and scanning electron microscopy, respectively. Cement and waste glass powder contents were determined through previous laboratory tests and literature reviews. Unconfined compressive strength tests were performed to determine the optimal sodium chloride content, which was used in this research as an alkaline precursor in geopolymer formation. The effects of cement, waste glass powder, and geopolymer (composed of soil+(5 and 15% waste glass powder)+1% sodium chloride) were investigated through unconfined compressive strength and splitting tensile strength tests. The results revealed that the specimens stabilised with geopolymer presented higher strengths, finding strengths approximately 24 times higher than the pure soil and 1.6 times higher than the soil stabilised with 8% cement. Adding waste glass powder and geopolymer allowed some blends to become suitable for use as a subbase in pavement applications. Microstructure analyses confirmed the formation of geopolymer through a more homogeneous structure. Finally, it was concluded that stabilising with geopolymer based on waste glass powder is an ecological and effective technique for increasing soil strength.

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KEYWORDS
Waste glass powder; geopolymer; stabilization; alkaline precursor; soil improvement

1. Introduction

Stabilizing soils unsuitable for civil construction projects has been challenging in geotechnical engineering (Abbaspour *et al.* 2020, Habibi *et al.* 2021, Tajaddini *et al.* 2023). Silt and clayey soils with high plasticity are sensitive to changes in humidity and can undergo swelling and shrinkage, leading to various damages in civil construction projects. The expansion or retraction of soil causes the settlements to generate damage to constructions, such as cracking in the ground, lifting grooves in the pavement, and building cracks (Pushpakumara and Mendis 2022, Aswad *et al.* 2023). Therefore, the improvement of the geotechnical properties of the soil needs to be carried out to meet the requirements of the civil construction project.

The Guabirotuba geological formation consists of a geotechnical profile based mainly on clays and silts. These soils can develop expansion deformation and shrinkage stress under varying climatic conditions of rainfall and medium and high temperatures. In such cases, it is necessary to stabilise and/or reinforce the soils of the Guabirotuba formation to make them suitable for civil engineering works (Baldovino *et al.* 2018).

Soil improvement includes soil replacement, mechanical compaction, and physical and chemical stabilisation. The most common applications are constructing railway tracks, pavements, and airfields, where the objective is to reduce the pavement layer's thickness and increase the pavement structure's load capacity and stiffness (Umar Verma 2015, Pushpakumara and Mendis 2022).

Portland cement is currently the most used material in soil improvement (Fraccica *et al.* 2022). Although the stabilisation of soils with cement effectively increases the performance in terms of strength, its manufacture generates severe environmental impacts (Tajaddini *et al.* 2023). Approximately 8% of global carbon dioxide emissions are the product of cement manufacturing processes. Reducing these emissions is increasingly challenging, especially in the civil construction sector (International Energy Agency 2018, Fraccica *et al.* 2022).

Among the different methods to reduce the pollution caused by Portland cement in soil improvement, alternative materials stand out, for instance, rice husk ash, fly ash, waste glass dust, marble powder, silica fume, and rice husk silica; these materials do not only reduce the

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use of cement but also improve the geotechnical properties of different soils (De Jesús *et al.* 2020, Ordoñez Muñoz *et al.* 2021, Shariati *et al.* 2021, Jassim *et al.* 2022, Muñoz *et al.* 2023).

The use of recycled and waste materials in civil construction works contributes to the reduction of solids dumped in landfills, in addition to being an alternative to a decrease in the consumption of natural resources for manufacturing materials such as cement (Tho-In *et al.* 2016).

Brazil produced approximately 82.5 million tons of solid urban waste in 2020. In addition, areas of inadequate disposal, such as open dumps and landfills, received about 40% of the total urban waste collected, including waste from cutting and polishing flat glass (ABRELPE 2023). Waste glass from cutting and polishing flat glass has been investigated as a substitute material for cement in soil improvement mechanisms by researchers such as Blayi *et al.* (2020), Javed and Chakraborty (2020), de Jesús Arrieta Baldovino *et al.* (2020), Pourabbas Bilondi *et al.* (2018a) and Salpadoru Tholkamudalige *et al.* (2022). Waste glass powder (WGP) has pozzolanic characteristics due to its amorphous structure and high silica content (Tho-In *et al.* 2016, Jiang *et al.* 2019). WGP reactivity is related to particle size, with 75 µm being the one with which pozzolanic reactivity is noticeable (Pereira-De-Oliveira *et al.* 2012).

Researchers who studied the WGP found that including this material in clayey soil increased the unconfined compressive strength (UCS), where the UCS went from 205.01 kPa in pure soil to 360.10 kPa in the soil plus 15% of WGP. In addition, the thickness of the subgrade subbase has decreased by approximately 63% (Blayi *et al.* 2020). Kamali and Ghahremaninezhad (2016) mention that WGP with microscale size distribution can be used as pozzolanic material in cement-based blends. Table 1 summarises the literature review on recent studies that have improved the geotechnical properties of different types of soils with materials such as PC and WGP.

On the other hand, several authors have used glass powder as a base for geopolymers in concrete and soil improvement (Pourabbas Bilondi *et al.* 2018a, Blayi *et al.* 2020, Baldovino *et al.* 2021, Tajaddini *et al.* 2023). Geopolymerization is a technique based on the reaction of solids rich in silica (SiO_2) and alumina (Al_2O_3) with alkaline salt solutions, resulting in gels and crystalline compounds that form a more strength and rigid material (Verdolotti *et al.* 2008). Geopolymers are among the most suitable alternatives for replacing cement (Pourabbas Bilondi *et al.* 2018a, Al-Dossary *et al.* 2023). In the opinion of Xu and Van Deventer (2002), any material with pozzolanic characteristics and amorphous morphology based on silica, which is soluble under an alkaline activator, can be suitable for geopolymerization. The geopolymer formation mechanism involves the hydrolysis and dissolution of naturally occurring silicon-aluminate minerals in an alkaline solution. Where silicon and aluminium atoms react to form molecules that are chemically and structurally comparable to those that form natural rocks (Davidovits 1982). During geopolymerization processes, alumina and silica are activated by alkaline solutions, forming alumina-silicate polymers and increasing clayey soil strength (Pourabbas Bilondi *et al.* 2018a).

Pourabbas Pourabbas Bilondi *et al.* (2018b) investigated using a geopolymer based on recycled glass powder to improve clay soils. The authors analysed levels of glass powder (0, 3, 6, 9, 12, 15, 20, 25) and sodium hydroxide (NaOH) as an alkaline activator in different molar concentrations (1, 2, 3, 4, 5, 6, 7, 8 Molar). The results showed that the UCS of the specimens formed by the geopolymer (15% glass powder and 2 Molar NaOH) and clay soil plus was 10.7 times greater than the pure soil and 1.42 times greater than the stabilised soil with 5% cement after 28 days of curing.

Despite several studies on stabilising soils with different materials derived from glass, studies comparing the effect of Portland cement, waste from polishing and cutting flat glass (WGP), and WGP-based geopolymers in soil improvement are limited. In this context, this research aims to contribute to studies on waste from polishing and cutting flat glass through its use as a possible substitute for cement. This study compared clayey soil's stabilisation and geopolymerization processes from the Guabirotuba formation. For this, WGP and PC as stabilisers were evaluated. In addition, a geopolymer based on WGP was developed using NaCl as an alkaline precursor. This research intends to contribute to the knowledge of one of the alternatives for the use of common waste in Brazil, aiming to reduce the area occupied in landfills, where the waste produced in the glass cutting and polishing industry is usually dumped, in addition to lowering the high amounts of Portland cement used in soil improvement processes.

2. Experimental program

2.1. Materials

In the present study, the reddish soil of the Guabirotuba formation, waste from the cutting and polishing of the

Table 1. Effect of WGP, PC, and other materials on the mechanical strength of some soils reported in the literature.

Author	Type of soil	WGP content (% by weight)	Other materials content (%)	Cure time (days)	Best Result
Blayi *et al.* (2020)	Clay	2.5, 5, 10, 15, and 25	-	-	The UCS went from 205.01 kPa in pure soil to 360.10 kPa for soil and 15% WGP blends. Besides, improving expansive subbed soil with 15% WGP decreases the thickness of the pavement sub-base layer by about 63%.
Javed and Chakraborty (2020)	Clay	2, 4, 6, 8 and 10.	-	-	UCS increased to 8% of WGP, with values from 63.2 kPa in pure soil to 133.5 kPa in the soil blend plus 8% of WGP. For 10% of WGP, the UCS decreased to 119.7 kPa.
De Jesús *et al.* (2020)	Silty	5, 15, and 30.	PC: 3, 6 and 9	7, 28 and 90	Contents of 30% WGP and 9% PC result in STS of approximately 2100 kPa after 90 days of curing.
Pourabbas Bilondi *et al.* (2018a)	Clay	3, 6, 9, 12, 15, 20.	alkaline activator CCR: 7%	7, 28, and 91	The maximum UCS obtained was after 91 days of curing (2150 kPa) for contents of 15% of the WGP, compared with the UCS of the pure soil (200 kPa). For contents of 20% of WGP, the UCS had a slight decrease (aprox 2050 kPa)
Pourabbas Bilondi *et al.* (2018b)	Clay	0, 3, 6, 9, 12, 15, 20, and 25	Alcaline ativator: NaOH (1, 2, 3, 4, 5, 6, 7 and 8 Molar)	7, 28, and 91	UCS of soil + 15%WGP+NaOH 2 Molar blends for 28 and 91 days of curing were approximately 10.7 and 14 times higher than for soil + 5%PC blends
Salpadoru Tholkamudalige *et al.* (2022)	Clay	Crushed glass: 0, 5, 10, 15, and 20	-	0	Increasing the crushed glass content from 0% to 10% caused the UCS to increase from 153.73 to 334.01 kPa, then reduced to 306.69 kPa by the greater addition of glass up to 20%
Zhang *et al.* (2022)	Dredged sediment (DS)	5, 10, 15, and 20.	Cement: 6, 8, 10, and 12	7 and 28.	The optimal content resulted in 15% of WGP, where UCS went from approximately 370 kPa in DS + 6%PC to 475kPa in DS + 15%WGP
Xiao *et al.* (2021)	Fine limestone	4, 8,12, 16, and 18	Hydrated lime: 2, 4, 8, 12, and 16	7, 14, 21, and 28.	The best results of UCS and STS were obtained after 28 days, where UCS ranged from 850 kPa to 1950 kPa and STS ranged from approximately 100 kPa to 300 kPa in blends composed of soil + 16% glass powder + 4% hydrated lime, respectively
Ibrahim *et al.* (2021)	Clay	0, 6, 12, 18, 27, and 36	-	0	The optimal content was 27% of WGP, where the UCS went from 282.3 kPa in pure soil to 560.1 kPa. For the content of 36%, the UCS had a slight decrease to 517.6 kPa
Ashiq *et al.* (2022)	clay	5, 10, 15, and 20	-	0	The authors found that 20% of GP produced an improvement of 110% (232) kPa. On the other hand, a 26% reduction in swelling strain
Tajaddini *et al.* (2023)	clay	0, 1, 2, 4, and 5	Copper slag: 0, 1, 2, 4, and 5	7, 28, and 56	For 5% copper slag at UCS at 56 days of curing and CBR at 7 curing days increased by 3.11 and 1.68 times, respectively. While these values were 4.03 and 1.90 times, respectively, when applying 5% of WGP
Sheob *et al.* (2023)	clay	2.5, 5, 7.5, and 10	PC: 5	0	The CBR. of the treated soil increased by 260% when a combination of 5% PC and 5% of WGP was used
Mohammadzadeh *et al.* (2023)	Clay	1, 3, 9, 15, and 21	PC: 10	7	UCS has increased from 140 kPa in pure soil to 4800 kPa in soil + 15% WGP

Where: CCR is calcium carbide residue.

flat glass (WGP), Portland cement (PC) of high initial strength, and sodium chloride (NaCl) were the materials used.

2.1.1. Soil

The soil used in the present research was obtained in the city of Curitiba, Paraná, coordinates (25°26’43"S 49° 21’14"W) (Figure 1). The soil was collected in the deformed and undeformed state at a depth of approximately 1 metre, corresponding to the first layer of the Guabirotuba formation, in its natural state, presented moisture of 32.25%. The soil is reddish due to haematite, a common mineral in surface soils resulting from weathering mainly in tropical and subtropical zones (Blake *et al.* 1966, Li *et al.* 2016, Singh *et al.* 2018).

Table 2 presents the results of the physical characterisation of the soil analysed based on the results of three replications. Figure 2 depicts the particle size distribution of the soil particles analysed in this research. The soil under study was classified using the unified soil classification system ASTM D2487-17 (2017), ASTM D 3282-15 (2015), and the methodology for classifying tropical soils with lateritic and non-lateritic behaviour MCT (Miniature, Compacted, Tropical) (DNIT 259-ME, DNIT 258-ME).

The results revealed that the soil was categorised as MH – high plasticity silt (Figure 3a) according to USCS ASTM D2487-17 (2017), A-7-5 (high plasticity clays) according to ASTM D 3282-15 (2015), and finally, as a clayey lateritic LG’ according to (DNIT 259-ME ,

Figure 1. Location of the collection area of the studied soil.

Table 2. Physical properties of the soil and WGP.

