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Use of waste glass powder in improving the properties of expansive clay soils

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Graphical abstract

Abstract

Expansive soils pose a danger to the foundations of engineering structures due to their poor engineering properties. These soils are usually treated using mechanical techniques, and chemical stabilizers. However, the production of these chemicals is not friendly to the environment, thus a need to adopt waste materials. Therefore, this research investigated the efficacy of utilizing waste crushed glass to alter the engineering properties of the soil. The study's objectives were achieved by conducting experiments on non-stabilized soil, and waste glass powder (WGP) stabilized soil in the percentages of 3, 5, 7, and 9% of dry weight of the soil. The findings showed that adding glass powder to subgrade soil strengthens it and reduces its susceptibility to volume change. The highest compressive strength was obtained after mixing 7% waste glass powder with the soil, and beyond that, the strength reduced. The study found that the inclusion of 7% waste glass powder content is suitable for the stabilization of the soil possessing properties similar to the ones in the study area.

Keywords. Clay soil, environmental conservation, soil stabilization, waste glass powder, waste management

1. Introduction

Expansive soils (ES) vary in volume with water content. This term characterizes rock or soil material with a significant swell/shrink potential (Nelson *et al.*, 2015). These soils are highly plastic materials with an enormous fraction of clay-silt and are very sensitive to moisture variation (Niyomukiza *et al.*, 2020a; Schaefer *et al.*, 2008). The clay mineral in these soils exhibits swelling behavior as the moisture content increases and shrinks when the moisture content decreases (Fondjo and Theron, 2021; Nelson *et al.*, 2015; Niyomukiza *et al.*, 2020a).

Civil engineering infrastructures constructed on problematic or expansive soils deteriorate due to volumetric soil changes (shrinking and swelling). These abrupt changes in volumes lead to cracks in the civil engineering structures, for example, highway embankments, buildings, etc. (Niyomukiza *et al.*, 2021; Papagiannakis and Masad, 2008; Wasif *et al.*, 2022). Records show that the damages attributed to expansive soils in civil engineering infrastructures yearly are more significant than those triggered by natural disasters like earthquakes, storms, torrential rains, and hurricanes (Amakye and Abbey, 2021; Wu *et al.*, 2019). In pavement construction, several layers are used, and the foundation layer comprises subgrade soils. In some parts of the world, these subgrade soils possess poor engineering properties, thus incapacitated to support the succeeding layers and the traffic loadings. Therefore, to ensure that the subgrade performance is improved, the soil needs to be modified or stabilized to enhance its capacity to support both stationary and moving loads. If the soils are not stabilized or modified, they can cause premature deterioration and failure of the pavement structure (Al-soudany *et al.*, 2018; Amakye and Abbey, 2021).

Different scholars have investigated the measures of mitigating early pavement distress by improving the strength of subgrade soils. One of the techniques for strength improvement of expansive soils is to use chemical and mechanical stabilization (Jones *et al.*, 2010;

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Nelson *et al*., 2015). Mechanical stabilization is achieved by using mechanical means, such as compaction. On the other hand, chemical stabilization entails using traditional stabilizers, e.g., lime, ordinary Portland cement, fly ash, etc. Chemical stabilization methods, such as use of lime, cement, fly ash, etc. are said to have been utilized to solve the issues associated with expansive or problematic subgrade soils. Chemical stabilizers play a significant role in altering the properties of soils having huge quantities of clay (Amadi and Okeiyi, 2017; Eisazadeh *et al*., 2012). Among the chemical stabilizers, lime and cement are preferred in numerous soil stabilization projects (Sohail *et al*., 2018). However, due to the amount of carbon dioxide (CO_2) emitted during the manufacturing process, these chemicals have proven to be exceedingly expensive to produce and unsustainable for the environment (Amakye and Abbey, 2021; Petry and Little, 2002).

