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Effect of Waste Glass on Properties of Treated Problematic Soils: A Comprehensive Review

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***Abstract*—Soils are the most commonly used construction material in engineering projects. Fine-grained soils especially clayey soil may expand and lose strength when wet and shrink when dry, resulting in a significant volume change. Construction on weak soils has created challenges for various civil engineering projects worldwide, including roadways, embankments, and foundations. As a result, improving weak soil is vital, particularly for highway construction. The properties of this type of soil can be improved by waste-recycled materials such as waste glass (WG). The WG must be crushed and ground to a fine powder first and then can be mixed in various proportions with the soil. The primary objective of this study is to review the effect of WG on geotechnical properties of fine-grained soils treated by WG. To demonstrate the effects, the treated fine-grained soils at varying percentages of WG are compared with untreated soils. Physical properties (e.g., Atterberg limits, swelling, and maximum dry density), mechanical properties (e.g., California bearing ratio, and unconfined compressive strength) are evaluated. The test results from the literature show that adding a certain percentage of WG leads to a substantial effect on the properties of fine-grained soils; hence, using WG could reduce the required thickness of subbases in the construction of driveways and roads.**

***Index Terms*—Stabilization, Problematic Soil, Waste Glass, Physical Properties, Mechanical Properties.**

I. Introduction

Clayey soils are extensively spread on many parts of the earth (Behnood, 2018; Ramos, et al., 2015). Some of the clayey soils are expansive soils whose volumes are directly proportional to moisture content, they expand when the water content increases and shrink when the water content decreases (Sharma and Bhardwaj, 2018). These soils also lose strength when they get wet. The swelling and low-strength properties of the clayey soils make them problematic and difficult to be handled in civil engineering projects (Ikeagwuani and Nwonu, 2019; Thyagaraj and Zodinsanga, 2014), such as pavement foundations, slopes, embankments, and retaining walls (Fatta, et al., 2003). Therefore, it is often necessary to improve their properties before or during construction by stabilization of these soils (Sharma and Hymavathi, 2016). Soil stabilization (mechanical and chemical stabilization) may be achieved through mixing clayey soils with another geomaterial or chemicals to improve their geotechnical engineering properties according to the project's requirements (Gangwar and Tiwari, 2021; Olufowobi, et al., 2014; Patel, 2019). Mechanical stabilization by mixing soil with another soil of different gradation (e.g., sands and crushed stones) changes the soil gradation and properties. However, chemical stabilization, such as lime, cement, and fly ash, involves the alteration of soil properties (Patel, 2019). Increased uses of sand, crushed stones, and chemicals increase their prices and reduce natural resources, which are not sustainable. To provide sustainable construction, waste materials have been increasingly used as alternative materials in recent years to save natural resources and protect the environment. It is even more beneficial when wastes are used to strengthen soils and reduce their potential to swell (Parihar, Garlapati and Ganguly, 2019). Mixing waste materials with clayey soils to improve their soil properties is one of such applications, which makes the clayey soils more suitable for construction and more beneficial to the environment (Sharma and Hymavathi, 2016) because the waste materials from industrial processes negatively influence the environment (Balkaya, 2019; Ibrahim, Mawlood and Alshkane, 2019).

Waste glass (WG) is one of the most widely used in the world. WG is non-biodegradable; it does not decompose in landfills, causing it to its permanent accumulation in ever-increasing amounts and posing serious risks to the environment and ecosystems (Balan, Anupam and Sharma, 2021). According to the data from Environmental Protection Agency (EPA) in 2005, WG accounted for 12.5 million tons of municipal solid waste in the USA, with only 18.8% being recycled (Parihar, Garlapati and Ganguly, 2019; Rivera, et al., 2018). In 2006, the percentage of recycled WG in the USA increased to 22%. According to the EPA report in 2018, 12.3 million tons of WG was generated in the USA

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which consists of 4.2% of municipal solid waste, of which only 3.1 million tons were recycled. However, according to the National Waste Report in 2020, Australia generated 1.16 million tons of WG from 2018 to 2019 with only 57% to 59% was recycled (Naeini, et al., 2019; Parera, et al., 2022). It was reported that 180 million tons of glass is produced every year and this quantity continues rising at the rate of 2 % to 4 % yearly (Bilgen, 2020a). Glass is produced in different forms: container or packaging glass (e.g., jars and bottles); flat glass (e.g., windows and windscreens); bulb glass (e.g., light globes); and cathode ray tube glass (e.g., TV screens and monitors) (Shayan and Xu, 2004; Siddique, 2007). Among all the glass materials, flat glass and container glass cover nearly 90% of the worldwide manufactured glass. Only approximately 20% of 90% of waste flat and container glass materials has been recycled, in other words, approximately 70% of the manufactured waste flat and container glass is disposed of as waste materials in landfills (Bilgen, 2020a; Rivera, et al., 2018). This situation is even worse in the Iraqi Kurdistan region because there is no factory for recycling waste. As a result, massive waste materials are thrown away yearly (Aziz, et al., 2011). In addition, this practice has undesirable environmental effects (Olofinnade, et al., 2018; Rashad, 2014).

Actually, some waste materials like WG have favorable properties, such as durability, high resistance, and strength, which can provide economic and environmental benefits when they are used for the construction of highways and structure foundations (Igwe and Adepehin, 2017; Zhang, Korkiala-Tanttu and Borén, 2019). For example, WG can be used to stabilize clayey soils and reduce negative impacts on the environment and waste degradation (Ibrahim, Mawlood and Alshkane, 2019). WG has been used in various forms for soil stabilization purposes including WG powder. The study (Bilgen, 2020b) showed that using WG powder for soil stabilization is the most economical way among other ways of recycling all WG.

A. Objective and Significance of the Research

Table I lists the published articles on the effects of WG on the characteristics of various treated problematic soils reviewed in this study. Table II shows that very few reviews on the use of WG in soil stabilization are available in the literature. Mohajerani, et al. (2017) reviewed the uses of crushed WG, glass powder, and foamed WG to improve the properties of base and subbase materials. They also found that crushed WG could be used as an aggregate alternative in asphalt mixtures. In addition, Mohajerani, et al. (2017) determined the optimum ratio of glass to aggregate used in the mixture to have appropriate performance and durability of the mixture. Rai, Singh and Tiwari (2020) conducted a comparative investigation of the engineering properties of a soil mixed with varying percentages of WG powder.