Properties	Soil	WGP	Standard
Atterberg limits			
Liquid limit (LL). %	57.07		ASTM D 4318 (2010)
Plastic limit (PL). %	42.41		
Plastic index (PI). %	14.65		
Grain Size Distribution			NBR 7181 (2018)
Gravel. %	0.4		
Coarse sand (0.6 mm<D <2 mm). %	1.7	0	
Medium sand (0.2 mm<D <0.6 mm). %	13.7	0	-
Fine sand (0.06 mm<D <0.2 mm). %	11.3	12.7	-
Silt (0.002 mm<D <0.06 mm). %	14.0	85.45	-
Clay (D <0.002 mm). %	58.6	1.85	-
Other properties			
Specific gravity of soil (SG)	2.625	2.23	ASTM D 854 (2010)
AASHTO Soil Classification Systems	A-7-5	-	DASTM D 3282-15 (2015)
USCS Classification Systems	MH	-	ASTM D2487-17 (2017)
MCT	LG’	-	DNIT 259-ME (), DNIT 258-ME ()
Color	Red	White	
Effective size (D10) mm	-	0.010	
Diameter (D30) mm	-	0.019	
Mean particle diameter (D_{50}) mm	-	0.029	
Diameter (D60) mm	-	0.036	
Uniformity coefficient (Cu)	-	3.50	
Coefficient of curvature (Cc)	-	1.04	

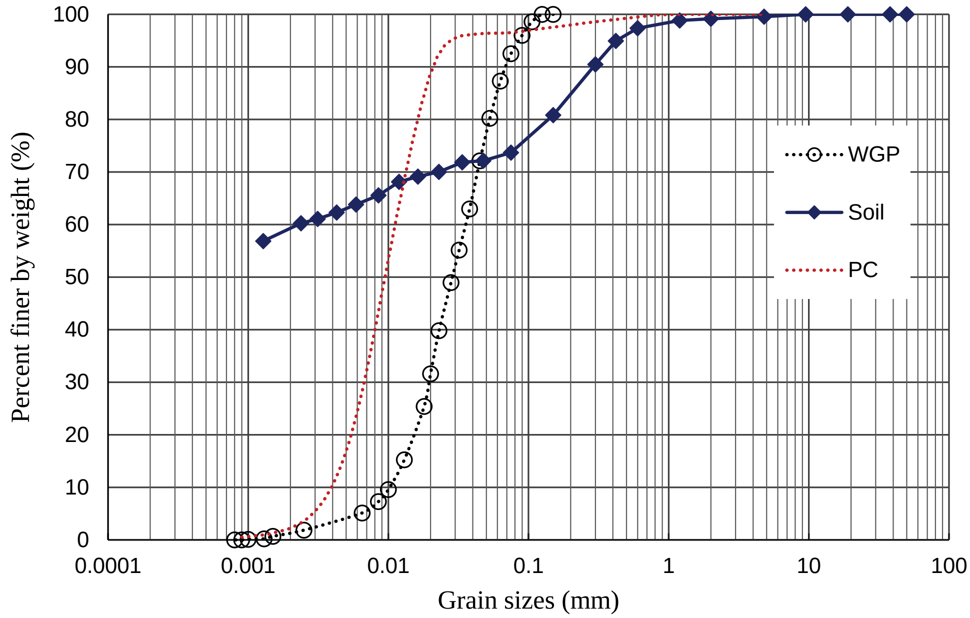

Figure 2. Grain size distribution of soil, WGP, and PC.

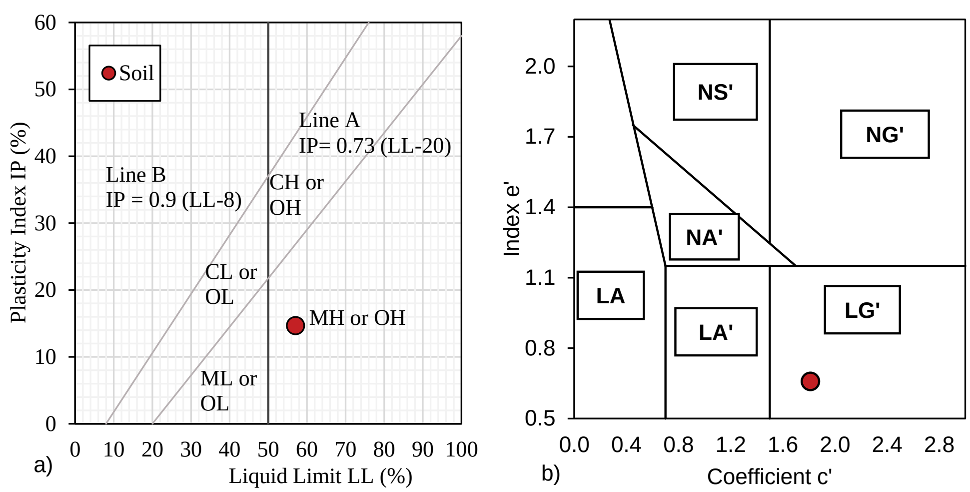

Figure 3. Soil classification according to a) Unified soil classification System (USCS), b) MCT classification.

DNIT 258-ME) (Figure 3b). Traditional classifications based on temperate soils labelled the soil in this study as poorly behaved for use in pavements. However, employing the classification system for tropical soils characterised the soil as clay belonging to the clayey lateritic group LG'.

X-ray fluorescence (XRF) analyses were performed to investigate the chemical composition of soil, WGP, and PC; the results are shown in Table 3. Silica (SiO_2) and aluminium oxide (Al_2O_3) are the chemical compounds that prevail in the soil, which coincides with the typical compositions found in soils of the Guabirotuba formation (de Jesús Arrieta Baldovino *et al.* 2023, Muñoz *et al.* 2024).

Table 3. Soil, WGP, and PC chemical composition.

Element	Soil	PC	WGP
Na_2O	5.476	-	-
SiO_2	48.773	26.38	78.153
SO_3	4.552	8.01	2.943
K_2O	0.799	1.43	0.927
CaO	-	54.74	13.074
Al_2O_3	39.256	9.44	3.483
TiO_2	0.817	-	
Fe_2O_3	0.246	-	0.074

According to de Jesús Arrieta Baldovino *et al.* (2020), soils containing silica and aluminium oxide are considered suitable for stabilisation processes. Khale and Chaudhary (2007) states that the primary

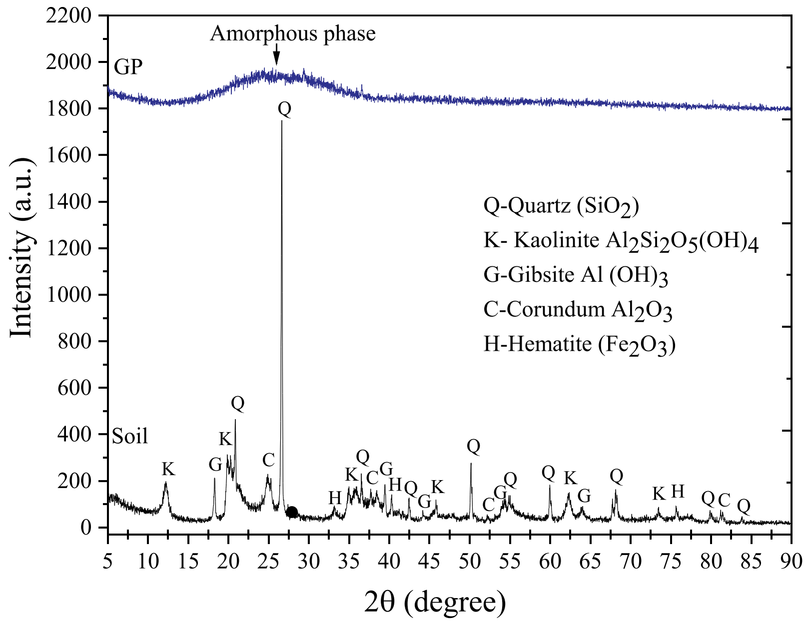

Figure 4. X-ray diffraction (XRD) analysis of pure soil and WGP.

requirement for undergoing the geopolymerization process is the abundance of Si and Al in the materials. On the other hand (Shivaramaiah Amulya *et al.* 2020), mention that lateritic soil, rich in SiO_2 and Al_2O_3, contributes to the polymerisation reaction with alkaline solutions.

X-Ray Diffraction (XRD) tests were performed to determine soil and WGP mineralogy, and Figure 4 displays these results. The prevalence of minerals such as quartz, kaolinite, and haematite was observed, which coincides with the silicon and aluminium oxides found in the chemical composition of the soil.

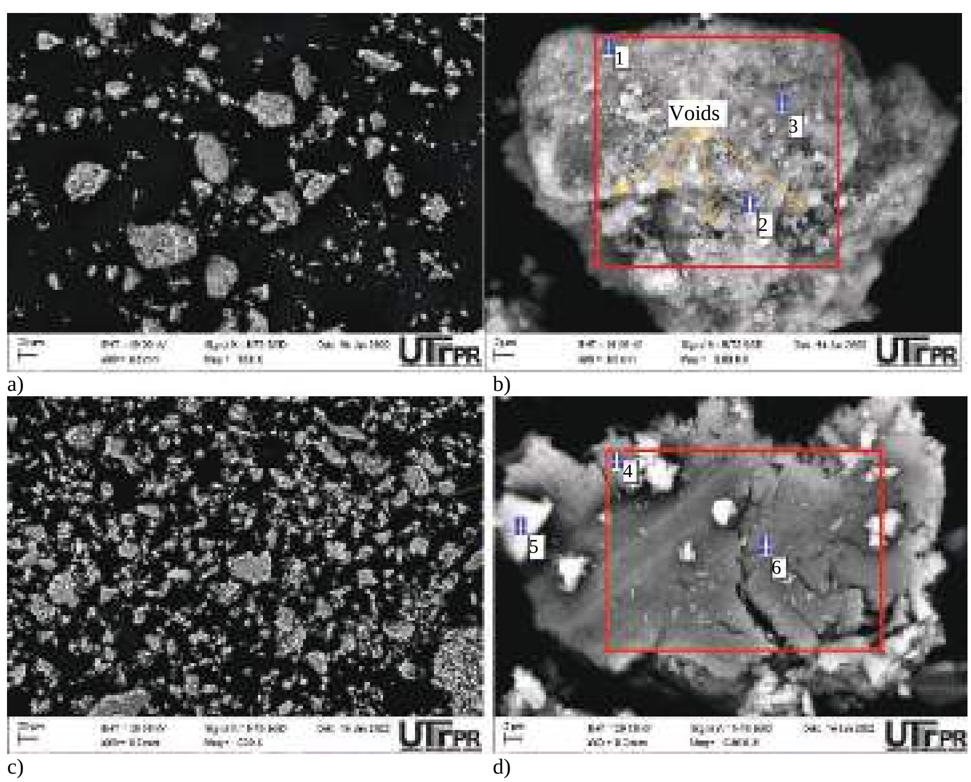

Figure 5. SEM micrographs of (a-b) pure soil (e, f) WGP.

Figure 5 presents the scanning electron microscopy (SEM) analyses of pure soil at 500× and 5KX magnification. The soil is composed of varying-sized grains, and possibly the presence of clay minerals adhered to the larger particles. Figure 5b shows the agglomeration of smaller fractions in the surface part of the analysed particle and the presence of voids.

Table 4 presents the microanalysis points' Energy Dispersive X-Ray analysis (EDX) (1, 2, 3, 4, 5, and 6). In the soil, oxygen, silicon, and aluminium prevail, representing mineralogically quartz, kaolinite, and corundum and coinciding with the XRF and XRD analyses performed in pure soil.

2.1.2. Waste glass powder

The waste glass was supplied by a glass polishing and cutting plant in Curitiba, Brazil. The WGP used in this study is a residue (sludge) from the water treatment necessary for cutting and polishing the flat glass. For its use in the soil improvement process, the WGP was subjected to the following processes: a) drying at 100 ± 5°C; b) fragmentation with the help of the Los Angeles abrasion equipment for approximately 3 hours; c) sieving through sieve No. 200, obtaining particles smaller than 75 µm (Figure 6). According to Baldovino *et al.* (2021), particles smaller than 0.75 µm are precursors of geopolymerization processes in soil stabilisation mechanisms.

Table 2 presents the physical characterisation of the WGP, where 85.45% of the particles are classified as 'silt'. Figure 2 presents the particle size analysis of the WGP, the particle diameters corresponding to 10%, 30%, 50%, and 60% were measured as $D10 = 0.010$ mm, $D30 = 0.019$ mm, $D50 = 0.029$ mm, $D60 = 0.036$ mm. Consequently, the ratio D60 to D10 (coefficient of uniformity) equals 3.5, and the curvature coefficient equals 1.04. Thus, WGP used in this research was classified according to the USCS as a silty material (ASTM D2487-17, 2017). The specific gravity of the WGP was determined following ASTMD854 (2010), obtaining a value of 2.23.

Table 4. EDX analysis of soil and WGP particles (%).

Spectro	O	Al	Si	Ti	Fe	Na	Mg	K	Ca	C
1	58.36	5.42	32.91	0.39	2.92	-	-	-	-	-
2	60.99	2.23	35.29	-	1.49	-	-	-	-	-
3	59.14	4.48	34.72	0.25	1.41	-	-	-	-	-
4	60.61	0.5	24.28	-	-	9.26	2.05	0.14	3.15	-
5	62.22	1.49	24.31	-	-	7.92	1.34	0.12	3.75	-
6	59.54	0.46	34.72	-	-	7.26	1.88	0.17	2.98	4.23

Figure 6. Preparation of the waste glass powder a) waste glass (sludge); b) drying c) fragmentation; d) sieving; e) blend composed by soil, PC, and WGP; f) moulded specimens with soil, PC, and WGP.

Table 5. Properties of high early strength cement (PC V-ARI).

Parameters	PC V-ARI
Setting time (minutes)	≥60
MgO (%)	≤6.5
Loss on ignition (%)	≤6.5
Insoluble residue (%)	≤3.5*
SO_3 (%)	≤4.5
Compressive Strength (MPa)	
1 day	≥14.0
3 days	≥24.0
7 days	≥34.0

Table 3 displays the chemical composition of the WGP obtained through XRF. WGP predominantly comprises SiO_2 (78.153%) and CaO (13.074%). Conversely, XRD analyses reveal a non-crystalline amorphous phase in the WGP (Figure 4), indicating that the WGP primarily comprises amorphous silica. According to (Liu *et al.* 2015, Manikandan and Vasugi 2021), one of the key characteristics of WGP, enabling its dissolution in the presence of an alkaline activator for pozzolan formation, is its composition of more than 70% silica.

According to Pourabbas Bilondi *et al.* (2018a), in the processes of geopolymerization aiming at soil improvement, an amount of alumina or amorphous silica is necessary; this demonstrates the potential of WGP as a precursor material in improving soil geotechnical properties.