Different techniques such as polymerization have been proposed and used to address the mentioned issues. Geo-polymerization is a trending technology for making use of by-products such as fly ash, bottom ash, blast furnace slag, kiln dust, marble and pumice powder, agricultural wastes, and many others (Bhurtel & Eisazadeh, 2020; Çadir & Vekli, 2022; Fauzi *et al*., 2013; Jamsawang *et al*., 2017; Niyomukiza *et al*., 2021), as well as for the halting of toxic metals in the management process of hazardous wastes. It is considered a cost-friendly alternative because of its decreased impact on landfills and the reduction of about 80% CO_2 emissions compared to the use of ordinary Portland cement (Arrieta Baldovino *et al*., 2020).

Among the latest materials used to make geopolymers is the glass residue. It has high quantities of silica. Besides, it is non-crystalline, and amorphous (Aboud & Alkaseem, 2017; Arrieta Baldovino *et al*., 2020; Blayi *et al*., 2020; Ibrahim *et al*., 2019; Mahdi *et al*., 2018; Preve Machado *et al*., 2022; Rai *et al*., 2020). Different sources of glass residue exist in the environment where we live, for example, glass bottles, glass windows, and glass doors. These glass wastes can be pulverized to obtain the preferred size for concrete aggregate and to produce fine-particle powder for enhancement of soil properties. Improvement in waste generation represents sustainable development and economic benefit. However, the poor disposal of these wastes poses a noteworthy problem for towns in both developed and developing countries. One way to utilize these wastes is to recycle them and use them in civil engineering structures (Niyomukiza *et al*., 2022). Glass recycling is a way to reduce poor management and increase pressure on landfills where they are dumped (Kinobe *et al*., 2015), lower construction costs and eco-friendly (Mahdi *et al*., 2018). However, the utilization of glass wastes in soil stabilization is still in its infancy and thus needs more research (Arrieta Baldovino *et al*., 2020). It is believed that waste glass powder possesses desirable chemical properties, e.g., a high amount of silica that would make the soil cemented (Arrieta Baldovino *et al*., 2020; Rai *et al*., 2020). In few countries where glass wastes were used in the stabilization of the soil, promising results were observed, e.g. Blayi *et al*. (2020) utilized waste glass powder in different percentages (2.5%, 5%,10%, 15%, and 25% of the dry unit of the soil) to stabilize the soft clays of Soran-Jundean road in Iraq. In their study, they noticed an improvement in the index properties of the soil and increased strength. Another study by Arrieta Baldovino *et al*. (2020) using recycled glass powder to improve silty soil properties in Brazil showed that recycled glass wastes increased durability and strength properties. The study by Zamin *et al*. (2021) showed a reduction in the swelling potentials of waste glass powder modified expansive soils. All the studies mentioned showed the successful application of recycled glass powder as a soil stabilizer in the countries where it was applied. However, field implementation as far as the applicability of waste glass powder in stabilizing the problematic soils is still missing. This could be due to inadequate publications or lack of design standards for stabilizing soil using waste glass powder. It is thought that when enough studies are done, correlations can be developed, which could help in formulating the design guidelines of stabilizing soils using waste glass powder. Therefore, this study contributes to the existing knowledge by utilizing different mix proportions of waste glass powder (WGP) that passed 75 µm sieve to improve the properties of expansive soil. The study becomes helpful to the policy makers and practitioners, especially in coming up with design guidelines for soil stabilization. The methods to achieve the study's objectives were conducting chemical analysis tests on recycled waste powder and determining the geotechnical properties of both waste plastic powder modified and non-modified soil. The properties determined included physical property tests, such as particle size distribution and consistency limits tests, and mechanical property tests, such as compaction, California bearing ratio (CBR), and unconfined compressive strength (UCS).

2. Materials and methods

2.1. Materials

The materials utilized in the current study of recycling waste glass power for soil stabilization include expansive soil and waste glass powder.

2.1.1. Expansive clay

The Expansive clay used in this research, as seen in Figure 1, was collected from Kawanda Town Council, Wakiso District, Uganda. It was light grey. The collection spot point was: 0o24’46.628” N and 32o32’18.776” E at a depth of about 0.5 m. This depth was chosen to ensure that the organic matters are not included in the soil sample. The soil samples were first sun-dried prior to testing. The physical and strength properties were determined in accordance with British Standards. The physical qualities of expansive clay soils are characterized primarily by low bearing capacity, high settlement, low shear strength, and increased water absorbability.