Perera, et al. (2021) reviewed the application of glass in base, subbase, and subgrade and assessed the effects of glass powder, glass fibers, foamed glass, WG aggregates, fine to coarse recycled glass, and glass geopolymers with various particle sizes on the properties of these soils, such as maximum dry density (MDD), optimum moisture content (OMC), unconfined compressive strength (UCS), California bearing ratio (CBR), resilient modulus, swelling-shrinkage, direct shear strength, and triaxial shear strength.

However, a comprehensive review of the effect of WG powder with particle sizes smaller than 4.75 mm on problematic subgrade soils has not been conducted yet based on the recent publications from 2013 to 2021. Therefore, the objective of this study is to fill the above gap. Table III shows the differences between the present study and the published literature by Perera, et al. (2021), in terms of the reviewed papers and the particle size of WG. Table III shows that only a few papers (in bold fonts) were used by these two review papers. This study reviewed the effect of WG powder on the physical and mechanical properties of subgrade soil including: Atterberg limits (liquid limit [LL], plastic limit [PL], and plasticity index [PI]), linear shrinkage (LS)/swelling, MDD, OMC, UCS, and CBR. In addition, pavement thickness design based on the CBR value of subgrade treated with WG has not been well considered yet.

II. Types, Preparation, and Utilization of WG for Soil Stabilization

Glass is produced from melting limestone, dolomite, sand, sodium sulfate, and soda at 1500–1600°C. Various techniques, such as cast rolling, rolling, blowing, flotation, and pressing, are used to obtain the most desired forms of glass. Some glass forms need cutting, tempering, and coloring (Chesner, et al., 2012). Several forms of WG have been produced, researched, and applied in the practice, such as glass powder (Bilgen, 2020b; Mohajerani, et al., 2017; Rai, Singh and Tiwari, 2020), waste soda lime (Canakci, Aram and Celik, 2016), fine to coarse recycled glass (Disfani, et al., 2011), recycled crushed glass, foamed glass, glass fibers, and glass geopolymers (Alqaisi, Le and Khabbaz, 2019). Most of these WG materials are produced from damaged windows of demolished buildings (Sharma and Bhardwaj, 2018) and drinking containers (Olufowobi, et al., 2014). Soda-lime glass is the most obtainable type of WG. The main uses of waste soda lime glass are in bottles and jars, tableware, and flat glass (Siddique, 2008). The chemical compositions of waste soda lime glass are as follows; SiO_2 (70–75%), Al_2O_3 (1.3–2%), CaO (9.1–10.5%), and Na_2O (13–14.4%) (Canakci, Aram and Celik, 2016; Siddique, 2008). WG is crushed in a crusher machine and then thoroughly powdered in a planetary mill passing a No. 200 sieve. Particles passing the No. 200 sieve (i.e., smaller than 75 μm) have been used as a source material for soil stabilization and geo-polymerization. Finally, the glass powder should be uniformly mixed for required tests (de Jesús Arrieta Baldovino, et al., 2020). Table I provides the information about soil type, WG type, content, waste size, and properties investigated in the past studies.

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TABLE I
UTILIZATION OF WASTE GLASS IN POOR SOILS

References	Soil type	Waste or binder type	Content of waste or binder (%)	Optimum content of waste glass (%)	Waste size (mm)	Properties of waste
Blayi, et al., 2020	Low- plasticity clay	Glass powder	2.5, 5, 10, 15, and 25	15	<0.250	G_s=2.55
Bilgen, 2020a	Clayey soil	Glass powder	10, 20 and 25		<0.425	G_s=2.57
de Jesús Arrieta Baldovino, et al., 2020	Silty soil	Glass powder	5, 15, and 30		<0.075	G_s=2.40, Cu=5.43, Cc=1.09 and D50=0.015 mm
Bilgen, 2020b	Clayey soil	Glass powder Lime	10, 20 and 25 5		<0.425	
Arrieta Baldovino, et al., 2020	Silty soil	Glass powder Cement	5, 15, and 30 3, 6, 9		<0.075	G_s=2.40
Ibrahim, Mawlood and Alshkane, 2019	Clayey soil	Glass powder	6, 12, 18, 27, and 36	18	<0.075	G_s=2.52
Siyab Khan, Tufail and Mateeullah, 2018	Loose subsoil (CL-ML)	Glass powder	4, 8, and 12		<0.075	G_s=2.56
Adetayo, et al., 2021	Fine sand and silty or clayey gravel sand	Glass powder Cow Bone Ash	1, 2, 3, 4, and 5 1, 2, 3, 4, and 5		<0.075	
Canakci, Aram and Celik, 2016	Clayey soil	Waste soda lime glass	3 , 6 , 9, and 12		<0.075	
Sharma and Bhardwaj, 2018	High-plasticity clay	Glass waste Construction and demolition waste	3, 5, 7, and 9 12, 16, 20, and 24		<4.75 <4.75	
Parihar, Garlapati and Ganguly, 2019	Clayey soil	Waste soda lime glass	3, 6, 9, and 12		<0.425	
Bilondi, Toufigh and Toufigh, 2018a	Low-plasticity clay	Glass powder	3, 6, 9, 12, 15, 20, and 25	15	<0.075	
Fauzi, Djauhari and Fauzi, 2016	Clayey soil	Crushed glass and waste plastic	4, 8, and 12		<0.075	
Olufowobi, et al., 2014	Clayey soil (high and medium plasticity)	Glass powder Cement	1, 2, 5, 10, and 15 15		<0.075	G_s=2.5-2.9
Baldovino, et al., 2021	Sedimentary silty soil (with sand)	Glass Powder Lime	5, 15, and 30 5		<0.075	G_s=2.4
Güllü, Canakci and Al Zangana, 2017	Low-plasticity clay	Waste soda lime glass	3, 6, and 9		<0.150	
Kumar, et al., 2020	Clay, loam, and red soil	Crushed glass Reclaimed asphalt pavement	5 30, 50, 55, 60, 65		<4.75 <12.5, >4.75	G_s=2.51 G_s=2.63
Mujtaba, et al., 2020	Clayey soil	Glass powder	2, 4, 6, 8, 10, 12, 14		<4.75	G_s=2.70
Fauzi, Rahman and Jauhari, 2013	Clayey soil	Crushed glass Waste plastic bottle	4, 8, 12 4, 8, 12			G_s=0.96 G_s=2.53

G_s: Specific gravity, Cu: Coefficient of uniformity, Cc: Coefficient of curvature, D50: Mean particle size

III. Evaluated Soil Properties

This study presented the physical properties (e.g., LL, PL, PI, LS, swelling, and MDD) and the mechanical properties (e.g., CBR, and UCS) of WG powder treated soils in the literature, as summarized in Table IV. In the reviewed studies, the soil was dried and sieved. Subsequently, the soils were mixed with WG. Grain-size analysis, Atterberg limits, MDD, OMC, and swelling tests were conducted following the ASTM standard. In addition, CBR and UCS also were carried out according to ASTM standards; the studies used modified mold for UCS tests.