Figure 5e-f presents the microstructure of the WGP, observing the irregular and varied shaped particles and some cubic-shaped structures in laminated cross-section. Due to this shapeless structure, WGP is considered a suitable material for soil improvement processes. The EDX (Table 4) spectra for areas 4, 5, and 6 resulted mainly in elements such as oxygen and silicon, demonstrating the presence of amorphous silica in XRD analyses.

2.1.3. Portland cement

The PC used in this research was high early strength cement of type PCV-ARI, which has a high reactivity at low curing ages. The PC has an average specific mass of 3.12 g/cm^3. The characteristics of the PC are shown in Table 5.

2.1.4. Sodium chloride

The NaCl used in this research was acquired in a commercial establishment in Curitiba. NaCl has an analytical purity of 99%, and its specific mass is 2.17 g/cm^3.

3. Method

For the development of the present research, fourth phases were carried out (see Figure 7): in the first phase, the research variables were defined, and the

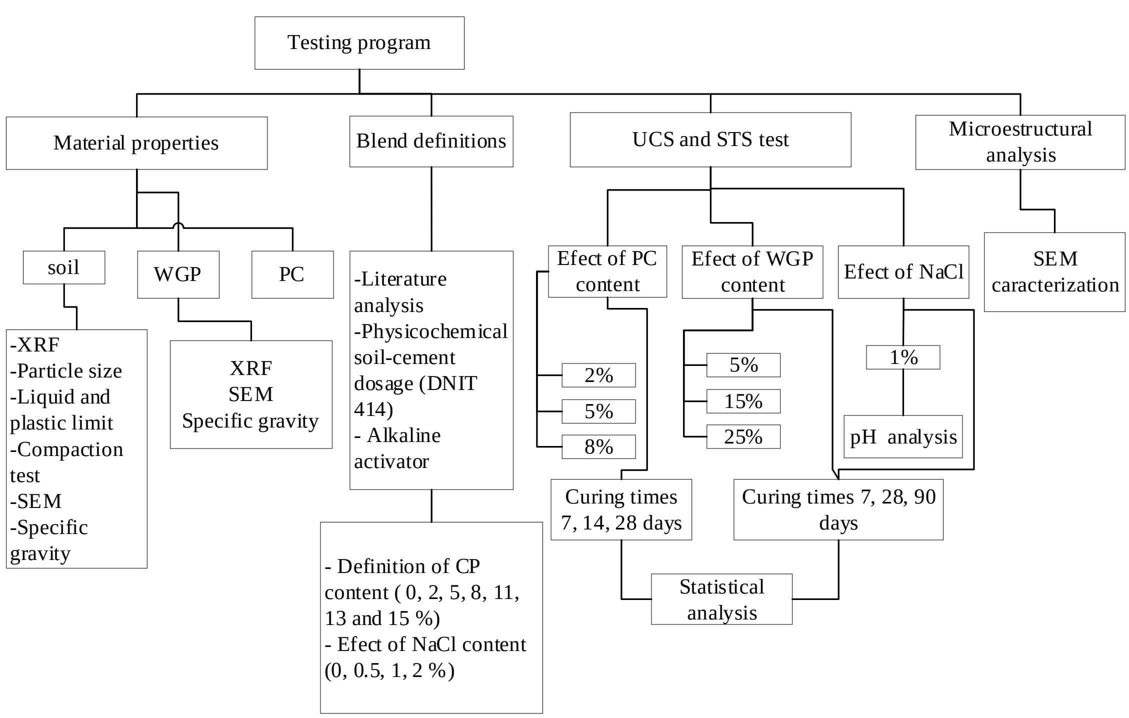

Figure 7. Experimental program flowchart.

materials used were characterised; in the second phase, the blends were defined based on analyses of the literature and laboratory test; in the third phase, the unconfined compressive strength (UCS) and splitting tensile strength (STS) test and the verification of the pH of the blends were developed. Subsequently, these results were statistically analysed. Finally, in the fourth phase, the blends' microstructure was analysed by scanning electron microscopy.

3.1. Determination of cement content

The recommendation by standard DNIT 414 () of the National Department of Transport Infrastructure was followed to determine PC contents, which allows the determination of the cement content that chemically satisfies soil, ensuring a continuous matrix of connections.

The test is based on the electrical interaction between the cement and clay particles; it is a simple procedure that allows a quick orientation of the minimum cement content to stabilise a specific type of soil completely. Seven samples of 20 g of soil were required to perform the tests, placed in 250 ml graduated cylinders; the first graduated cylinder was the control with pure soil, and from the second graduated cylinder was added a minimum PC content of 2% even a maximum content of 15%.

The variation of the PC content in each assay was ~2% to 3%, meeting the standard DNIT 414 (), which recommends a variation of less than 2% for sandy soils and clay soils, a variation between 2% and 3%. The data collected from the test were the volumetric variation or volume occupied by the sediments in each graduated cylinder during six days.

Figure 8 shows the curve of variation of cement content versus volumetric variation (ΔV). It is observed that the highest peak of volumetric variation is around 8% of cement, evidencing, according to the DNIT 414 (), that at least the soil could require 8% of cement for its stabilisation. On the other hand, this result indicates the clayey character of the soil analysed; it coincides with that observed by Ferreira *et al.* (2021), who found a maximum variation in contents of 9% for clay-silty soil and 4% for sandy-clayey soil. In general, it was observed that the tendency of sandy soils to demand lower cement contents compared to clay soils.

Thus, for this research, three cement contents were defined, considering as maximum content the result obtained from the physicochemical dosage methodology equal to 8%. In addition, an average content of 5% and a minimum content of 2% were considered, aiming to reduce the amount of cement in soil improvement from the addition of materials, such as WGP and NaCl.

Although 8% cement is not considered economical for soil stabilisation processes, it was evaluated in this research because it represented the minimum amount required to stabilise the studied soil following the standard DNIT 414 (). Additionally, this study aimed to demonstrate that using recyclable materials could reduce the high levels of cement typically used in stabilising soils for base or subbase layers of pavements.

According to Table 1, presented in the literature review in the introduction, researchers analysed the addition of WGP in various soils, employing levels within the range of 0% to 36% of WGP. Based on this, 40% of the studies concluded that a 15% addition of WGP enhanced the UCS characteristics of the analysed soils. On the other hand, the remaining 60% corresponds to other contents, such as 8%, 10%,

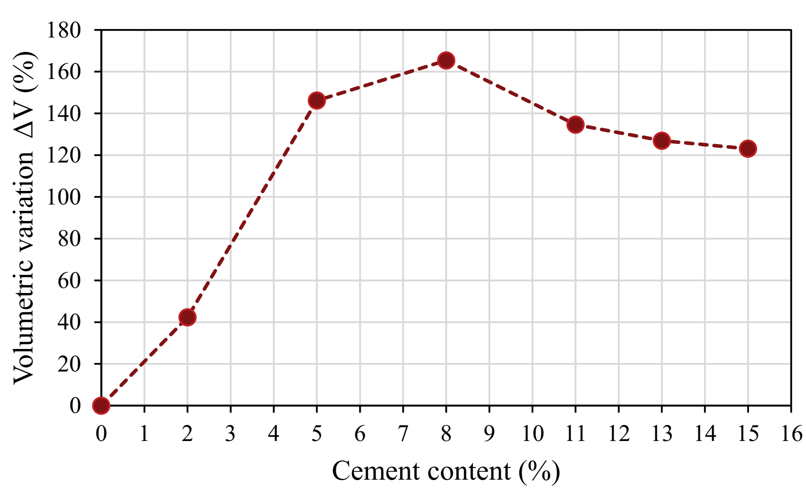

Figure 8. Results of the physicochemical dosage test for soil-cement blends.

16%, 20%, 27%, and 30%. Researchers such as Manikandan and Vasugi (2021) and Soliman and Tagnit-Hamou (2016) mention that WGP contents lower than 20% have developed better mechanical properties in the concrete hydration process. Thus, this research evaluated three WGP contents to analyse a significant range with low, moderate, and high contents: a low content of 5%, a moderate of 15%, and a maximum of 25%.

According to the literature analysis, the curing ages ranged from 0 to 91 days; for the present research, 7, 14, and 28 days were considered for soil-PC blends and 7, 28, and 90 days for blends composed by soil+PC+WGP and the geopolymer (Soil+PC+WGP+NaCl). In the opinion of Islam *et al.* (2017), the WGP contributes to the increase of the UCS at late ages, such as 90 days, because the WGP needs a longer time for pozzolanic reactions to occur.

3.2. Determination of sodium chloride content

A pilot test was carried out to find the optimal sodium chloride (NaCl) content, which consisted of UCS tests for specimens with dimensions of 50 mm in diameter and 100 mm in height. The specimens were moulded, varying the sodium chloride content from 0.5% to 2%, in blends composed of average contents of PC (5%) and WGP (15%) to provide a representative result. Saldanha *et al.* (2016) aimed to accelerate the increase in UCS by varying the amount of sodium chloride between 0%, 0.5%, 1%, and 1.5% in compacted coal fly ash and carbide lime blends. The authors found that 1% NaCl was the dosage that showed the best response in the UCS of lime-stabilised fly ash. Narendra *et al.* (2003) studied the optimal lime content in fly ash with sodium chloride. The authors found that the free swell volume, liquid limit, and strength of fly ash increased with each addition of lime (1% to 6%) and 1% sodium chloride compared to blends without sodium chloride.

After moulding, the specimens were cured for 28 days and tested in a universal press with a 1 mm/min loading speed following the standard ASTM D2166 / D2166M-16 (2016). Figure 9 presents a boxplot of the results of the pilot assay, noting that the highest UCS was obtained with 1% NaCl. In addition, it is possible to observe that the UCS increases in the range of 0.5% to 1% of NaCl and decreases with higher contents. The previous results are similar to those found by Saldanha *et al.* (2017), where higher levels than 1% of NaCl caused a decrease in the strength of soil-lime blends. Thus, for the present research, 1% NaCl was used as an alkaline precursor aimed at the formation of geopolymers in the process of soil improvement analysis through UCS and STS tests.

Considering the previous studies and aiming to determine the effect of the PC, WGP as stabilising materials, and the conformation of a geopolymer from the addition of an alkaline precursor (NaCl) on the mechanical performance of a clayey soil of the Guabirotuba formation, the experimental conditions were defined as shown in Table 6.

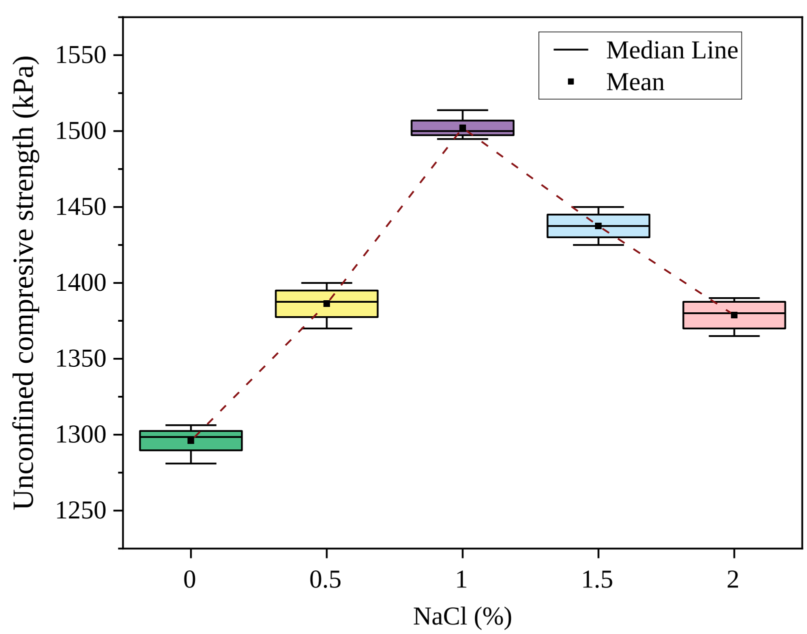

Figure 9. Boxplot of UCS results of soil + 5%PC + 15%WGP blends and different NaCl contents.

Table 6. Blends content, curing periods, and tests performed.