2.1.2. Waste glass powder

The waste glass materials used in this research were collected from the Kitezi landfill. They mainly consisted of broken soda bottles and glasses, as seen Figure 2 a). The waste glasses were cleared from dust and other toxic materials, and manually crushed into suitable sizes. After crushing the glasses to eligible pieces, they were put in a rolling mill machine to transform them into powder, as seen in Figure 2 a), and screened using sieve size No. 200 (75µm). The chemical composition of glass powder was scanned using an X-ray fluorescence (XRF) Epsilon 1 machine. The glass powder was used as an additive material in four varying percentages, i.e., 3, 5, 7, and 9% of the dry unit weight of the soil. The percentages were chosen based on previous studies that utilized waste glass powder in stabilizing soil, e.g. (Aboud & Alkaseem, 2017; Blayi *et al*., 2020; Canakci *et al*., 2016; Mahdi *et al*., 2018; Siyab & Tufail, 2018).

Figure 1. Sample of expansive clay.

2.2. Methods

During the study, the soil particle distribution, liquid limit, plastic limit, compaction parameters to determine optimum moisture content (OMC) and, maximum dry density (MDD), and strength properties (CBR and UCS) of the expansive clay sample were investigated according to British standards. During conducting the laboratory tests, at least three samples on each test were used, and then the average was used. The physical properties of the soils are shown in Table 1. The soil was classified based on two parameters, i.e., particle size distribution and Atterberg (consistency) limit tests. Particle size distribution was conducted using sieve analysis and hydrometer test. The cone penetrometer device was used to determine the liquid limit (LL). The classification system used was the American Association of State Highway and Transportation Officials (AASHTO) and the Unified Soil Classification System (USCS). The chemical composition of waste glass powder was analyzed using the X-Ray Fluorescence (XRF) method. The second phase of experiments was carried out where 3%, 5%, 7%, and 9% of waste glass powder were added to the clayey soil by dry weight. The soil and glass powder were mixed thoroughly using hands and trowel to obtain a homogeneous mixture.

3. Results and discussion

3.1. Chemical composition of waste glass powder

The major components present in waste glass powder are shown in Table 2. It was observed that silica (SiO_2) was the glass powder's highest (33.88%) chemical compound, followed by calcium oxide (12.36%). The aim of stabilizing soil is to make it cemented so that it can withstand loads imposed on it. Silica has that potential of making soil cemented. It is a sand form and, thus non-plastic, an essential property of improving expansive clay (Canakci *et al*., 2016). When non-plastic material is partially used to replace expansive clay partially, improved workability is observed, as seen in this study. This phenomenon is due to cation exchange capacity that increases the plastic limit whilst reducing plasticity index (Amadi & Okeiyi, 2017). Reducing the liquid limit from 30.7% to 23.3% symbolizes improved workability. However, the percentage of silica in the material used in the current study was much lower compared to previous research on the chemical composition of waste glass powder, where it was found to be about 74% according to Abdul and Mahdi (2018), 71.21% according to Blayi *et al*. (2020), and 70% according to Sohail *et al*. (2018). The changes in silica percentages could have resulted from a mixture of waste glass materials used.

Figure 2. a) Waste glass bottles b) Waste glass powder that passes through a 75µm sieve.

3.2. Particle size distribution

The gradation curve obtained from the hydrometer test and wet sieving are shown in Figure 3. The results show that fines (silts and clays) dominated the soil since they had a higher percentage content (62%). Silts were 6% while clays were 56%. Based on the proportions of different particle sizes, a soil textural category was observed from the soil textural triangle (Okalebo *et al*., 2002) and described as low-plasticity clays (CL).

3.3. Atterberg limits

The findings for Atterberg limit tests are shown in Table 3. For varied percentages of waste glass powder, the moisture content obtained at a cone penetration of 20 mm was used as the liquid limit. Modification of expansive clay with waste glass powder reduced the liquid limit from 30.7% to 23.3% with the addition of 9% of waste glass powder. This behavior agrees with the findings of several researchers, e.g. (Zamin *et al*., 2021) added up to 20% of WGP. The liquid limit dropped from 52.5% to 36%. Glass powder has lower water retaining ability than expansive clay, which increases desiccation in soil- glass powder mixture, hence lowering the minimum water content for the soil to flow under a specified small disturbed force. (Ibrahim *et al*., 2019) also noticed a decrease in liquid limit from over 50% to less than 40%.

