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Use of waste stone powder to improve the performance of problematic soils - A Review

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ABSTRACT

Problematic soils, especially clayey soil, are problematic for engineering projects in their natural state because of clay's swell-shrinkage phenomenon. Numerous methods and stabilizer materials have been used to enhance clay's geotechnical properties and make them appropriate for construction. One of the significant methods of stabilization of problematic soil is using waste materials like waste glass, waste stone, waste plastic, etc. Due to the waste stone's consistency reducing water content and increasing the soil's strength, it has been employed in many civil engineering studies. Waste stone is available in various forms, including waste stone powder (WSP). WSP is produced by blasting tunnels or cutting huge stone blocks. Hence, the main aim of this study is to review the influence of WSP on improving the geotechnical properties of problematic soils treated with WSP, for this purpose, the treated problematic soils with various percentages of WSP are compared with natural soils. This study evaluates physical properties (i.e., Index properties, linear shrinkage/swelling, optimum moisture content, and maximum dry density) and mechanical properties (i.e., unconfined compressive strength and California bearing ratio). Also, the effect of WSP on decreasing the thickness of pavement layers was reviewed.

1. Introduction

The problematic soils such as; expansive clay [1], [2], dispersive clay [3][4], marl soil [5], and collapsible soil [1],[6] are those whose volume increases when they become moist [7]. These soils are considered a natural risk to engineering construction as they can seriously harm lightweight structures and highway pavements [8]. There are significant issues with the stability of development structures due to the Middle East's problematic soils, particularly in the northeast and southeast of Iraq [9]; hence, improving soil geotechnical properties is essential [10]. In recent decades, because of new construction sites, the use of ground improvement techniques has grown significantly [11]. One of the significant techniques for enhancing soil properties is the stabilization process[12]. Soil stabilization refers to any method used to alter the qualities of natural soil to serve an engineering objective[13], whether it be mechanical, chemical[14]–[16], physical, biological, or a combination of these [16], [17]. The most important factors determining the stabilization method for problematic soils in construction projects are the type of soil foundation,

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the required time to complete the project, the stabilization cost relative to the project cost, and the full replacement cost of the problematic soils [18]. It is essential to know the characteristics of the soil prior to and after soil stabilization, and based on the soil's characteristics, an appropriate stabilizing material or stabilization technique should be chosen [16]. Several materials have been studied to improve soil, according to their suitability [19], including waste stone [20]–[22]. However, using certain materials often increases the construction cost; therefore, alternative, easily obtained, and cost-effective materials are needed [23].

Using waste materials in soil stabilization makes problematic soils more suitable in the construction projects and reduces the negative influence on the environment [24], [25]. Stone is an inorganic material; if it is not recycled, it might cause an environmental hazard. Therefore, it is crucial to use stone as a soil stabilizer [26]. One of the substituted alternative additives for improving problematic soil properties is waste stone powder (WSP), which is economical and environmentally friendly [27]–[29]. Granite and waste marble were made of natural stone [30], which can now be utilized as a filler for roads, concrete aggregates, and soil stabilizers when their particles are not larger than 100 microns [31]. WSP is a type of industrial quarry waste, which is also known as quarry dust, granitic sludge waste, or granite powder [20], [32], [33]. Also, marble and granite, which are types of stone powder, are mostly by-products of the manufacturing industries [34]. WSP is the main building material used for construction in many countries [35], such as; in the construction of homes, industries, and sewers [36], [37]. The cutting and finishing of stone buildings produces a significant volume of crushed limestone in Iraqi masonry factories [38].

Additionally, many factories in Erbil city in the Iraqi Kurdistan Region produce limestone powder for filler in the composition of asphalt mixture [39]. It can benefit from these factories for soil stabilization with a mix of crushed limestone by-product because a significant volume of stabilizer is needed [39].Waste stone could be used for different engineering purposes to reduce the negative impact of waste stone, one of them is using waste stone powder on improving the properties of problematic soils.

1.1. Objective and significance of the research

The published articles about the effect of different types of waste stone powder (WSP) on the soils reviewed in this study between 2005- 2023 are shown in Table 1.
However, there is a gap because there are no review articles about the effect of waste stone powder on the geotechnical properties of problematic soils. Hence, this study aims to determine the effect of various types of stone powder on the physical properties (e.g., Index properties, maximum dry density (MDD), optimum moisture content (OMC), and Swelling) and mechanical properties (e.g., unconfined compressive strength (UCS) and California bearing ratio (CBR)) of problematic soils.

2. Preparation and types of waste stone (WSP) in soil stabilization

Waste stone powder (WSP) is available in several forms, including stone powder [40], limestone powder [39], [41], [42], Waste marble dust [6], waste marble [43], Stone dust, [44], rock powder [45], and basalt stone powder [42]. Stone dust, also called crushed sand, is a kind of fine aggregate [44]. The WSP can be obtained from the collection of natural stones and crushing by crusher machine in the factories [45], or it can be obtained from a natural quarry [40], [41]. Waste stone with smaller particles than 0.075 mm stabilizes the soil [39]. Researchers investigated various percent of waste stones to stabilize problematic soils, as shown in Table 1.

Table 1. Utilization of waste stone powder in problematic soils.