Condition	Blend n°	PC (%)	WGP (%)	NaCl (%)	Curing time (days)	Compaction test	UCS	STS	MEV
Stabilization	Pure soil	0	0	0	0	x	x	x	x
	B1	2	0	0	7-14-28	x	x	x	x
	B2	5	0	0	7-14-28	x	x	x	x
	B3	8	0	0	7-14-28	x	x	x	x
	B4	2	5	0	7-28-90	x	x	x	x
	B5	5	5	0	7-28-90	x	x	x	x
	B6	8	5	0	7-28-90	x	x	x	x
	B7	2	15	0	7-28-90	x	x	x	x
	B8	5	15	0	7-28-90	x	x	x	x
	B9	8	15	0	7-28-90	x	x	x	x
	B10	2	25	0	7-28-90	x	x	x	
	B11	5	25	0	7-28-90	x	x	x	
	B12	8	25	0	7-28-90	x	x	x	
Geopolymerization	B13	2	5	1	7-28-90		x	x	x
	B14	5	5	1	7-28-90		x	x	x
	B15	8	5	1	7-28-90		x	x	x
	B16	2	15	1	7-28-90		x	x	x
	B17	5	15	1	7-28-90		x	x	x
	B18	8	15	1	7-28-90		x	x	x

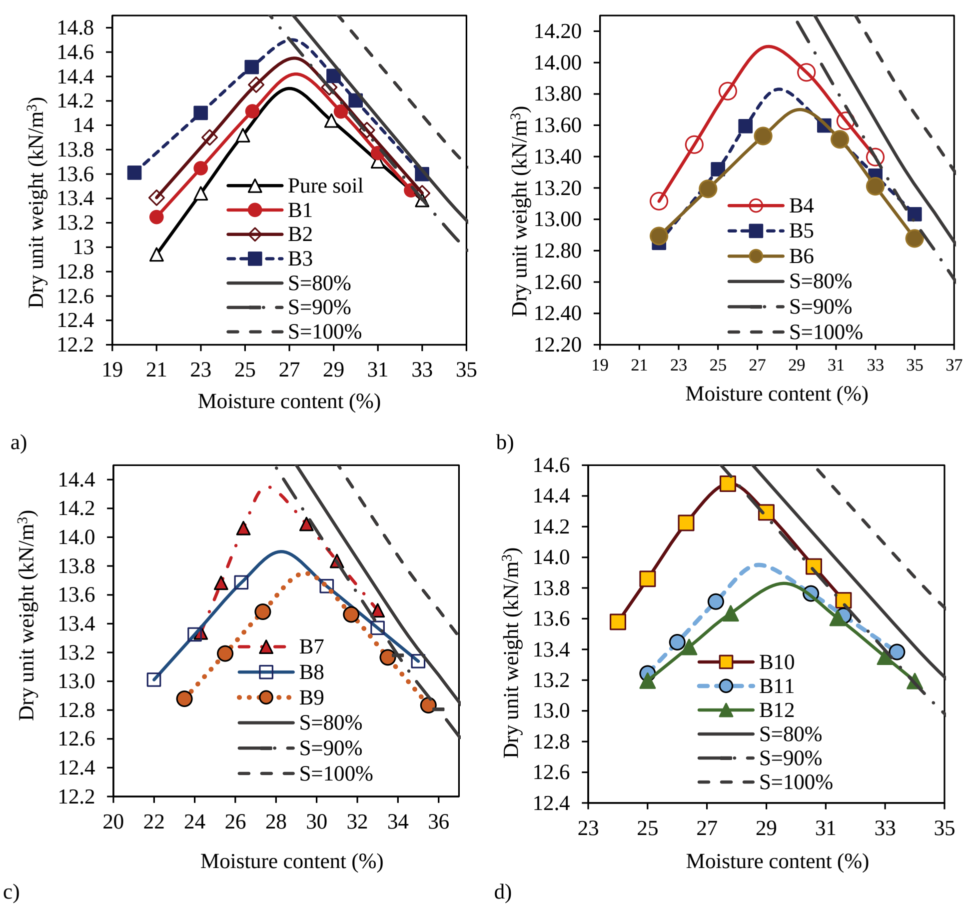

Figure 10. Compaction curves of pure soil and blends analysed in this research.

3.3. *Standard proctor test*

Proctor compaction tests were performed to define the moulding characteristics of the pure soil and blends. Each compaction curve was generated from 6 points, constituting 3 points on the wet branch and 3 points on the dry branch (see Figure 10). The test was performed following the procedures recommended by ASTM D 698 (2012).

It is observed in Figure 10a that the addition of PC to the clay soil caused an increase in the maximum dry density (MDD) and the optimum moisture content (OMC). The MDD of pure soil went from 14.3 to 14.7 kN/m^3, and the OMC went from 26.9% to 27.2% when 8% of the PC (B3) was added. This behaviour may be due to the higher average specific mass of the PC (3.12 g/cm^3)

compared to the SG of the pure soil (2.625). On the other hand, the increase in the OMC can be attributed to the increase in the PC's specific surface area, which requires more water to reach the MDD (Gupta and Kumar 2017, Ordoñez Muñoz *et al.* 2021). On the other hand, in blends with the addition of WGP (Figure 10b-d), there was an increase in the OMC and a decrease in the MDD when the PC and WGP content increased. Consequently, the OMC and MDD went from 26.9% to 29.63% and from 14.3 to 13.83 kN/m^3 in pure soil for the B12 blend (Soil +8%PC + 25%WGP). The decrease in MDD may be due to the lower SG of WGP (2.23), which was added in contents of 5%, 15%, and 25% to the soil. Finally, the decrease in OMC may be due to the replacement of clay soil by WGP, which has low water absorption capacity concerning clay soil (Canakci *et al.* 2016, Siyab Khan *et al.* 2018, Blayi *et al.* 2020, Ibrahim *et al.* 2021).

3.4. Molding specimens

Specimens composed of pure soil and blends stabilised with PC-WGP and geopolymer (PC+WGP+NaCl) were moulded to perform the UCS and STS tests. Four specimens were moulded under the OMC and MDD conditions obtained in the standard Proctor compaction test for each blend and curing time, according to Figure 10

In total, 421 specimens with dimensions 100 ± 5 mm in height and 50 ± 5 mm in diameter were moulded. Before the moulding procedure, the soil was dried in an oven at a temperature of 100 ± 5°C for at least 24 hours, then it was sieved, and the moisture content was determined. Later, the dry materials (soil, PC, and WGP) were weighed and mixed, and then a quantity of distilled water was added to obtain the OMC.

In the case of blends with added sodium chloride, the NaCl content was fully dissolved in the distilled water required to achieve OMC. Each blend was mixed manually until a homogeneous mixture was obtained; in this step, three samples were collected for the moisture control of the blends. For this study, we considered the specimens that do not differ from (±0.5%) in the OMC, aiming to maintain homogeneous conditions for each blend analysed; the desired density was obtained by controlling the mass and volume of the specimens. Subsequently, the specimens were moulded in 3 layers in a hydropneumatic press with a maximum capacity of 15 Ton. Finally, the specimens were wrapped in plastic film, identified, and taken to Styrofoam boxes in a wet chamber until they reached the curing time corresponding to 7, 14, 28, and 90 days.

Researchers such as Alam *et al.* (2019) evaluated the strength and durability properties of a geomaterial using ambient curing conditions ranging from 25°C to 30°C. In the present study, no ambient temperature cure tests were performed because the preparation of the PCs was carried out during the transition between the summer, autumn, and winter seasons. These conditions could imply that significant temperature changes might introduce a noise factor interfering with the variation of the mechanical resistances obtained in this research. Additionally, the curing process was conducted in a humid chamber to facilitate the replication of this research in other locations worldwide. Unlike the environmental condition, the laboratory condition can be easily reproduced, unlike the ambient temperature cure condition, which could pose difficulty.

3.5. Unconfined compressive strength and splitting tensile strength tests

A series of UCS and STS tests were conducted to determine the mechanical properties of pure soil and the studied mixtures. The UCS technique enables the

Figure 11. Preparation of specimens for UCS and STS tests a) submersion of specimens; b) UCS test; c) STS test.

assessment of compressive strength under remodelled or reconstituted soil conditions by applying axial load with controlled strain. On the other hand, the STS test is based on applying a uniformly distributed compressive load, generating a stress state formed by tensile stresses in the region of the applied load plane. Both UCS and STS methods were employed because the analysed soil was classified as clay, and the UCS test is recommended in soils of fine grain size, such as silt and clay. Al-Dossary *et al.* (2023) mention that UCS is a significant criterion for evaluating the minimum standard for stabilised pavement base/sub-base material that can withstand typical construction and traffic loads. Baldovino *et al.* (2018) and Puppala (2016) point out that UCS and STS are essential parameters in predicting the suitability of materials used in civil construction.

Following the procedure described in ASTM D2166 / D2166M-16 (2016), the UCS tests were conducted on cemented specimens by applying a fixed load at 1 mm/min (Figure 11b). The STS tests followed the one described in NBR 7222 (2011). The test is performed by applying a uniformly distributed compression load, generating a state of tensile stress in the region of the load plane (Figure 11c).

After the curing time (7, 14, 28, and 90) days and before the UCS and STS test, all specimens were submerged in a tank with water for 4 hours (Figure 11a). This was done to saturate the specimens to minimise the possible effect of suction on the final result of strength (Baldovino et al. 2020, 2021).

The values of UCS and STS are important for the prediction of several studies in the field of civil engineering. In addition, this type of test has been used by other researchers, such as Javed and Chakraborty (2020), de Jesús Arrieta Baldovino *et al.* (2023), Pourabbas Bilondi *et al.* (2018a) and Pourabbas Bilondi *et al.* (2018b) who studied the improvement of soils mainly with glass powder residue and WGP-based geopolymers aiming at improving the geotechnical properties of soils.

3.6. Statistical analysis

The results obtained in the UCS and STS tests were submitted to statistical treatment, where random measurement errors and errors of the measurement equipment were considered.

In this research, four specimens were made for each blend and each type of test; this number of samples is considered statistically *small*, so a statistical correction was made where the standard deviation (σp) was multiplied by the value of the t-Student correction (1.320 and 1.197) for three or four specimens of proof, respectively.

The final errors associated with different tests were obtained by combining the statistical error and the systematic error provided by the instrument used for the measurements in each test. The significance of the results obtained was made by analysing how many times the error is less than the difference of the mean values of the results of each test performed.

After obtaining the average values and associated errors, it was possible to compare the results within statistical certainties of 95% and adjust the curves to the statistical quantities obtained.

3.7. Microstructural analysis

Scanning electron microscopy (SEM) analysis investigated the agglomeration and binding behaviour between soil grains, stabilising, and geopolymer materials.

The pure soil samples and blends were mounted on pins with ~12–13 mm heads covered by a conductive adhesive. Subsequently, the samples were covered with gold for analysis under a Zeiss scanning electron microscope, model EVO-MA 15. The chemical microanalysis of the samples analysed in the SEM was performed in the energy spectrometer X-ray dispersion (EDX), X-Max of 20 mm^2.

3.8. pH measurement

The effect of NaCl on the alkalinity of blends was investigated from pH measurements following the method performed by Räsänen and Penttala (2004). The samples of the specimens tested in the UCS and STS tests were used to measure the pH. The samples were dried at 100 ± 5°C for one day, crushed, and passed through sieve #200 (75 μm); later, samples of 10 g of powder from the blends and 10 g of distilled water were weighed with the precision of 0.1 g and placed in test tubes to obtain a homogeneous blend, after the tubes were shaken manually for 3 minutes.

After the sample preparation, the pH was measured in a Quimis Q400AS benchtop pH metre with an accuracy of ±0.2°C and ±0.02 pH using the standard methodology (4500-H^+ B). The test was performed in triplicate to reduce the variation and noise caused by external factors such as the non-homogeneity of the blends. The pH value was accepted when the rate of change of the value was less than 0.01 units per minute, thus avoiding errors in the measurement.

This research measured the pH for the blend composed of geopolymer specimens cured during 90 and 0 days to analyse the pH change in the curing process. Also, some stabilised blends (B5, B8, and B11) were analysed to compare the pH of stabilised blends and those composed of geopolymer.

4. Results and discussion

4.1. Effect of cement, waste glass powder, and NaCl on the unconfined compressive and splitting tensile strength

The UCS and STS test was performed to evaluate the increase in the mechanical strength of an improved soil through the techniques of stabilisation and geopolymerization of clayey soil, with different levels of PC, WGP, and NaCl in the increase of mechanical strength after three curing times.

4.1.1. Unconfined compressive strength test

The results of the average UCS of the improved soil with three PC contents and the associated errors are presented in Figure 12 It is observed that with the increase in curing time and PC content, the UCS increased, being higher for contents of 8% PC where the strength went from (126 ± 4) kPa in pure soil to (1871 ± 4) kPa in the soil + 8% of PC (B3) after 28 days of curing, representing an increase of (1385 ± 44) %. Adding PC to clay soils improves the interfacial bonds of the particles and, therefore, increases the mechanical strength of the soil (Yi *et al.* 2015).

Toghroli *et al.* (2018) state that adding PC to the soil enables the formation of a denser structure resulting from cation exchange reactions. The authors also mention that voids tend to decrease after 28 days of curing due to the formation of cementitious compounds associated with developing pozzolanic reactions. This assertion by Toghroli *et al.* (2018) can be confirmed in this research through the SEM results. When comparing the microphotographs of the pure soil (Figure 5) with those of the soil-PC blends (Figure 17), the presence of voids in the compacted pure soil is evident, contrasting with a denser structure and a reduction in voids on the analysed surface of soil-PC blends. However, the use of PC has been questioned, mainly due to the environmental impact. Hence, this research evaluated the addition of WGP and geopolymer as a potential substitute for PC in soil improvement processes.

According to the Brazilian standard DNIT 143 () and American standard TxDOT (), the minimum UCS value for a material suitable for use as a sub-base of pavements is 1200 kPa at 7 days of curing. In Figure 12, the dotted line represents this minimum value, demonstrating that only the B3 blend (8% PC) complies with this minimum value.

Figure 13 presents the results of the UCS mean and the associated errors of the blends with the addition of PC, WGP, and geopolymer through alkaline activation with NaCl.

For the case of soil stabilised with PC and WGP, the UCS of the specimens was increased with the addition of

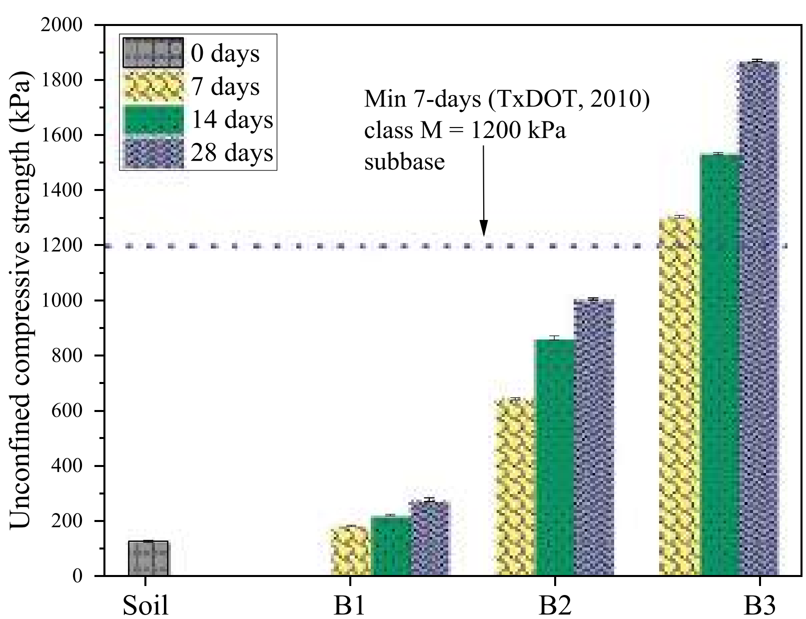

Figure 12. Effect of three levels of PC (2, 5, 8) on the UCS.