The plasticity index of stabilized expansive clays decreased with an increase in glass powder content. Glass, a non-plastic material, replaced a portion of plastic soil. The plasticity index of soil can be adopted as an effective indirect quantification for swell potential. Therefore, a decrease in soil plasticity index indicates a decrease in swelling characteristics of the modified soil. Different researchers (Syafrudin *et al*., 2022; Ikeagwuani *et al*., 2019; Niyomukiza *et al*., 2020b; Ogundipe & Olumide, 2013) who conducted various studies on soil stability confirmed that a decrease in the plasticity index of the soil leads to improvement in its properties (Mosa, 2017). Decreased plasticity index leads to improvement in workability (Amadi and Okeiyi, 2017; Niyomukiza *et al*., 2020a; Niyomukiza *et al*., 2020b). This improvement is vital because little compaction efforts are required to attain higher soil densities, thus saving time and money.

Table 1. Physical properties of the soil under study

No	Property	Result
1	Percentage passing BS No 200 (75µm) sieve	63%
2	Liquid limit	30.7%
3	Plastic limit	19.7%
4	Plasticity index	11.0%
5	AASHTO classification	A-6 (5)
6	Unified soil classification system	Low plasticity clay (CL)

Table 2. Chemical composition of glass powder

Component	Al_2O_3	SiO_2	CaO	K_2O	TiO_2	MnO	Fe_2O_3	SO_3	SiO
Value (%)	0.75	33.88	12.36	0.28	0.24	0.04	0.64	0.22	0.08
Detection limit	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.01	1.0

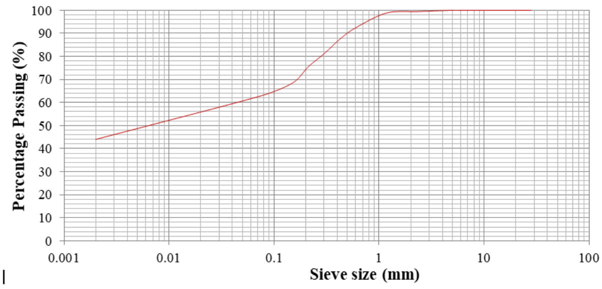


Figure 3. Gradation curve for the soil sample used.

3.4. Classification of the soil sample

The soil was classified based on particle size distribution and Atterberg limits results. The AASHTO soil classification system classified the soil under study as A-6 (5), and clay of low plasticity (CL) using the unified soil classification system. Based on AASHTO soil classification system, soils under class A-6 possess fair to poor engineering properties, hence a need for stabilization (Niyomukiza *et al*., 2021). The higher the group index (GI), the less desirable the soil for use as a subgrade. A GI of zero (0) indicates a good subgrade, and a GI greater or equal to 20 indicates a very poor subgrade material (ASTM, 2004).

Table 3. Atterberg limits results for varying percentages of waste glass powder

Property	Waste Glass Powder (%)				
	0	3	5	7	9
Liquid limit (%)	30.7	30.1	29.6	26.5	23.3
Plastic limit (%)	19.7	19.3	19.1	16.8	14.3
Plasticity index (%)	11.0	10.8	10.5	9.7	9.0

3.5. Compaction test

A relationship between moisture content and soil compacted dry density was established to determine the optimum moisture content (OMC) and maximum dry density (MDD) for unstabilized soil; values of OMC and MDD for the unstabilized sample were 15.6% and 1533 kg/m^3, respectively as seen in Figure 4.