IV. Results and Discussions

This study evaluated the physical and mechanical properties of different soils treated by the WG in the literature. The effects of WG on the soil property changes are discussed below.

A. Effects on Soil Physical Properties

Atterberg limits and LS

Atterberg limits (e.g., LL, PL, and PI), LS, and swelling are basic indices to describe soil behavior with moisture (Parihar, Garlapati and Ganguly, 2019). These limits can be used to evaluate soil plasticity characteristics and deformation behavior of treated and untreated soils (Blayi, et al., 2020). These indices of soils (e.g., clayey soils) can be changed by adding WG and will be discussed below.

LL

LL is a basic property for fine-grained soils, which is defined as a boundary moisture content of the soil to distinguish its liquid and plastic states. Adding WG to fine-grained soils is expected to influence the LLs of the soil. Fig. 1 shows the effect of WG on the LL ratios of fine-grained soils. The LL ratio is defined as the ratio of the LL of the soil after treatment to that before treatment. Fig. 1 shows a general trend that an increase in the WG content

TABLE II
Comparison Between Review Articles And The Current Review Study On The Use Of WG For Soil Stabilization

References	Published year of reviewed articular	Papers reviewed	Pavement layer	Replacement/ addition	Specific gravity	Chemical composition (%)	Physical properties	Mechanical properties
Mohajerani, et al., 2017	2012–2019	8	Base and subbase	Crushed WG	2.4–2.8	SiO_2=(32-75), Ai_2O_3=(0.5–24.5), Na_2O=(0.5–17), CaO=(2-10), MgO=(0.1–10.5)	Particle Size Distribution, MDD, OWC	Los Angeles abrasion test, CBR, modified compaction test, direct shear, and UCS
Rai, Singh and Tiwari, 2020	2016–2019	5	subgrade	Glass Powder Waste	2.62		PL, LL, PI, MDD, OMC	Proctor test, UCS, CBR
Perera, et al., 2021	1996–2021 1999–2021	29 29	Base and Subbase Subgrade	Glass powder, Glass fibres, Foamed glass, Glass aggregates (WG), (fine, medium, coarse) recycled glass, and Glass geopolymers	1.3–14.79	SiO_2 = 72.58, Ai_2O_3 = 1.48, Na_2O = 12.54, CaO = 10.49	Specific gravity, bulk density, index of flakiness, particle size distribution, water absorption, permeability, pH value	Compaction , Direct Shear, Triaxial shear, Resilient Modulus, Swelling-Shrinkage, UCS and CBR
Current study	2014–2021	19	Subgrade	WG (WG powder, crushed glass)	0.96–2.7	SiO_2=(63-81), Ai_2O_3=(0.4–2.61), Na_2O=(4-17), CaO=(0.26–13.3), MgO = (0.2–3.89)	LL, PL, PI, LS, MDD, and OMC	UCS, and CBR

WG: Waste glass, UCS: Unconfined compressive strength, CBR: California bearing ratio, LL: Liquid limit, PL: Plastic limit, PI: Plasticity index, LS: Linear shrinkage, MDD: Maximum dry density, OMC: Optimum moisture content

TABLE III
Variations Between the Current Review and the Published Review (Perera, *et al.*, 2021) of using Waste Glass on Subgrade Soil (2013–2021)

Year	Current study		Study (Perera, et al., 2021)	
	Paper reviewed	Waste glass particle size (mm)	Paper reviewed	Waste glass particle size (mm)
2013	Fauzi, Rahman and Jauhari (2013)	-	Fauzi, Rahman and Jauhari (2013)	-
2014	Olufowobi, et al. (2014)	<0.075		
2016	Canakci, Aram and Celik (2016)	<0.075	Canakci, Aram and Celik (2016)	<0.075
	Fauzi, Djauhari and Fauzi (2016)	<0.075	Ateş (2016)	l=4, w=2, t=0.4
2017	Güllü, Canakci and Al Zangana (2017)	<0.150	Patel and Singh (2017a)	d=0.15
			Patel and Singh (2017b)	l=10,20,30
2018	Sharma and Bhardwaj (2018)	<4.75	Bilondi, Toufigh and Toufigh (2018a)	<0.075
	Siyab Khan, Tufail and Mateeullah (2018)	<0.075	Bilondi, Toufigh and Toufigh (2018b)	<0.075
	Bilondi, Toufigh and Toufigh (2018a)	<0.075		
2019	Parihar, Garlapati and Ganguly (2019)	<0.425	Arulrajah, et al. (2019)	1.5
	Ibrahim, Mawlood and Alshkane (2019)	<0.075	Onyelowe, et al. (2019)	10
			Patel and Singh (2019)	0.15
2020	Bilgen (2020a)	<0.425	Pacheco-Torres and Varela (2020)	≤10
	Bilgen (2020b)	<0.425	Blayi, et al. (2020)	<0.250
	de Jesús Arrieta Baldovino, et al. (2020)	<0.075	Mujtaba, et al. (2020)	<4.75
	Blayi, et al. (2020)	<0.250	Sujatha, et al. (2020)	l=12, d=0.019
	Arrieta Baldovino, et al. (2020)	<0.075	Más-López, et al. (2020)	≤40
	Kumar, et al. (2020)	<4.75	Patel and Singh (2020)	l=20, d=0.15
	Mujtaba, et al. (2020)	<4.75		
2021	Adetayo, et al. (2021)	<0.075	Yaghoubi, et al. (2021)	≤4.75
	Baldovino, et al. (2021)	<0.075	Rabab'ah, et al. (2021)	l=30

l: Length of glass fiber, w: Width, t: Thickness, d: Diameter.