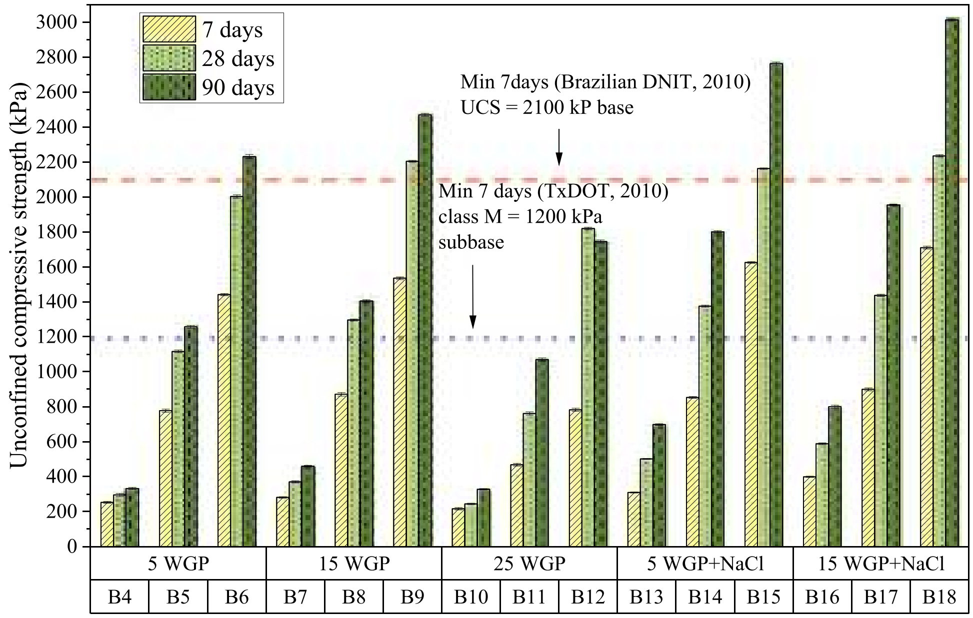

Figure 13. Effect of WGP, PC, NaCl, and curing time on UCS.

WGP up to an ideal amount of (15%). However, when 25% of WGP was added, the UCS decreased by approximately (49 ± 1)% in blend B12 concerning blend B9. For this reason, in this research, the geopolymers formed by Soil+PC+WGP+NaCl were evaluated with contents of 5% and 15% of WGP.

Similar behaviour was observed by Pourabbas Bilondi *et al.* (2018a), who found increases in UCS up to 15% WGP levels in clayey soil. In addition, the authors explain that the extra amount of WGP did not participate in the agglomeration process of the soil particles with the cementitious material.

For blends stabilised with PC and WGP, the best results were observed in blend B9 (Soil +8PC + 15WGP), which presented increments of (18 ± 1)% and (32 ± 1)% for 28 and 90 days, respectively, concerning UCS at 28 days of the blend B3 stabilised with 8% of PC.

Researchers mentioned in the course of this study who studied WGP as a stabiliser found results similar to those observed in this research; for instance, Blayi *et al.* (2020) found that UCS increased from 205.01 kPa to 360.10 kPa as the amount of WGP increased by up to 15%, and decreased to 332.54 kPa when 25% of WGP was added.

According to Zhang *et al.* (2022), the UCS of improved soil with PC and WGP may be due to the fineness of the WGP that effectively contributes to pozzolanic reactions, in addition to the microfiller effect and the increase in the specific surface area between the particles, factors of great importance in the gain of strength of the improved soil.

For blends stabilised with geopolymer, the best results were observed in blend B18 (Soil +8%PC + 15% WGP +1%NaCl), where the UCS was approximately 24 times higher than the UCS of the pure soil and 1.6 times higher than the soil stabilised with 8% of PC.

In Figure 13, the dotted line represents the minimum values required by the American TxDOT standards () and Brazilian DNIT 143 () standards. For this study, the blends B6, B9, B15, and B18 met the UCS requirements at 7 days of curing to be used as a subbase in pavement applications. On the other hand, none of the blends met the requirements to be used as pavement base in the first 7 days, and strengths greater than 2100 kPa were only reached by blends B9, B15, and B18 after 28 days of curing and by blend B6 after 90 days of curing. It can be inferred that for the case of the blends analysed in this research, short curing periods such as 7 days are not suitable for the development of agglomeration and geopolymerization processes.

Pourabbas Bilondi *et al.* (2018b) found similar results using a geopolymer to stabilise clayey soil, finding as optimal content 15% of WGP and 2 Molar of NaOH, where the UCS was 10.7 times higher than the pure clay and 1.42 times higher than the stabilised soil with 5% of PC.

Mohammadzadeh *et al.* (2023) evaluated UCS of the recycled glass powder-based geopolymer for stabilisation of clay; when comparing the geopolymer-stabilised and PC-stabilised specimens, the authors found that UCS was 4 times higher with soil improved with geopolymer formed by 15% WGP and 3 Molar of NaOH

Table 7. Comparison of the increase in the UCS of stabilised blends with WGP, PC, and geopolymer. The values correspond to a confidence level of approximately 95%.

Blends	Increment (%)		
	7 days	28 days	90 days
B4 > B1 (S + 2PC + 5WGP) >; (S + 2PC)	39 ± 3	6 ± 4	-
B5 > B2 (S + 5PC + 5PV) >; (S + 5PC)	21 ± 2	11 ± 1	-
B6 > B3 (S + 8PC + 5PV) >; (S + 8PC)	11 ± 1	7 ± 1	-
B7 > B4 (S + 2PC + 15PV) >; (S + 2PC + 5WGP)	11 ± 3	25 ± 4	39 ± 3
B8 > B5 (S + 5PC + 15PV) >; (S + 5PC + 5WGP)	12 ± 2	16 ± 1	12 ± 1
B9 > B6 (S + 8PC + 15WGP) >; (S + 8PC + 5WGP)	7 ± 1	10 ± 1	11 ± 1
B10 < B7 (S + 2PC + 25WGP) <; (S + 2PC + 15WGP)	− 23 ± 3	− 34 ± 2	− 29 ± 1
B11< B8 (S + 5PC + 25WGP) <; (S + 5PC + 15WGP)	− 46 ± 2	− 41 ± 1	− 24 ± 1
B12 < B9 (S + 8PC + 25WGP) <; (S + 8PC + 15WGP)	− 49 ± 1	− 17 ± 1	− 29 ± 1
B13 > B4 (S + 2PC + 5WGP +1NaCl) >; (S + 2PC + 5WGP)	18 ± 2	41 ± 4	110 ± 3
B14 > B5 (S + 5PC + 5WGP +1NaCl) >; (S + 5PC + 5WGP)	9 ± 1	19 ± 1	43 ± 1
B15 > B6 (S + 8PC + 5WGP +1NaCl) >; (S + 8PC + 5WGP)	11 ± 1	7 ± 1	24 ± 1
B 16 > B7 (S + 2PC + 15WGP +1NaCl) >; (S + 2PC + 15WGP)	30 ± 2	37 ± 2	74 ± 2
B17 > B8 (S + 5PC + 15WGP +1NaCl) >; (S + 5PC + 15WGP)	11 ± 2	10 ± 1	39 ± 1
B18 > B9 (S + 8PC + 15WGP +1NaCl) >; (S + 8PC + 15WGP)	10 ± 1	13 ± 1	22 ± 1

Where: (-) means decrease in UCS.

compared to those stabilised with 10% PC. Other researchers have also shown that the UCS of soils stabilised with geopolymers was higher compared to those stabilised with PC (Yi et al. 2015, 2015).

The results of the statistical analyses showed with 95% certainty that there are significant differences between the blends of clayey soil stabilised with PC, PC+WGP, and geopolymer (PC+WGP+NaCl). Table 7 presents the UCS increments, associated errors of the blends with the same PC contents, plus the addition of WGP and the blends stabilised with PC and WGP compared to the geopolymer. The negative values represent the percentages of decrease in the UCS that suffered the stabilised blends with 25% of PC.

For the case of blends with 2% PC after 28 days of curing, statistically significant increments were found in all blends, finding that B4 was (6 ± 4)% higher than B1; this increase was due to the addition of 5% of WGP in the blend B4. The addition of 15% of WGP caused the UCS increases by approximately (34 ± 3)% for the same PC content concerning B1 after 28 days of curing. On the other hand, for 90 days of curing, the UCS of blend B7 increased (166 ± 1)% compared to the UCS of B1 (Solo +2PC) after 28 days of curing.

The results of UCS in blends B16, B17, and B18 formed by geopolymer demonstrated that the addition of the alkaline precursor (1% NaCl) allowed increments of up to (74 ± 2) % in the UCS of B16 (2PC + 15PV +NaCl) concerning the B7 (2PC + 15WGP).

The rates of increase in all blends (B4-B12) were significant for 28 days, while for 90 days of curing, it was slower, confirming that the processes of agglomeration and geopolymerization happened mainly during the first 28 days of curing.

Finally, statistical analysis indicated with 95% certainty that there are significant increments concerning pure soil and blends stabilised with PC and WGP. However, the main differences resulting in the blends stabilised with geopolymers in which, although the only difference was the alkaline activator, its addition allowed the gain in the UCS, still allowing them to become suitable for use as a sub-base of pavement according to the requirements of the Brazilian and American standards (DNIT 143 , TxDOT).

4.1.2. Splitting tensile strength test

The results of the STS mean of the soil improved with PC and the associated errors are presented in Figure 14 On the other hand, it was observed that with the increase in curing time and PC content, the STS increased, finding the best strength in blends B2 and B3, where the STS went from (14 ± 2) kPa in pure soil to (163 ± 4) and (255 ± 5) kPa in B2 and B3, respectively. In Figure 14, the dotted line represents the minimum value required for subbase constructions; according to the American TxDOT standards (), the B3 complies with the standard requirements for which 180 kPa are required in the first 7 days. For this study, none of the blends met the requirements to be used as pavement base in the first 7 days, and strengths greater than 180 kPa were only reached by blend B3 after 28 curing days.

The average of the STS and its associated errors obtained from the peak load of the splitting tensile strength test are shown in Figure 15 It is observed that both the curing time and the 15% of WGP contributed to the increase of the STS of the stabilised soil. The highest strengths in STS were observed in blends stabilised with geopolymer. The strengths with the addition

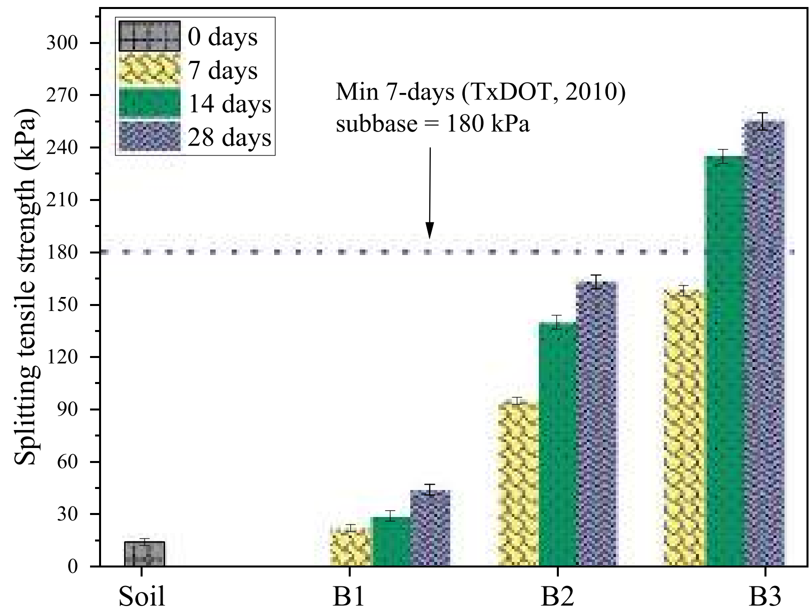

Figure 14. Effect of three levels of PC cement (2, 5, 8) on STS.

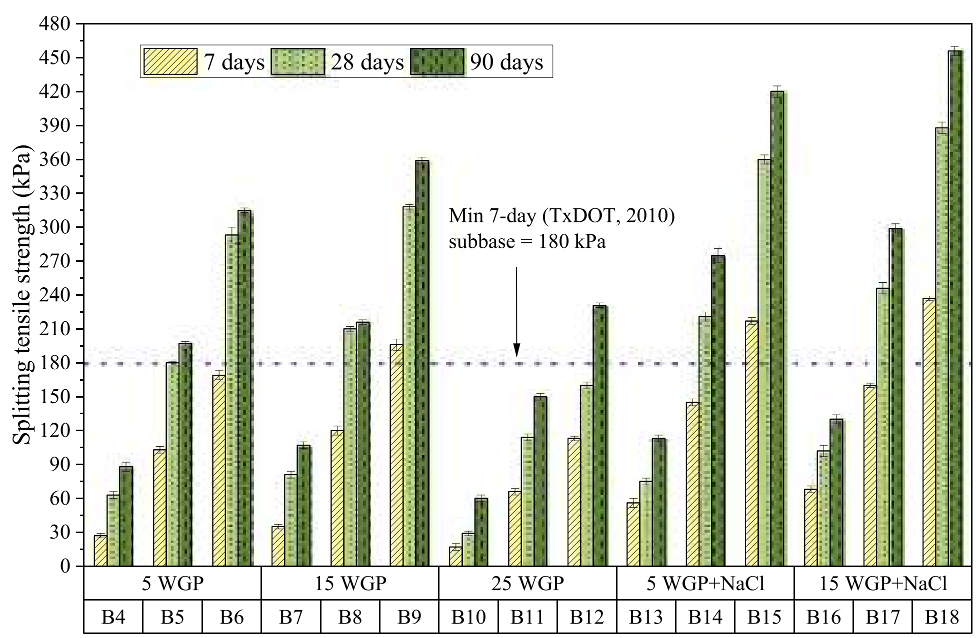

Figure 15. Effect of WGP, PC, NaCl, and cure time on STS.

of 25% of WGP presented similar behaviour to the results of the UCS, where the STS decreased, finding the ideal value of 15% of WGP.