Similar relationships were established for samples stabilized with different contents of waste glass powder. Figure 5 illustrates the results of OMC and MDD values for unstabilized and stabilized samples. As seen in Figure 5 (a), a relationship between OMC and different percentages of WGP is illustrated. The OMC values decreased with the increase of waste glass powder content. This behavior could be attributed to the inclusion of waste glass powder that is believed to have lower water absorbing capacity than the expansive clays (Blayi *et al*., 2020; Canakci *et al*., 2016; Ibrahim *et al*., 2019). The trend could also be justified by the reasons mentioned earlier, similar to those stated to justify liquid limit behavior. The relation between MDD and different percentages of waste glass powder is illustrated in Figure5 (b). The values of MDD increased with an increase in glass powder content, as the bulk density of glass powder is higher than that of the original soil. The same observation was noticed by other researchers, e.g. (Blayi *et al*., 2020; Siyab and Tufail, 2018).

3.6. California bearing ratio (CBR) test

CBR was determined on the soaked samples. Figure 6 (a) exhibits the CBR results of the samples that were soaked in water for four days. It was found that there is an increase in the CBR values with an increase in glass powder. The increased CBR results from pozzolanic lime in the glass powder, incompressibility of glass powder and an increase in soil toughness due to tight structure formation and increased friction among the soil particles (Mahdi *et al.*, 2018). This behavior conforms to what several studies have found before. For example, Canakci *et al.* (2016) added up to 12% of soda lime glass powder, and the CBR value increased to 140% due to the high silica and lime content present in the soda lime glass. Blayi *et al.*, 2020) also noticed an increase in CBR. The study found that CBR increased from 4.5% to 12.20% for non-stabilized soil and 15% for waste glass stabilized soil. The CBR swell was determined too. During pavement design, some agencies use the CBR parameter to assess the thickness of the pavement layers (NCHRP, 2004). The CBR for the soaked specimen above 5% is recommended for subgrade (NCHRP, 2004). The higher the CBR, the lower the thickness of the succeeding layers. This phenomenon is valid because the increase in CBR raises the coefficient (a) of the layer, thus lowering the pavement thickness (Aboud & Alkaseem, 2017). The results in Figure 6 (b) showed that the swelling decreased with an increase in the percentage of glass powder. The decrease in swelling was an expected result due to a reduction in soil plasticity because of the non-cohesive property of the glass powder. The addition of WGP significantly improved the penetration resistance at all percentages. Therefore, glass waste powder could be a potential candidate for stabilizing expansive clay.

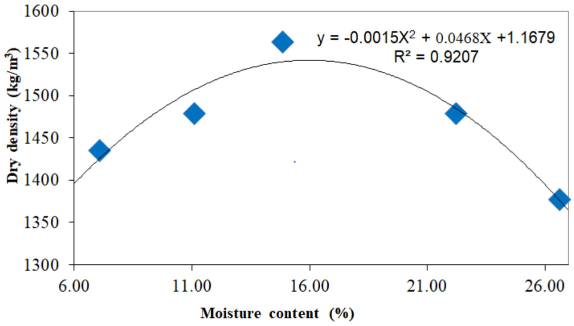
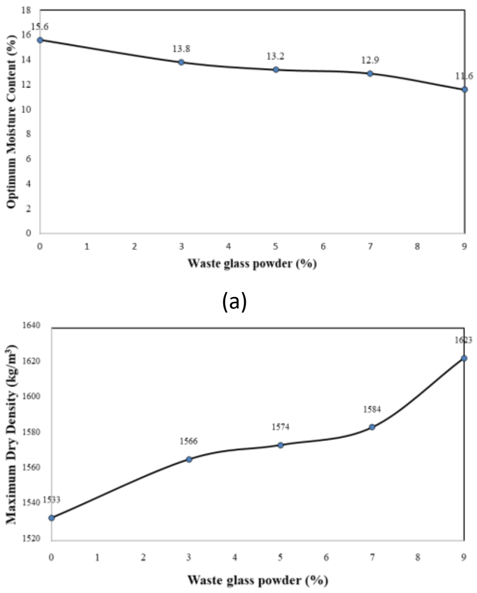


Figure 4. Relationship between moisture content and dry density.