reduced the LL of the soil. Blayi, et al. (2020) used five WG contents (2.5%, 5%, 10%, 15%, and 25%) and found that when the WG content increased by 25%, the LL of the soil decreased from 44.10% to 22.19%, that is, by approximately 50% reduction ([(22.19–44.10 %)/49.19%]*100). Bilgen (2020a) investigated the influence of WG on three different types of soil (Alapli clay soil, Eregli clay soil, and Bentonite clay soil). This research showed that an increase in the WG content from 10% to 25% reduced LL by 14.3%, 12%, and 8.8%, respectively, for these three types of soil. Ibrahim, Mawlood, and Alshkane (2019) also showed that when the WG content increased by 0%, 6%, 12%, 18%, 27%, and 36 %, the LLs of the soil decreased by 50.93%, 48.97%, 46.90%, 41.92%, 39.96%, and 38.84%. This change is equivalent to a 23.7% reduction in the LL ratio of the soil when 36% WG was added, as shown in Fig. 1. This reduction in LL is due to lower water absorption properties of WG particles compared to that of the clay particles.

Fig. 1 shows a decreasing trend with the WG content (red line) since WG works as an inner material and its particles' ability to absorb water is less than soil particles. In addition, all studies in Fig. 1 used clayey soils with specific gravity

TABLE IV
Physical and Mechanical Properties of Soils Treated By Waste Glass Powder In The Literature

Referernces	Physical properties							Mechanical properties	
	LL (%)	PL (%)	PI (%)	LS (%)	Swelling (%)	Compaction test		UCS (kPa)	CBR (%)
						OMC (%)	MDD (g/cm^3)		
Blayi, et al., 2020	✓	✓	✓	✓	✓	✓	✓	✓	✓
Bilgen, 2020a	✓	✓	✓			✓	✓	✓	✓
de Jesús Arrieta Baldovino, et al., 2020	✓	✓	✓			✓	✓		
Bilgen, 2020b	✓	✓	✓			✓	✓	✓	✓
Arrieta Baldovino, et al., 2020	✓	✓	✓			✓	✓	✓	
Ibrahim, Mawlood and Alshkane, 2019	✓	✓	✓	✓	✓	✓	✓	✓	
Siyab Khan, Tufail and Mateeullah, 2018	✓	✓	✓			✓	✓		✓
Adetayo, et al., 2021	✓	✓	✓			✓	✓		✓
Naeini, et al., 2019						✓	✓		✓
Canakci, Aram and Celik, 2016	✓	✓	✓		✓	✓	✓	✓	✓
Sharma and Bhardwaj, 2018	✓	✓	✓			✓	✓	✓	
Parihar, Garlapati and Ganguly, 2019	✓	✓	✓			✓	✓		✓
Bilondi, Toufigh and Toufigh, 2018a	✓	✓				✓	✓	✓	
Fauzi, Djauhari and Fauzi, 2016	✓	✓	✓			✓	✓		✓
Olufowobi, et al., 2014	✓	✓	✓			✓	✓		✓
Baldovino, et al., 2021	✓	✓	✓			✓	✓	✓	
Güllü, Canakci and Al Zangana, 2017	✓	✓	✓			✓	✓	✓	
Kumar, et al., 2020						✓	✓		✓
Mujtaba, et al., 2020	✓	✓	✓		✓	✓	✓	✓	✓
Fauzi, Rahman and Jauhari, 2013	✓	✓	✓			✓			

UCS: Unconfined compressive strength, CBR: California bearing ratio, LL: Liquid limit, PL: Plastic limit, PI: Plasticity index, LS: Linear shrinkage, MDD: Maximum dry density, OMC: Optimum moisture content

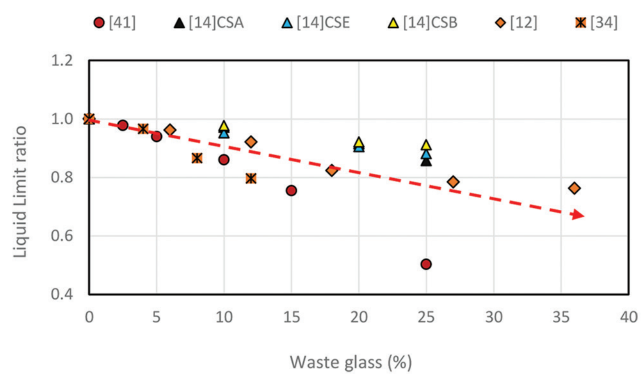

Fig. 1. Liquid limit ratios of soils treated with waste glass.

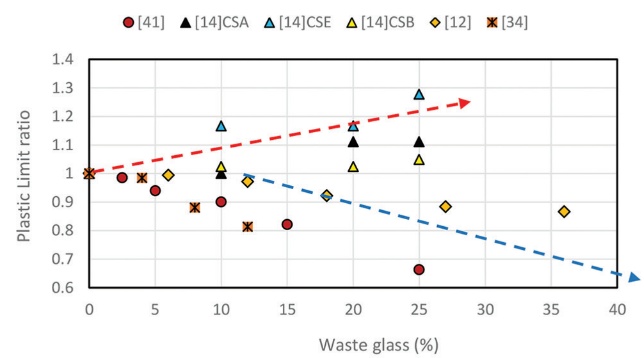

Fig. 2. Plastic limit ratios of treated soils from the literature.

between 2.51 and 2.74, particle sizes of WG between 0.075 and 0.425 mm, and the silica content of WG between 70.2% and 72%. It is noticed that the decrease in LL in the study (Blayi, et al., 2020) is more significant and affected by the addition of WG as compared to that in other studies. The reason behind this difference is due to the quality and accuracy of the test procedure by studies.

PL

Fig. 2 shows the collected data from the previous research on the effect of WG on the PL (PL) ratios of fine-grained soils. The PL ratio is defined as the ratio of the PL of the soil treated by WG to that without any WG. Fig. 2 shows two different trends: (1) The use of WG reduced PL and (2) the use of WG increased PL. The study (Blayi, et al., 2020) indicated that the PL of low-plasticity clay was 24.81% and WG at different contents reduced PL. When the WG content was increased by 25%, the PL was reduced by 16.44% due to a large amount of silica in WG, which is equivalent to nearly 34% loss in the PL for this soil [i.e., (16.44 - 24.81)/24.81*100%]. Bilgen (2020a) evaluated three soils treated at WG contents of 0%, 10%, 20%, and 25% and found that the use of WG at 25% increased PL by 11%, 28%, and 5%, respectively, for Alapli, Eregli, and Bentonite clayey soils. Ibrahim, Mawlood, and Alshkane (2019) reported that the use of WG at different contents of 0%, 6%, 12%, 18%, 27%, and 36% reduced PL by a maximum of 13.4% (i.e., from 22.5% to 19.5%). However, PL changed slightly when the WG content was more than 18%, in other words, adding 27% and 36% WG led to a less significant change in PL for the clayey soil.