Blends B9, B15, and B18 have met the American TxDOT standards () requirements to be used as a subbase in pavement applications. It is important to note that B6 has not reached the 180 kPa required by the standard. However, it comprises the same amount of cement (8%) as the B9, B15, and B18 blends, demonstrating that the geopolymerization processes make the soil suitable for field applications.

On the other hand, it was observed that for a longer curing time (28 days) than required by the standard (7 days), eight of the eighteen blends analysed would comply with the minimum value in the STS appropriate for subbase applications in pavements.

Table 8. Increased unconfined compressive strength values correspond to a confidence level of ~95%.

	Increment		
Blends	7 days	28 days	90 days
B4 > B1 (S + 2PC + 5WGP) >; (S + 2PC)	*	43 ± 3	-
B5 > B2 (S + 5PC + 5PV) >; (S + 5PC)	*	10 ± 3	-
B6 > B3 (S + 8PC + 5PV) >; (S + 8PC)	*	15 ± 4	-
B7 > B4 (S + 2PC + 15PV) >; (S + 2PC + 5WGP)	30 ± 11	29 ± 7	22 ± 6
B8 > B5 (S + 5PC + 15PV) >; (S + 5PC + 5WGP)	17 ± 5	17 ± 1	10 ± 1
B9 > B6 (S + 8PC + 15WGP) >; (S + 8PC + 5WGP)	16 ± 4	9 ± 2	14 ± 1
B10 < B7 (S + 2PC + 25WGP) <;(S + 2PC + 15WGP)	− 51 ± 11	− 64 ± 5	− 44 ± 4
B11< B8 (S + 5PC + 25WGP) <; (S + 5PC + 15 WGP)	− 45 ± 4	− 46 ± 2	− 31 ± 2
B12 < B9 (S + 8PC + 25WGP) <; (S + 8PC + 15WGP)	− 42 ± 3	− 50 ± 1	− 36 ± 1
B13 > B4 (S + 2PC + 5WGP +1NaCl) >; (S + 2PC + 5WGP)	52 ± 18	16 ± 7	28 ± 6
B14 > B5 (S + 5PC + 5WGP +1NaCl) >; (S + 5PC + 5WGP)	29 ± 4	19 ± 2	40 ± 3
B15 > B6 (S + 8PC + 5WGP +1NaCl) >; (S + 8PC + 5WGP)	22 ± 3	19 ± 3	33 ± 2
B 16 > B7 (S + 2PC + 15WGP +1NaCl) >; (S + 2PC + 15WGP)	49 ± 12	21 ± 7	21 ± 5
B17 > B8 (S + 5PC + 15WGP +1NaCl) >; (S + 5PC + 15WGP)	25 ± 4	15 ± 3	38 ± 2
B18 > B9 (S + 8PC + 15WGP +1NaCl) >; (S + 8PC + 15WGP)	17 ± 3	18 ± 2	27 ± 1

Where (*) means there are no statistically significant differences, and (-) decrease in STS.

Table 8 presents the results of the statistical analyses that indicate with 95% certainty that there were significant differences between the blends composed of the same PC content but with the addition of WGP and geopolymer. The negative values represent the percentages of STS decrease of the blends with 25% WGP content.

No statistically significant differences were found in B4, B5, and B6 when 5% WGP was added during a seven-day curing period. However, when 15% of WGP was added, significant differences emerged after 28 days of curing. Conversely, the addition of 1% NaCl resulted in increases of STS for B16 compared to B7 at 7, 28, and 90 days, which were (49 ± 12)%, (21 ± 7)%, and (21 ± 5)%, respectively.

In general, it was found that the addition of 15% of WGP presented the best strengths, finding increments in the three PC contents. The STS was even higher when NaCl was added, forming the geopolymer, observing that blends with contents of 2%PC + 15%WGP presented increments of up to 49% in the STS after adding 1% of NaCl.

The increase in STS can be explained by the fact that the pore spaces of the clayey soil were filled by a thin and silica-rich material (78.153%). On the other hand, filling voids allows better interaction between the particles, consequently improving the STS and UCS (Ashiq *et al.* 2022). The increase in the strength of fine soils mixed with glass dust residues was also observed by Blayi *et al.* (2020), Ibrahim Mawlood, and Alshkane (2021), Jalal *et al.* (2022), and de Jesús Arrieta Baldovino *et al.* (2023).

Table 9 presents the results of studies that used glass powder and different alkaline precursors in soil improvement reported in the literature. It can be inferred that few studies have evaluated the STS test, and knowledge of this test is essential since it allows us to imitate the flexible pavement response (Kumar and

Table 9. Effect of WGP and other materials on UCS and STS in some soils reported in the literature.

Reference	Type of soil USCS/ AASHTO	WGP (%)	Other materials/(%)	Alkali activators	Curing time (days)	UCS (kPa)	STS (kPa)
Javed and Chakraborty (2020)	CL	8	-	-	-	133.5	-
Blayi *et al.* (2020)	CL	15	-	-	-	360.10	-
Canakci *et al.* (2016)	CL	6	-	-	28	723	-
Pourabbas Bilondi *et al.* (2018b)	CL	15	PC/5	NaOH/2 Molar	91	~ 2250	-
Ashiq *et al.* (2022)	/A-7-6 (9)	20	-	-	0	232	-
Ibrahim *et al.* (2021)	CH	27	-	-	0	560.1	-
Jalal *et al.* (2022)	CL-OL	16	-	-	28	552.59	-
Baldovino *et al.* (2021)	MH	30	Lime/5	-	90	2750	~630
Du *et al.* (2020)	CL	-	- PC/8 silica - Fume + plant ash/ 11	NaOH/1%	60	3044.25	
Hosseini *et al.* (2022)	SM	15	-	Calcium Carbide/ 7%	28	909	
Present research	/A-7-5	15	PC/8	NaCl/1%	90	2764 ± 7	495 ± 7
		15	PC/5	NaCl/1%		1704 ± 7	115 ± 6
		15	PC/2	NaCl/1%		723 ± 6	296 ± 5

Gupta 2016). On the other hand, it was observed that the WGP contents that effectively contributed to the increase in strength were 15% to 20%. It was also possible to observe how the presence of alkaline activators further increased the strength of the analysed materials.

To date, no studies have been found on the geopolymerization of the red clay soil belonging to the Guabirotuba formation. However, studies on the geopolymerization of soil classified as yellow silt, which also belongs to the same geological formation, were conducted by (De Jesús *et al.* 2020, Baldovino *et al.* 2021).

In the study conducted by (Baldovino *et al.* 2021), the utilisation of WGP as a precursor for geopolymerization in compacted blends of lime and yellow-coloured silty soil from the Guabirotuba formation was investigated. The authors employed varying percentages of WGP (5%, 15%, and 30%) along with a fixed 5% lime content. The results indicated enhancements in the microstructure and mechanical properties of UCS and STS of the geopolymer comprised of soil, WGP, and lime. The most substantial strengths were observed in the geopolymer composed of soil + 30% WGP + 5% lime, where the UCS was 956%, 171%, and 137% higher than the UCS of the soil + 5% WGP + 5% lime blends after 7, 28, and 90 days, respectively. Concerning STS, the authors identified increases of 692%, 244%, and 184% in the UCS of mixtures comprising soil + 30% WGP + 5% lime compared to soil + 5% WGP + 5% lime blends after 7, 28, and 90 days of curing, respectively.

In the study carried out by de Jesús Arrieta Baldovino *et al.* (2020), a WGP-based geopolymer for the stabilisation of silty soil collected in the Guabirotuba formation was investigated. The researchers assessed the increase in STS in compacted mixtures of soil, cement (3%, 6%, and 9%), and WGP (5%, 15%, and 30%), cured for periods of 7, 28, and 90 days. The most promising results were observed in the geopolymer composed of soil + 30% WGP + 9% cement, which exhibited an STS approximately 77.4% higher than the geopolymer composed of soil + 5% WGP + 9% cement. The authors highlight that WGP is a sustainable binder that enhances the engineering properties of soils with inadequate geotechnical characteristics, rendering them potentially suitable for use in pavement layers.

In conclusion, adding WGP and geopolymers improved the UCS and STS of the analysed clayey soil. This enhancement can be attributed to the combined effect of WGP, PC, and geopolymers in reducing voids within the specimens, promoting increased densification and agglomeration of particles within the analysed blends. Consequently, internal stresses and fractures in the specimens decrease, leading to an overall increase in strength.

4.2. Effect of PH on the increase of UCS and STS

Figure 16 presents the results of the means and associated errors of the pH measurements performed in the blends stabilised with PC and WGP (B5, B8, B11) and with geopolymer (B13, B14, B15, B16, B17, and B18) after 0 and 90 days of curing.

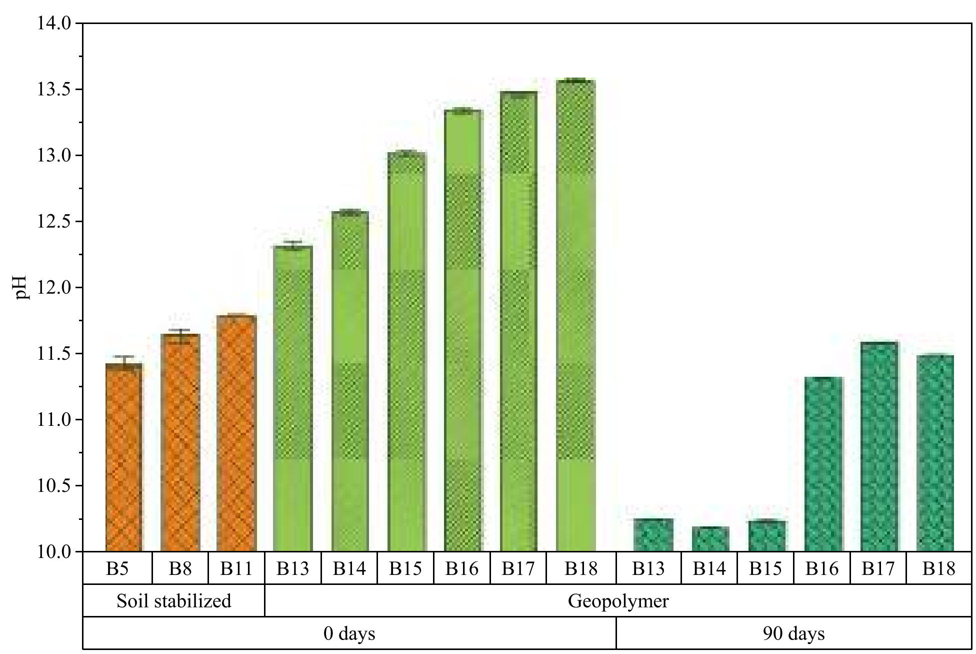

Figure 16. pH values of samples stabilised with PC, WGP, and geopolymer.

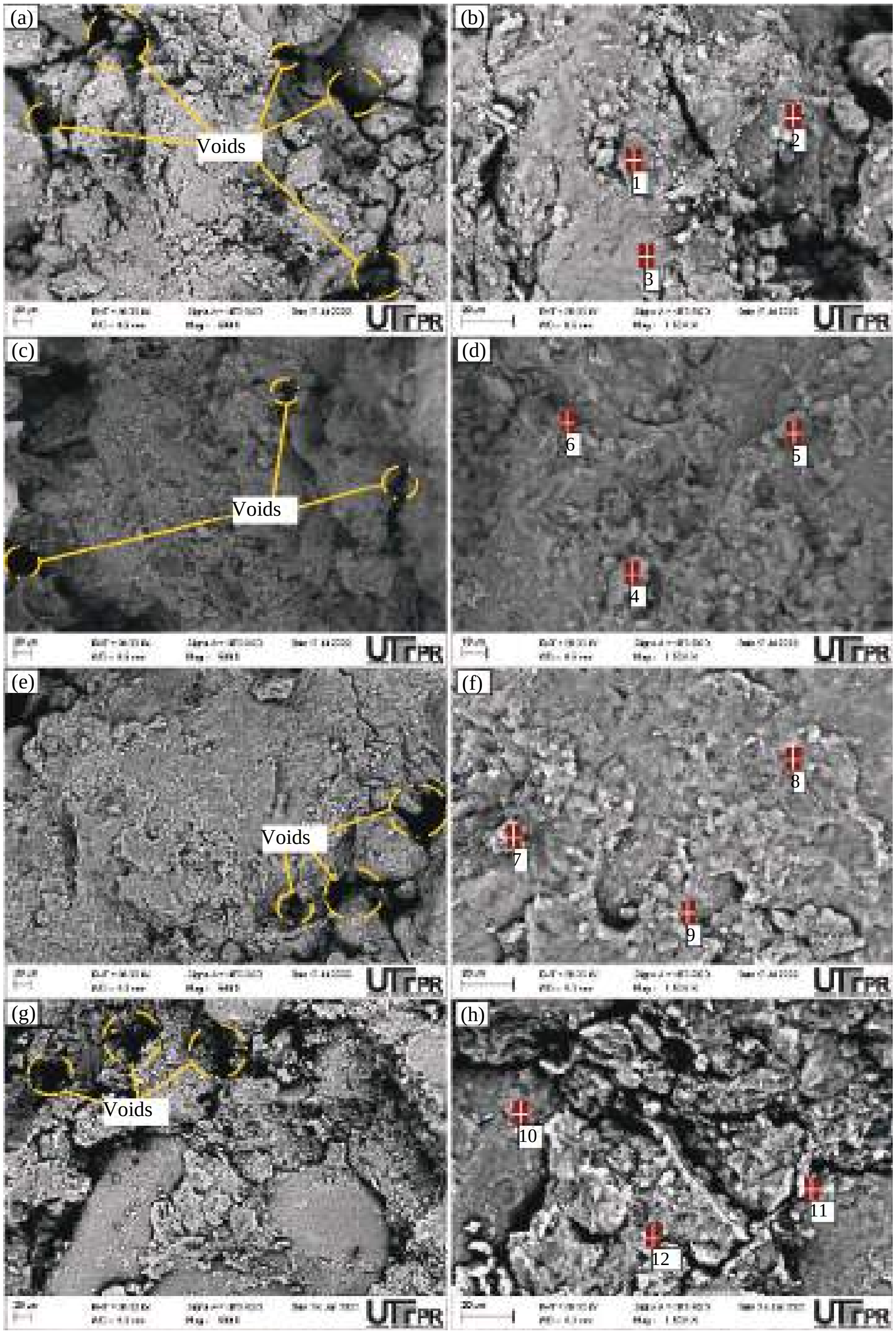

Figure 17. SEM micrographs of blends soil-pc: (a, b) pure soil compacted at standard proctor energy; (c, d) B1; (e, f) B2; (g, h) B3.

