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

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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;
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 Okeiysi, 2017; Eisaadreh 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\textsubscript{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 & Eisaadreh, 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\textsubscript{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-Jundea 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 powder 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: 0°24’46.628” N and 32°32’18.776” 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
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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 (SiO₂) 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.

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 (Syarudin et al., 2022; Ikeagwuani et al., 2020b; Ogundipe & Olumide, 2020b; Niyomukiza et al., 2019; Niyomukiza et al., 2020b; Canakci et al., 2016) 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>
<thead>
<tr>
<th>No</th>
<th>Property</th>
<th>Result</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Percentage passing BS No 200 (75µm) sieve</td>
<td>63%</td>
</tr>
<tr>
<td>2</td>
<td>Liquid limit</td>
<td>30.7%</td>
</tr>
<tr>
<td>3</td>
<td>Plastic limit</td>
<td>19.7%</td>
</tr>
<tr>
<td>4</td>
<td>Plasticity index</td>
<td>11.0%</td>
</tr>
<tr>
<td>5</td>
<td>AASHTO classification</td>
<td>A-6 (5)</td>
</tr>
<tr>
<td>6</td>
<td>Unified soil classification system</td>
<td>Low plasticity clay (CL)</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Component</th>
<th>Al₂O₃</th>
<th>SiO₂</th>
<th>CaO</th>
<th>K₂O</th>
<th>TiO₂</th>
<th>MnO</th>
<th>Fe₂O₃</th>
<th>SO₄</th>
<th>SiO</th>
</tr>
</thead>
<tbody>
<tr>
<td>Value (%)</td>
<td>0.75</td>
<td>33.88</td>
<td>12.36</td>
<td>0.28</td>
<td>0.24</td>
<td>0.04</td>
<td>0.64</td>
<td>0.22</td>
<td>0.08</td>
</tr>
<tr>
<td>Detection limit</td>
<td>0.1</td>
<td>0.1</td>
<td>0.1</td>
<td>0.1</td>
<td>0.1</td>
<td>0.1</td>
<td>0.1</td>
<td>0.01</td>
<td>1.0</td>
</tr>
</tbody>
</table>

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>
<thead>
<tr>
<th>Property</th>
<th>Waste Glass Powder (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Liquid limit (%)</td>
<td>30.7 30.1 29.6 26.5 23.3</td>
</tr>
<tr>
<td>Plastic limit (%)</td>
<td>19.7 19.3 19.1 16.8 14.3</td>
</tr>
<tr>
<td>Plasticity index (%)</td>
<td>11.0 10.8 10.5 9.7 9.0</td>
</tr>
</tbody>
</table>

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/m³, 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 Figure 5 (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.

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).

Figure 4. Relationship between moisture content and dry density.

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

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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References


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