Fig. 2 shows both increase (red line) and decrease (blue line) trends. The increased trend due to the addition of WG is related to its independence of the percentage of additives but dependence on the clay type (Ahmed, Swindale and EL-Swaify, 1969). However, the reason for the decreasing trend of PL is that WG acts as a non-plastic material due to a large amount of silica in the content of WG.

PI

Fig. 3 shows the collected data from the literature about the effect of WG on the PI ratios for fine-grained soils. The PI ratio is defined as the ratio of the PI of the soil treated by WG to that without any WG. Fig. 3 clearly shows that all the PI ratios except for one are below 1.0, indicating PI decreases with the addition of WG and the increase of the WG content. Blayi, et al. (2020) indicated that the PI decreased from 19.5% to 6.3% (i.e., 68% reduction) ([(6.3 %-19.5%)/19.5%]*100) as the WG content increased from 2.5% to 25%. Bilgen (2020a) reported that the increase of the WG content from 0% to 25% reduced their PIs by 41.2%, 41.7%, and 12.1%, respectively, for Alapli, Eregli, and Bentonite clayey soils. Ibrahim, Mawlood, and Alshkane (2019) found that the increase of the WG content from 0% to 36% reduced the soil PI from 28.5% to 19.5% (i.e., nearly 32% reduction). A similar result was obtained by Canakci, Aram and Celik (2016), in which they showed that WG at the contents of 3%, 6%, 9%, and 12% with a clayey soil reduced their plastic indices by 13.13%, 12.29%, 11.38%, and 10.04% (i.e., a maximum 44% deduction). The reduction of the plasticity indices of soils treated by WG is attributed to the fact that WG is a cohesionless material due to a large amount of silica (a non-plastic material) (Ibrahim, Mawlood and Alshkane, 2019).

This decreasing trend in PI in all studies due to the addition of WG is related to the cohesionless behavior of WG.

LS

Fig. 4 shows the collected data from two past studies about the effect of WG on the LS ratios of soils. The LS ratio is defined as the ratio of the LS of the soil treated by WG to that without any WG. Fig. 4 clearly shows that adding WG to soils reduced their LS ratios. For example, in the study (Blayi, et al., 2020), the LS of the natural soil was 9.1% and decreased by 8.7%, 8.0%, 7.0%, 5.5%, and 2.8%, respectively, when the WG content was increased by 2.5%, 5%, 10%, 15%, and 25%. These results indicate that the maximum percentage reduction in the LS was 69% (i.e., [2.8−9.1]/9.1*100%) when 25% of WG was added (Blayi, et al., 2020). Ibrahim, Mawlood, and Alshkane (2019) also found that, as the WG content increased from 0% to 36%, the LS decreased from 13.4% to 9.0% (i.e., a 33% reduction in the LS).

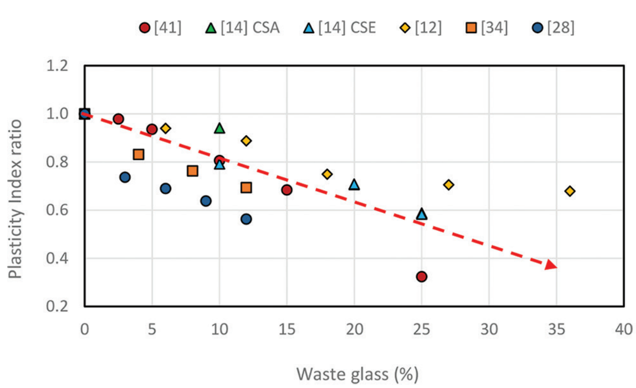

Fig. 3. Plasticity indices of soils treated by waste glass from the literature.

Fig. 4 shows that the results in Ibrahim, Mawlood and Alshkane (2019) were less affected by WG as compared with those in Blayi, et al. (2020) because the soil in the study (Ibrahim, Mawlood and Alshkane, 2019) was a high plasticity clay while that in the study (Blayi, et al., 2020) was a low plasticity clay. Hence, the LS of the low-plasticity clay decreased more.

MDD and OMC

MDD and OMC of soil with or without any treatment by additives can be determined by compaction tests. Compacted specimens can also be used to determine their UCSs and CBRs. Compaction tests can provide valuable information about the quality of compacted soil and help evaluate the suitability of the soil for construction and service.

Fig. 5 shows the collected data for the MDD ratios of soils treated by WG from the literature whereas Fig. 6 shows their OMC ratios. The MDD or OMC ratio is defined as the ratio of the MDD or OMC of soil treated by WG to that without any WG. Figs. 5 and 6 show that MDD increased but OMC

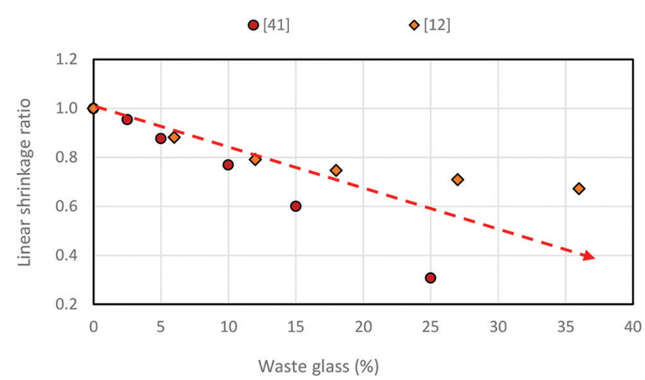

Fig. 4. Linear shrinkage ratios of soils treated by waste glass from the literature.