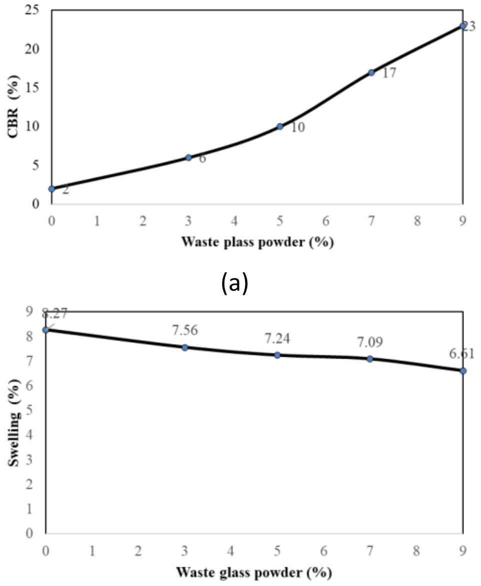
(a)

(b)

Figure 5.(a) Effect of waste glass powder on optimum moisture Content.(b). Effect of waste glass powder on maximum dry density.

3.7. *Unconfined compressive strength (UCS) test*

The results in Figure 7 exhibited that UCS values of soil mixed with waste glass powder and cured for seven days increased from 18.81 kPa for the control soil sample to 35.83 kPa after adding 7% of WGP. This increase shows a significant improvement in the soil strength. However, adding glass powder greater than 7% exhibited a lower UCS value. This behavior can be attributed to the combined influence of unconfinement conditions of the test procedure and a decrease in soil cohesion which causes local shear failure as the sample behaves similar to sandy soil (Mosa, 2017). This result conforms to past research by (Mahdi *et al.*, 2018; Mosa, 2017), and Canakci *et al.*, 2016), whose results also exhibited optimum percentages at 7%, 5%, and 6%, respectively. Studies by Wasif *et al.*, 2022) showed an increase in compressive strength when they used 3% waste marble powder, and beyond that, a decrease in unconfined compressive strength was noticed. The increase in unconfined compressive strength denotes an increase in the strength of the soil. This increase is attributed to the pozzolanic reactions that took place between the soil and the stabilizers. Besides, the stabilizers improve soil gradation, that is an important aspect in strength development (Niyomukiza *et al*., 2021; Wasif *et al*., 2022).



(a)

(b)

Figure 6.(a). Effect of waste glass powder on CBR values.(b). Effect of waste glass powder on swelling behaviors of the soil.

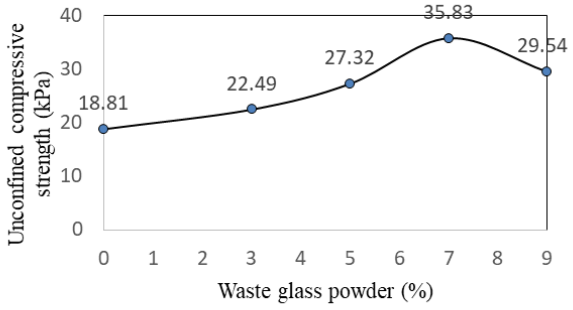


Figure 7. Change in UCS value with increase in percentages of soil-glass mix.

4. Conclusions and recommendations

The current study investigated the feasibility of using recycled waste glass powder (WGP) to improve the geotechnical properties of the problematic soils of Wakiso, Uganda. The soil used in the present study is classified as A-6 (5) according to AASHTO, which is soil with fair to poor engineering properties. The impact of waste glass powder passing 75µm sieve on the geotechnical characteristics of the soil sample was investigated by carrying out different consistency and strength tests. Based on the results, it was noted that gradation and consistency limits improved greatly, which in turn improved the strength properties of the soil. The unconfined compressive strength test revealed that 7% glass powder greatly improved the strength properties in the study area, thus chosen as the optimal percentage to be used as an additive to the soil possessing properties similar to the ones in the study area. This stabilization technique could be useful in reducing the costs of soil stabilization since glass wastes are readily available. It will also be valuable to municipalities in improving on recycling of waste glass since they do not decompose in the landfills where they are disposed due to their non-biodegradable nature.

However, there are still some knowledge gaps that still need to be filled. This study suggests further investigation on the stabilization mechanisms, for example, waste glass powder-soil interaction. Besides, a cost analysis of soil stabilization using glass powder could be made and compared with other chemical stabilizers.

Declaration of competing interest

The authors declare that there is no known conflict of interest that could have influenced the outcomes of this study.

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