It is observed that for the blends stabilised with PC and WGP, the mean pH was lower than 12. However, for the blends stabilised with geopolymer, the pH ranged from 12.32 to 13.56 at 0 days of curing, and after 90 days, the pH dropped and was in the range of 10.25 to 11.59.

In the opinion of Duxson *et al.* (2007) and Khale and Chaudhary (2007), the performance of geopolymers depends on both the amount of base material and the curing time, the structure of the alkaline activator, and the pH of the blend. In the research conducted by Saldanha *et al.* (2017), the durability of blends composed of fly ash and lime increased when 1% NaCl was added, which could allow the decrease of both the compaction energy and materials such as lime.

Table 10. Results of EDX chemical microanalyses of pure soil, B1, B2, and B3.

	Dominant elements (% by weight)							
Spectro	C	O	Al	Si	K	Ca	Ti	Fe
1		62.15	3.25	18.75	0.73	0.8	1.31	13.01
2		17.1	3.6	2.87			27.48	48.95
3		62.15	4.2	24.1	0.4		1.01	8.14
4	10.98	43.18	9.46	17.56		13.85	0.75	4.23
5	12.21	51.39	5.11	27.99		0.68	0.26	2.37
6		46.83	17.76	16.56	0.72	3.56	1.87	12.7
7		61.13	16.65	15.97	0.29	0.77	0.67	4.53
8	6.53	46.81	18.52	18.18	0.37	1.47	1.04	7.07
9		44.91	12.12	13.45	0.41	19.36	1.14	8.62
10		55.26	11.53	28.58	0.26	1.33	0.33	2.72
11		65.18	13.67	15.08	0.18	2.26	0.39	3.24
12		49.17	17.85	20.59	0.59	5.06	1.02	5.73

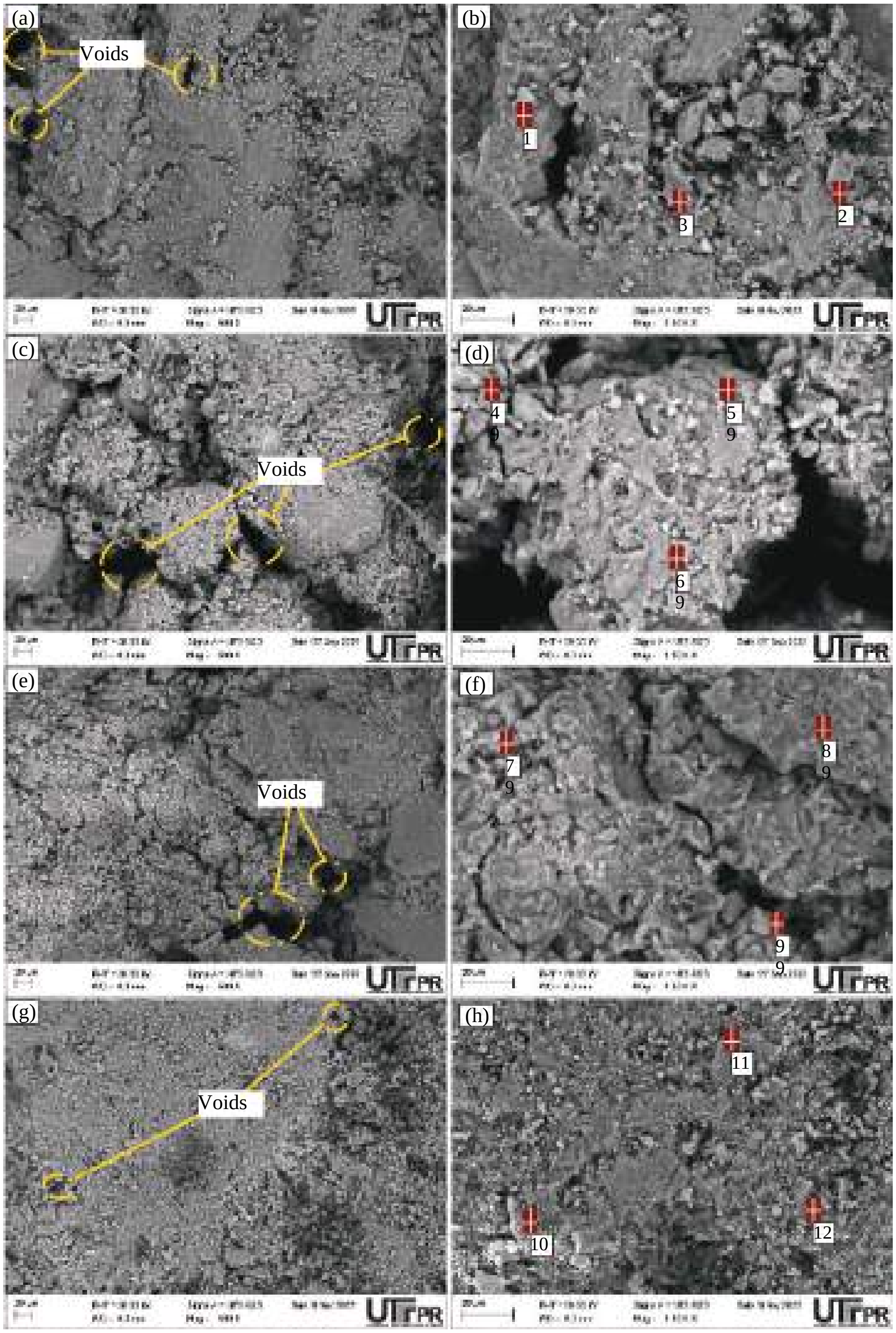

Figure 18a.

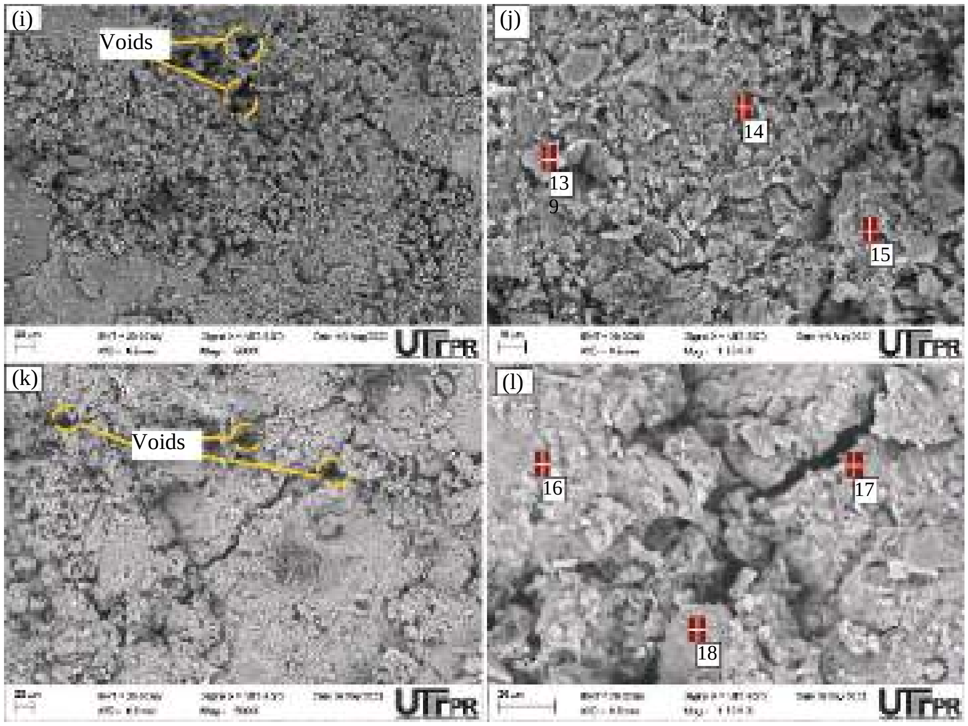

Figure 18b. SEM micrographs of blends: (a, b) B4; (c, d) B5; (e, f) B6; (g, h) B7; (i, j) B8; (k, l) B9.

In geopolymerization processes, a suitable alkaline environment and sufficient amounts of amorphous alumina and silica are essential (Pourabbas Bilondi *et al.* 2018a). In this research, the WGP and PC provided sufficient amounts of these materials, and the NaCl caused pH to be higher than 12, caused by the agglomeration of the materials and, consequently, increments in the UCS and STS.

In the opinion of Parthiban *et al.* (2022), alkaline pH promotes the dissolution of aluminate and silicate ions, increasing the rate of pozzolanic reaction, thus initiating the bond between the soil particles, leading to greater agglomeration and, therefore, increase in the strength of the material.

When geopolymeric solutions are not added to the stabilisation process, the improvement processes result from cation exchange, hydration, and cementation (Parthiban *et al.* 2022). However, when alkaline activators are introduced into the stabilised blend, the pozzolanic reaction rate may increase due to the dissolution of silica and alumina, thus initiating the binding of the particles of the stabilised material (Palomo *et al.* 1999). Subsequently, the alkaline activators reach the internal and external molecular spheres of the soil particles; consequently, gel formation occurs from the condensation of the soil particles (Winnefeld *et al.* 2010).

In this process, the water applied during the mixing process plays an important role in the development of gel in the pores of the soil since it contributes to the dilution process and, therefore, to the formation of gel and a large network of oligomers in the hydrolysis process (Romagnoli *et al.* 2012). The time it takes for gel networks to form depends on the stabilising materials and the alkaline solution (Penner and Lagaly 2001). In this way, all the materials present in this geopolymerization process beyond the curing time are important factors in increasing the strength of the improved material.

Finally, it is important to highlight, according to Alam *et al.* (2019) that one of the main challenges associated with geomaterials is the loss of strength and erosion due to exposure to adverse environments. In this study, we chose to focus on UCS and STS tests. These assays play a crucial role in characterising the mechanical properties of soils, offering a comprehensive understanding of mechanical strength and guiding the diverse applications for which improved soil can be utilised. Nevertheless, it is essential to acknowledge the necessity for future research to explore durability in contexts similar to those in the present study.

4.3. Microstructural analysis

Figure 17 shows the SEM characterisation of the microstructure of pure soil compacted at standard Proctor effort and the blends stabilised with PC, with magnifications of 500 and 1.5 kX, respectively. The edges of the

Table 11. Results of EDX chemical microanalyses of blends stabilised with PC, WGP, and geopolymer.

	Dominant elements (% by weight)									
Spectro	O	Na	Al	Si	K	Ca	Ti	Fe	Mg	Cl
1	67.60		14.02	13.95	0.23	0.59	0.44	3.18		
2	65.54	0.48	14.33	14.43	0.22	0.64	0.65	3.71		
3	54.65		6.54	35.67		0.64	0.30	2.20		
4	58.23		17.36	16.77	0.27	1.12	0.54	5.70		
5	60.70	0.35	15.71	15.79	0.23	1.42	0.66	5.15		
6	51.27	6.80	3.14	30.49	0.34	5.24		0.82	1.88	
7	59.14	5.14	3.72	23.99	0.17	5.37	0.18	1.09	1.19	
8	58.83		16.53	16.73	0.41	1.41	0.79	5.08	0.21	
9	63.31	1.29	4.22	10.00	14.98	0.34	5.34	0.53		
10	61.12	2.12	11.22	19.18	0.24	2.06	0.55	2.96	0.54	
11	51.67	1.41	12.37	22.76	0.66	4.84	0.70	5.07	0.53	
12	57.14	4.59	6.80	25.08	0.23	3.77		1.79	0.59	
13	50.57	1.50	6.03	13.46		20.11	0.80	6.98	0.56	
14	58.57	2.05	11.30	18.32		3.28	2.54	3.51	0.42	
15	53.15	5.67	4.57	28.24	0.22	5.92		1.36	0.86	
16	48.02	1.12	17.67	19.11	0.47	7.68	0.81	4.62	0.49	
17	59.95	0.43	16.65	16.24	0.25	1.09	0.77	4.62		
18	62.52	0.37	12.39	22.56		0.91	0.23	1.03		
19	55.82		11.68	32.09				0.41		
20	47.75	0.45	12.59	20.90	0.49	2.06	1.80	13.54		0.41
21	55.64	0.55	15.20	17.48	0.34	2.16	2.81	5.15	0.31	0.36
22	46.24	0.59	19.01	20.82	0.52	3.86	1.13	6.94	0.28	0.62
23	49.57	0.71	18.24	19.01	0.21	1.83	0.82	8.98		0.62
24	58.81	1.71	12.20	19.37	0.24	3.18	0.37	3.42	0.39	0.30
25	46.85	0.89	18.25	20.26	0.59	4.02	1.25	6.86	0.31	0.72
26	54.30	1.12	15.39	17.47	0.35	5.32	0.54	4.15	0.35	1.02
27	61.97	1.10	14.59	15.00	0.22	2.77	0.44	3.18	0.20	0.54
28	55.28	1.77	12.02	21.46	0.35	4.57	0.33	2.99	0.64	0.61
29	56.70	7.97	0.92	27.89	0.18	4.98		0.41	0.97	
30	51.39	1.00	16.61	19.67	0.44	2.15	0.76	6.93	0.36	0.71
31	52.46	1.60	12.75	21.27	0.30	5.27	0.73	4.33	0.48	0.79
32	59.03	0.98	16.60	17.44	0.31	1.05	0.84	2.98	0.23	0.54
33	47.03	0.35	4.69	45.95		0.40		1.58		
34	62.96	1.18	14.63	14.62	0.31	1.85	0.50	3.41	0.19	0.35
35	66.84	0.86	14.54	12.33	0.21	1.64	0.49	2.61	0.24	0.25
36	58.97	1.01	13.64	18.95	0.36	1.53	1.18	3.25	0.75	0.36

pure compacted soil particles (Figure 17a,b) are not well defined but have irregular shapes and possible clay mineral aggregates adhered to the larger soil particles. Microphotographs of blends B1, B2, and B3 (Figure 17c-h) reveal a dense and compact matrix with fewer voids than pure compacted soil (Figure 17a,b), evidencing that the agglomeration produced by adding PC to the soil caused a more densified matrix leading to the increase in the UCS and STS of the blends B1, B2, and B3 concerning the pure soil.