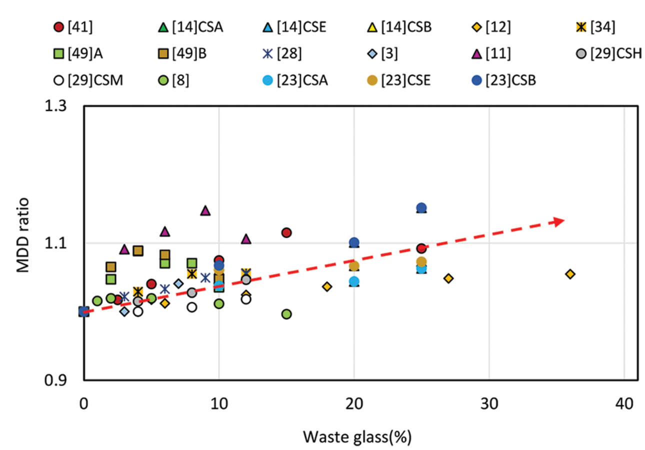

Fig. 5. Maximum dry density ratios of compacted soils treated by waste glass from the literature.

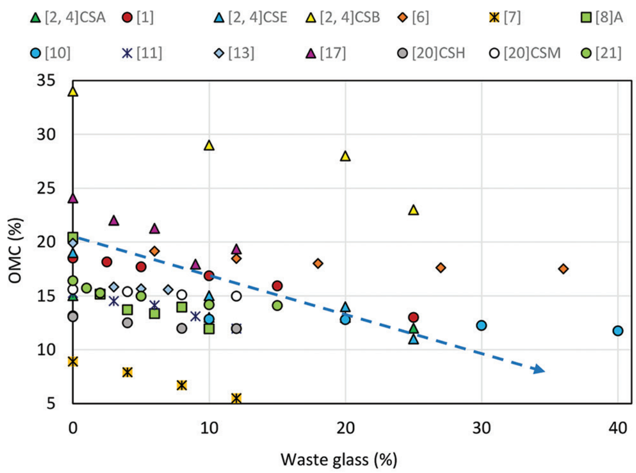

Fig. 6. Optimum moisture content ratios of compacted soil treated by waste glass from the literature.

decreased as the WG content increased. Ibrahim, Mawlood, and Alshkane (2019) investigated the effect of WG using different WG contents (6%, 12%, 18%, 27%, and 36%) in soils on their MDDs and OMCs and found that adding WG resulted in a maximum increase of MDD by 5.5% and a maximum reduction of OMC by nearly 15%. Bilgen (2020a) found that as the WG content increased from 0% to 25%, the MDD increased by approximately 5%, 7%, and 16%, but the OMC decreased by nearly 20%, 42%, and 32%, respectively, for Alapli, Eregli, and Bentonite clayey soils. Bilgen (2020b) use the same soils that used by the study (Bilgen, 2020a) with addition of 5% of cement. The results show that an increase of WG by 25% increased the MDD by 6%, 7%, and 15% and reduced the OMC by 11%, 32%, and 18%, respectively, for Alapli, Eregli, and Bentonite clayey soils. Canakci, Aram, and Celik (2016) found that the increase of the WG content from 0% to 12% reduced the MDD of the soil by more than 5% but reduced the OMC by nearly 22%. Parihar, Garlapati, and Ganguly (2019) investigated the effect of WG with different contents of 0%, 3%, 6%, 9%, and 12% (same as those in the study [Canakci, Aram and Celik, 2016]) and found that adding 9% WG to the soil increased its MDD by 14.7% but reduced its OMC by 25.6 %. Blayi, et al. (2020) used different WG contents of 0%, 2.5%, 5%, 10%, 15%, and 25 % in soils and found that the increase in the WG content from 0% to 25% led to a decrease in the OMC from 18.5% to 13% and an increase in the MDD from 1.74 g/cm3 to 1.94 g/cm3, which are equivalent to nearly 30% reduction in the OMC and more than 9% increase in the MDD when the WG content increased from 0% to 25%. Adetayo, et al. (2021) conducted field tests with two test pits (Pits A and B) at different depths (1.5 m and 1.25 m, respectively) to evaluate the effect of WG and Cow Bone Ash and found that the MDD of the treated soil in Pit A was increased by 8.8% (from 1.7 to 1.85 g/cm3) by adding 4% WG and Cow Bone Ash. However, a further increase in the WG and Cow Bone Ash content (e.g., 8%) in the soil reduced the MDD from 1.85 to 1.76 g/cm3 (the same result obtained by [Kumar, et al., 2020]). The increase in MDD in some studies after an increase in the percentage of WG in clay soils may be attributed to an increase in the voids within the soil structure, which reduces the MDD of the WG-soil mixture (Salpadoru Tholkamudalige, et al., 2022). In Pit B, the MDD increased from 1.69 to 2.87 g/cm^3 when the WG and Cow Bone Ash increased from 0% to 8%, but decreased to 1.77 g/cm3 when the WG and Cow Bone Ash content increased to 10% (i.e., nearly 5% increase in the MDD). In addition, the OMC decreased by 1.7% (from 17.01% to 16.73%) when the WG and Cow Bone Ash content increased from 0% to 10% (same as those in the study [Fauzi, Rahman and Jauhari, 2013]). The above discussion shows that adding WG into a soil increased its MDD and reduced its OMC. The increase in the MDD is attributed to the fact that WG has a higher density than clayey soils whereas the reduction in the OMC is attributed to the fact that WG has a lower absorption than clayey soils (Nuruzzaman and Hossain, 2014). In addition, the fineness of WG plays an important role (de Jesús Arrieta Baldovino, et al., 2020).

The increase of MDD with the WG content in Fig. 5 can be explained as WG is a cohesionless material that makes particles more easily rearranged into a dense state. The decrease of OMC with the WG content in Fig. 6 can be explained as WG having a lower water absorption ability.

Swelling

The percentage of expansion at a stable pressure of 1 kPa is known as free swelling (Ibrahim, Mawlood and Alshkane, 2019). Fig. 7 shows the collected data for the swelling ratios of soils treated by WG from the literature. The swelling ratio is defined as the ratio of the swelling of soil treated by WG to that without any WG. Mujtaba, et al. (2020) reported the influence of WG on the swelling of expansive soil. The study shows that increasing WG by 14 % reduced the percentage of swelling from 4% to 0.5 %. Blayi, et al. (2020) investigated the effect of WG on the swelling of expansive clayey soil and found that increasing WG by 25% reduced free swelling from 5.28% to 0.88% (i.e., 83.3% reduction in swelling). Canakci, Aram and Celik (2016) also observed that, the swelling of the soil with 0% WG was 5.51% and reduced by 4.5, 3.1, 2.02, and 1.65% as the WG content was increased by 3, 6, 9, and 12%. Ibrahim, Mawlood, and Alshkane (2019) examined WG's impact on the swelling of high-plasticity clayey soil and found that increasing WG from 0% to 36% reduced the swelling by 50.7%. In general, as the WG content increases in expansive soils, their swelling decreases due to the cohesionless behavior of WG. Furthermore, the reason for decrease in swelling is the breakdown of the bond between clay particles (clay-clay) and clay with water (clay – double diffused layer of water) breakage and replaced with clay-silica bonds along with enhancing particle packing (Parihar, Garlapati and Ganguly, 2019).

B. Effect on Soil Mechanical Properties

UCS

Fig. 8 shows the collected data for the UCS ratios of soils treated by WG from the literature. The UCS ratio is defined as the ratio of the UCS of soil treated by WG to

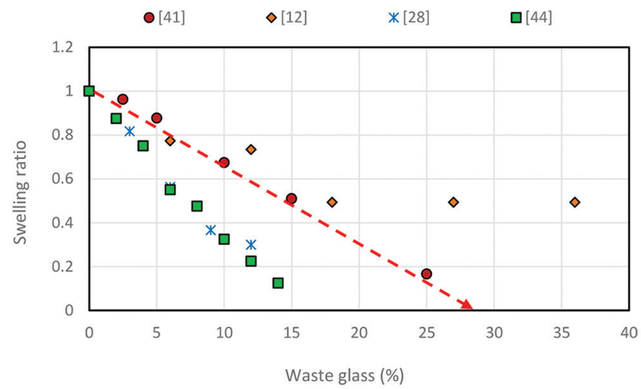

Fig. 7. Swelling ratios of compacted soil treated by waste glass from the literature.

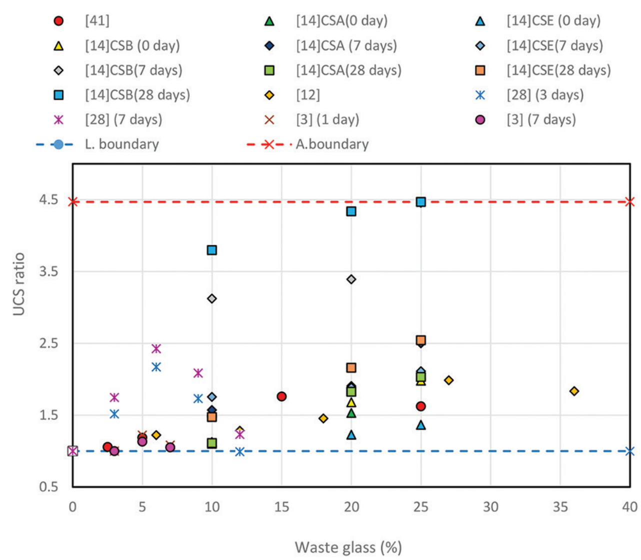

Fig. 8. Unconfined compressive strength ratios of soils treated by waste glass from the literature.

that of native soil (without any WG). Fig. 8 shows that UCS generally increased as the WG content increased. Sharma and Bhardwaj (2018) conducted UCS tests on a high-plasticity clay treated by WG at three different contents (3%, 5%, and 7%) at curing ages of 1, 7, and 28 days and found that as the WG content increased, the UCS increased. For example, adding 3% WG to the soil increased UCS from 303 kPa at 1 day, 678 kPa at 7 days, and 1155 kPa at 28 days of curing. Adding 5% WG to the soil increased the UCS to 371, 678, and 1239 kPa at 1, 7, and 28 days of curing, respectively. However, when 7% WG was used, the increase of UCS became less, 329, 713, and 1193 kPa at 1, 7, and 28 days of curing, respectively. The above changes in UCS at three curing ages can also be expressed as a percentage increase, for example, more than 13%, and 22% increase in USC at the WG content of 3%, and 5%. Blayi, et al. (2020) examined the effect of various percentages of WG (i.e., 0% to 25% of WG by dry weight of native soil) on UCS. They reported that as the WG content increased from 0% to 15%, its UCS increased from 205 to 360 kPa. However, with a further increase in the WG content (e.g., 25%), its UCS decreased to 332 kPa. The decrease in the UCS by adding an extra amount of WG might be due to the reduction of its cohesion due to the high amount of silica in WG (Ibrahim, Mawlood and Alshkane, 2019).

Bilgen (2020a) also investigated the effect of WG on USCs for three types of soil: Alapli, Eregli, and Bentonite clayey soils at different curing ages and found the UCS increased by 106%, 150%, and 103%, 36%, 111%, and 154%, and 97%, 345%, and 346% at 1, 7, and 28 days of curing, respectively. Ibrahim, Mawlood, and Alshkane (2019) evaluated the properties of soils mixed with WG at five different contents (6%, 12%, 18%, 27%, and 36%). They found that as the WG content increased by18%, the UCS increased by more than 45%. When the WG content increased from 18% to 27%, the UCS increased from 410 to 565 kPa. However, the WG content increased from 27% to 36%, the UCS decreased to 517 kPa. Canakci, Aram and Celik (2016) found that as the WG content increased by 6%, the UCS increased by nearly 117%, from 238 to 518 kPa; however, at the WG contents of 9% and 12%, the UCSs were 412 and 236 kPa, respectively, at 3 days of curing.

Fig. 8 shows that an increase of the WG content generally increased the UCS ratio and different soils had different responses to the WG content. The soil with high plasticity (e.g., the Bentonite clay in the study (Bilgen, 2020a)) had the highest UCS ratio.