Table 10 presents the results of the elements identified by EDX, where for the pure soil are mainly oxygen, silicon, and aluminium, which make up the main minerals found in the XDR analysis of the pure soil as quartz and kaolinite.

Figure 18 shows the microphotographs of the blends stabilised with PC and WGP (B4, B5, B6, B7, B8, and B9). It is observed that the stabilised blends present less voids than the pure soil (Figure 18a,b), and then the stabilised blends with PC, in addition to the conformation of denser material.

It is possible to observe how the surface of the specimens improves with the increase in WGP content from 5% to 15% of WGP, finding that the structure is more homogeneous when 15% of WGP is added (Figure 18h-l).

Thus, these results coincide with the UCS and STS tests, where the blends stabilised with WGP and PC presented higher strengths than those stabilised only with PC. Evidencing that in the healing process, there was the cation exchange that led to cementation and consequently to the increase in the UCS and STS. On the other hand, the results of the EDX analyses resulted mainly in elements such as oxygen, aluminium, silicon, calcium, sodium, and iron (Table 11). Cemented surfaces accompanied by the increase in the geotechnical properties of different materials, in addition to the presence of chemical elements such as those found in this research, were reported by researchers such as Bilgen (2022), Kufre Etim *et al.* (2021) and Tajaddini *et al.* (2023) who evaluated soil improvement with the addition of WGP.

Figure 19 shows the microphotographs of the geopolymer-stabilised specimens (B13, B14, B15, B16, B17, and B18). The microstructure of the

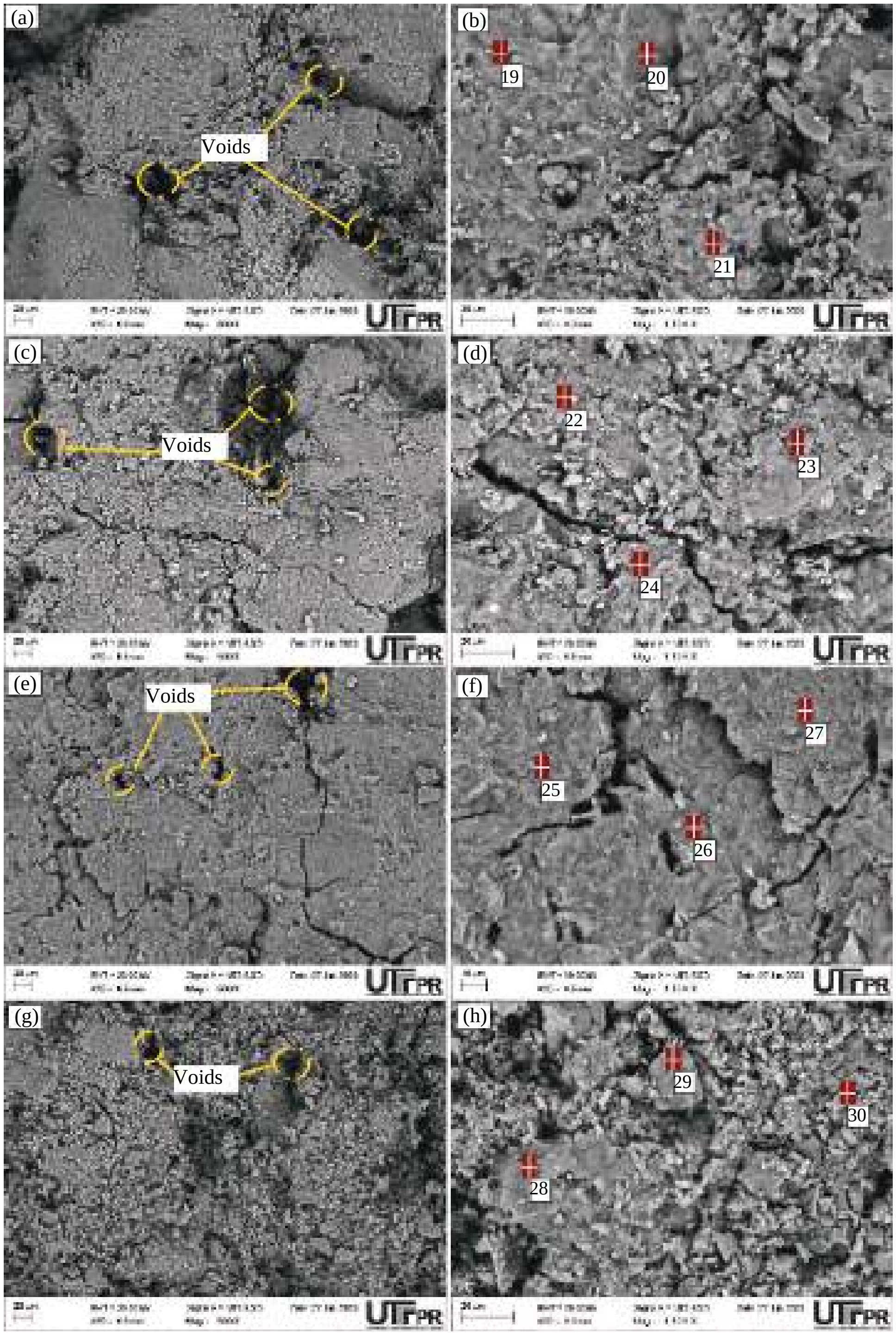

Figure 19b. SEM micrographs of blends: (a, b) B13; (c, d) B14; (e, f) B15; (g, h) B16; (i, j) B17; (k, l) B18.

geopolymer formed by all blends presents greater homogeneity than the blends stabilised with PC and WGP. The microcracks observed in the images may be due to shrinkage during the drying of the samples or even to the stress caused by the cutting and breaking in the preparation of the same. On the other hand, the flocculation process took place in all blends, which can be evidenced by the smaller pore size in the blends stabilised with geopolymer.

The disparity observed between pure compacted soil, soil improved with PC and WGP (blends B9 to B13), and the soil improved with geopolymer (B3 to B18)

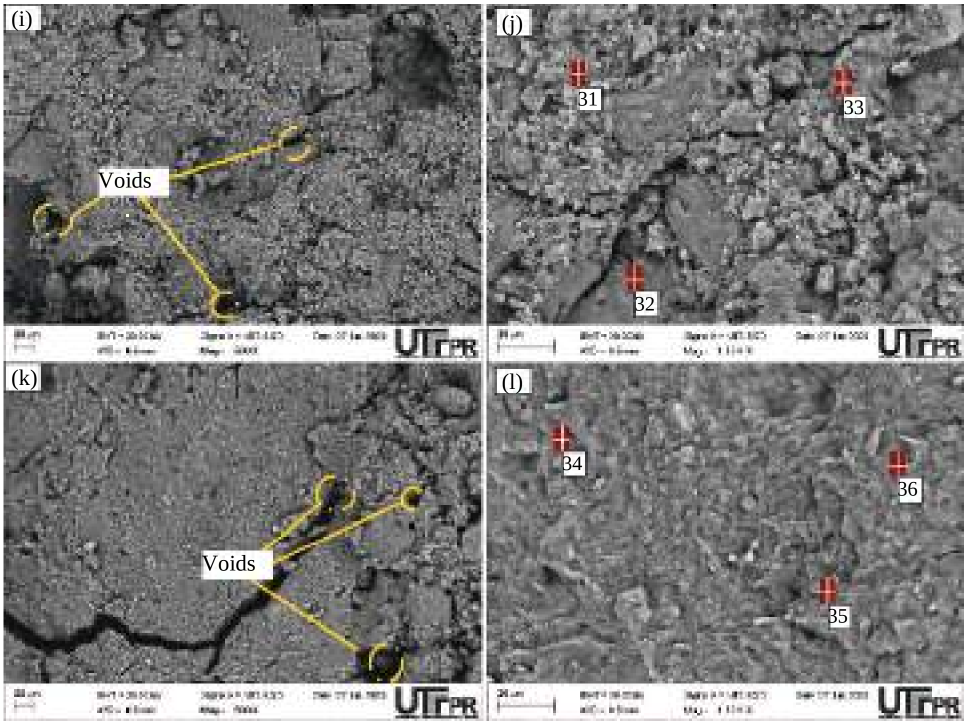

Figure 19a.

confirms that the dissolution of some minerals from clay contributes to forming new compounds.

In this way, a more agglomerated structure was observed because the alkaline activator (NaCl) used in this research contributed to the dissolution of aluminate and silicate ions, increasing the pozzolanic reaction rate (Parthiban *et al*. 2022)

This dissolution led to the binding of the particles and the formation of gel chains; consequently, the microstructure of the samples is observed to be more agglomerated, accompanied by increments in the UCS and STS of the blends stabilised with geopolymer. A more compact soil matrix improved with geopolymer indicates that the dissolution of clay minerals by the alkaline precursor was satisfactory (Vafaei and Allahverdi 2017).

Researchers point out that the dissolution and greater solubility of the precursor materials in the geopolymerization process lead to the production of a greater amount of cementitious gel, which is responsible for increasing the mechanical properties of the modified material (Xu and Van Deventer 2000, Kovalchuk *et al.* 2008).

The EDX analyses of the microanalysis points for the geopolymer-stabilised blends are presented in Table 11. The elements with the highest predominance were oxygen, sodium, aluminium, silicon, calcium, magnesium, and iron. These elements have also been found by researchers such as Baldovino *et al.* (2021), Pourabbas Bilondi *et al.* (2018b), Tajaddini *et al.* (2023), and Zhang *et al.* (2013), who evaluated soil improvement with geopolymers based on glass dust residues and different alkaline precursors.

Finally, as has already been demonstrated, geopolymerization processes can contribute to using rich aluminium-silicate waste materials in construction materials, aiming for better geotechnical properties.

From the present research, it was possible to observe the significant differences between the resistances obtained, both in blends stabilised with (PC and WGP), and with geopolymer, where it was possible to demonstrate that adding an alkaline precursor increased the strength of the analysed material.

This fact caused blends unsuitable for use in subbase applications in pavements according to Brazilian DNIT 143 () and American TxDOT () standards to become suitable for use in field applications.

Thus, it is considered that the evaluation of the performance of this type of compound should continue to be investigated to develop processes and techniques of use and maintenance in the field, especially in base and subbase pavement applications.

5. CONCLUSION

In this article, a series of unconfined compressive and splitting tensile strength tests and microstructural analyses were performed to explore the effects of PC, WGP, and NaCl on the mechanical properties of clayey soil. The main conclusions are described below:

- The UCS and STS of the specimens stabilised with PC and WGP increased with the addition of WGP up to an optimal amount of (15%). The best results for stabilisation blends were found in blend B9 (S + 8PC + 15WGP), which presented increments of (18 ± 1)% concerning the UCS of the stabilised blend with 8% PC (B3) after 28 days of curing.
- The ideal content of NaCl was equal to 1%, which is considered optimal for an adequate geopolymerization. NaCl allowed the increase in the properties of UCS and STS of the specimens at lower concentrations (0.5-1%) and a decrease in strength at higher concentrations (1.5-2%).
- For the case of the blends stabilised with geopolymer, the UCS of B18 (S + 8PC + 15WGP +1NaCl) resulted in approximately 24 times higher than the UCS of the pure soil and 1.6 times higher than the soil stabilised with 8% of PC.
- According to American and Brazilian standards, the blends B6, B9, B15, and B18 met the UCS requirements at 7 days of curing to be used as a subbase in pavement applications. None of the blends met the requirements to be used as a base in the pavement. For the blends analysed in this research, short curing periods such as 7 days are unsuitable for developing agglomeration and geopolymerization processes.
- The largest increase in STS was observed in the blend formed by the geopolymer (S + 8PC + 15WGP +1NaCl), which was approximately 33 times greater than the pure soil and 3 times greater than the stabilised soil with 8% PC.
- The STS of the B9, B15, and B18 blends complied with the requirements of the American standard to be used as a sub-base of pavements. Demonstrating that the geopolymerization processes could allow the reduction of the PC content, making the soil suitable for use in field applications.
- The PH measurements showed the increase of PH in the blends with the addition of the alkaline precursor, where at 0 days, the pH was greater than 12. Demonstrating that 1% of Nacl promoted the dissolution of aluminate and silicate ions, leading to greater agglomeration and, therefore, an increase in the strength of the material.
- The microstructure analyses SEM and XDR qualitatively confirmed the agglomeration of the particles with the increase of the homogeneity of the specimens, accompanied by the possible formation of geopolymeric gel. The previous was verified by observing the increase in the strength of the specimens when the alkaline precursor was added.
- Finally, the experimental analyses carried out in this research demonstrate the significant and positive effect of stabilisation and geopolymerization based on WGP of clayey soil, being the formation of geopolymer, the ecological and effective technique in increasing the strength of the material.

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Data availability statement

Enquiries about data availability should be directed to the authors.

CRediT authorship contribution statement

Yeimy Ordoñez Muñoz: Investigation, Conceptualization, Methodology, Writing – review & editing, Formal analysis. **Alvaro Javier Esteban Villota-Mora**: Investigation, Conceptualization, Writing – review & editing. **Felipe Perretto**: Supervision, Methodology. **Ronaldo Luis Santos Izzo**: Supervision, review & editing, Methodology, Project administration.

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