CBR

CBR is an essential geotechnical engineering parameter for evaluating subgrade and base course strengths and stiffness for pavement design including the determination of pavement thicknesses (Adetayo, et al., 2021; Siyab Khan, Tufail and Mateeullah, 2018). The typical range for CBR value of a subgrade layer is in the range of 2% to 12% [59]. Fig. 9 shows the collected data for the CBR ratios of soils treated by WG from the studied literature. The CBR ratio is defined as the ratio of the CBR of soil treated by WG to that without any WG. Fig. 9 shows that CBR generally increased as the WG content increased. Canakci, Aram and Celik (2016) investigated the effect of WG on the CBR value of the soil treated by WG at different contents (e.g., 3%, 6%, 9%, and 12%) and found that adding 12% WG to a clayey soil increased its CBR value by nearly 143%. Siyab Khan, Tufail and Mateeullah (2018) also showed that an increase of the WG content from 0% to 12% increased the CBR by 59% (i.e., more than 32% increase). Consequently, Blayi, et al. (2020) concluded that an increase in the WG content from 0% to 15% increased the CBR by 12.2%; however, with a further increase in the WG content to 25%, the CBR decreased to 10.8%. Blayi, et al. (2020) also concluded that the optimum WG content was 15%. Bilgen (2020a) showed that an increase in the WG content from 0% to 25% increased the CBR value by a lot and curing periods also affected the CBR of the treated soil. The results showed that, for immediately tested samples when 25% WG was added, the CBR increased by approximately 167%, 191%,

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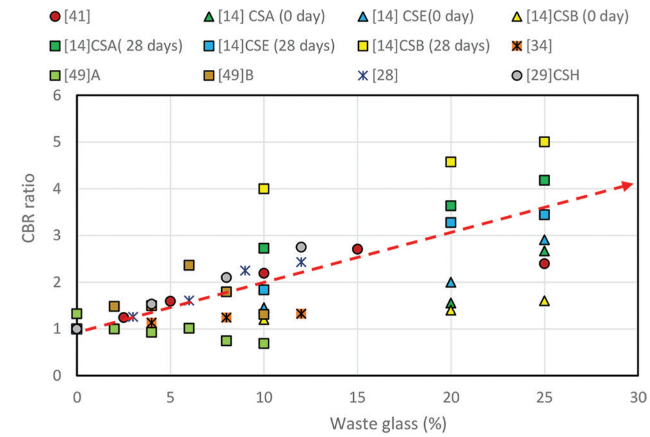

Fig. 9. California bearing ratio ratios of soils treated by waste glass from the literature.

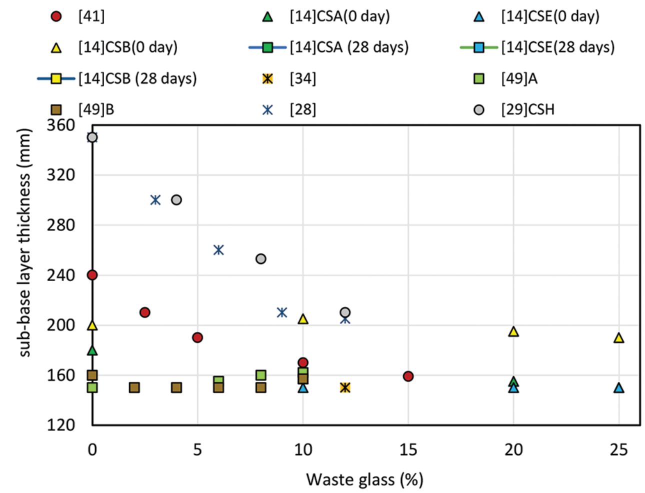

Fig. 10. Subbase thicknesses for subgrade soils treated by waste glass from the literature.

and 60%, respectively, for Alapli, Eregli, and Bentonite clayey soils. Consequently, after 28 days of curing, the CBR of soils treated with 25% WG increased by more than 318%, 244%, and 400% respectively, for Alapli, Eregli, and Bentonite clayey soils. Adetayo, et al. (2021) reported that an increase of the WG content by 10% increased the CBR value by 38% and 31%, respectively, for soil in pit A and soil in pit B.

V. Effect on Pavement Thickness Design

A design manual for roads and bridges (HD 26/06, 2006) provides the details needed to determine the thicknesses of capping and subbase layers of pavements based on subgrade CBR. This design manual suggests that, for a subgrade with a CBR equal to or greater than 15%, only a 150 mm thick sub-base is needed; however, for a subgrade with a CBR value lower than 15%, a capping layer of variable thickness is needed. Therefore, determination of the thicknesses of capping and subbase layers depends on the CBR of the subgrade. Blayi, et al. (2020) showed that adding 15% WG into a subgrade soil increased its CBR from 4.5% to 12.2%, thus reducing the subbase thickness from 240 to 150 mm; however, increasing the WG content to 25% increased the subgrade CBR to 10.8%, thus requiring a subbase thickness of 160 mm. Bilgen (2020a) reported that, adding 25% WG to Alapli, Eregli, and Bentonite clayey soils increased their CBRs from 9% to 24%, 11% to 32%, and 5% to 8%, respectively. As a result, their required sub-base thicknesses decreased from 180 to 150 mm, 160 to 150 mm, and 200 to 190 mm, respectively, as shown in Fig. 10. Canakci, Aram and Celik (2016) also reported that, increasing the WG content from 0% to 12% increased the subgrade CBR from 2.47% to 6%, which required a 150 mm subbase and a 235 mm capping layer. All these studies showed that an increase in the WG content increased the subgrade CBR, thus reducing the thicknesses of pavement layers.

VI. Conclusions

This paper reviewed the utilization and research results of WG for soil stabilization in the literature. The review focused on the effects of WG and its content on the physical and mechanical properties of treated soils and pavement thicknesses on treated subgrade soils. The following conclusions can be made from this study:

- The content of WG utilized for soil stabilization ranged from 2% to 25%.
- WG is composed of a high content of non-plastic silica, which generally reduces the Atterberg limits of soils after being mixed with WG.
- WG has low absorption property and when it is mixed with fine-grained soil, it reduces its OMC.
- WG powder is a cohesionless material. When an appropriate amount of WG is mixed with soil, it makes particles more easily rearranged to a dense state thus increasing its MDD and soil strengths, such as UCS and CBR. However, when an excessive amount of WG is used, it may reduce soil strength.
- Since the use of WG generally increases a subgrade CBR, it reduces the thicknesses of subbase and surface layers in pavements.

VII. Limitation

In recent years, the use of WG to enhance the geotechnical properties of problematic soils has been the subject of numerous studies. This assessment was limited to the impact of WG on subgrade soil in terms of its physical and mechanical properties. To gain a better understanding of the effect of WG on the durability, drainage, and deformation behavior of problematic soils, additional tests, such as freezing-thawing, one-dimensional consolidation, and direct shear tests, could be conducted. Furthermore, various types of glass and particle sizes (<4.75 mm) were investigated.

Therefore, there is a lack of utilization of specific categories of WG. The composition, particle size, and type of WG could potentially influence the properties of different soil types.

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