Ref.	Soil type	Waste types	Waste content (%)	Optimum waste content (%)	Size of waste (mm)	Waste stone properties
[46]	Middle and low plasticity clay	Marble	5, 10, 15, 20	15		
[39]	High-plasticity clay	Waste stone	6,12, 18, 24, 30, 36	18	< 0.075	G_s = 2.71
[6]	Clayey silt (CL-ML)	Marble	5, 10, 15	10		
[44]	Clayey silt (CL-ML)	Waste stone	10, 20, 30		< 0.075	
[47]	Low plasticity clay (CL)	Waste stone	0, 20, 30, 40		0.425	
[45]	High plasticity silt (MH)	Waste stone	0, 8, 16, 24, 32, 40	24	< 0.075	G_s = 2.78
[18]	Expansive soil	Waste stone	10, 20, 30		< 0.075	
[40]	Clayey soil	Waste stone	0, 15, 30, 50, 70		> 0.075, 0.075-0.02 < 0.02	
[48]	High plasticity silt(MH), High-plasticity clay(CH)	Marble	5, 10, 20, 30, 50			
[43]	High plasticity clay (CH)	Marble	5, 10, 15, 20	5	0.3	
[49]	Sand	Waste stone	10, 20, 30			G_s= 2.59, D_{10}= 0.09, D_{30}= 0.19, D_{60}= 0.29, C_c= 1.37, C_u= 1.53. C= 0.08 Kg/cm^2
[50]	Sandy clay	Marble	2, 6, 10		< 0.425	
[51]	Clayey soil	Marble	5, 10, 20, 30, 50		< 0.100	
		Granite	5, 10, 20, 30, 50		< 0.100	
[52]	Clayey soil	Marble and granite	10, 20, 30		< 0.200	
[53]	Clayey soil	Waste stone	25		< 0.08	
[54]	Silty soil	Waste stone	10, 20, 30 40, 50			G_s = 2.85

Note: G_s= specific gravity, D_{10}, D_{30}, and D_{60} = effective size of particles, Cu= coefficient of uniformity, Cc= coefficient of curvature, L= fibre length, D= fibre diameter.

3. Evaluated properties of soil

This study reviewed the physical properties (i.e., liquid limit, plastic limit, plasticity index, linear shrinkage, maximum dry density, optimum moisture content, and free Swelling) and mechanical properties (i.e., California Bearing Ratio (CBR), and unconfined compressive strength (UCS)) of problematic soils treated with waste stone powder (WSP). Table 2 summarizes the physical and mechanical properties of WSP-treated soils studied by researchers.

Table 2. Summarized physical and mechanical properties of problematic soils**.**

Ref.	Physical properties							Mechanical properties	
	Liquid limit (%)	Plastic limit (%)	Plasticity index (%)	Linear shrinkage (%)	Swelling (%)	Compaction test		UCS (kPa)	CBR (%)
						OMC (%)	MDD (g/cm^3)		
[46]					✓				✓
[39]	✓	✓	✓	✓	✓	✓	✓	✓	
[6]					✓	✓	✓	✓	✓
[44]						✓	✓		✓
[47]								✓	
[45]	✓	✓	✓	✓	✓	✓	✓	✓	✓
[18]					✓	✓	✓		
[40]	✓							✓	
[48]									✓
[43]								✓	
[49]						✓	✓		✓
[50]	✓	✓	✓			✓	✓	✓	
[51]			✓			✓	✓		
[52]				✓					
[53]								✓	
[54]	✓	✓	✓	✓	✓			✓	✓

4. Result and discussion

The results of reviewed research are discussed in the following sections.

4.1 Effect of waste stone powder (WSP) on the physical properties of soil

4.1.1 Index properties

The index properties (i.e., liquid limit (LL), plastic limit (PL), plasticity index (PI), and linear shrinkage (LS)) of treated and untreated problematic soils are shown in Figures 1, 2, 3, and 4. The figures show that the index properties of problematic soil decrease by increasing various percentages of waste stone powder (WSP) in the soil mixture.

(a) Liquid limit (LL)

Liquid limit is an index to predict soil behaviour and types. Adding waste stone powder (WSP) to the soil decreases the LL of problematic soils. Ibrahim et al. [39] reported that adding 36% WSP to soil led to a decrease in LL by 19.8%, from 51% to 40.9% as shown in Figure 1 . Blayi et al. [45] studied the effect of various percentages of WSP (i.e., 8%, 16%, 24%, 32%, and 40%) on the LL of expansive soil. They observed that adding 40% WSP caused a decrease in LL from 53% to 28.54%. Cabalar and Omer [54] studied the effect of 10%, 20%, 30%, 40%, and 50% of WSP on the silty soil. They observed that the LL decreased from 35.6% to 26.94% when 5% of WSP was added. Consequently, as the WSP content in the soil mixture increases, LL decreases because the main constituent in WSP is calcium. Calcium ions displace soil cations, leading to a reduction in water content around the soil particles. As a result, water absorption in the WSP-soil mixture is reduced [39].

(b) Plastic limit (PL)

The plastic limit of soil is the water content, where the soil starts to act like plastic. The influence of WSP on the PL of problematic soils has been shown in Figure 2. Ibrahim et al.[39] studied that using WSP at different percentages from 6% to 36% caused a decrease in PL from 27.8% to 21.6%, equal to more than 22% reduction in the PL compared to native soil . Blayi et al.[45] reported that as WSP increased by 8%, 16%, 24%, 32%, and 40% PL decreased by 27.9%, 25.7%, 23.9%, 21.7%, and 19.81%, respectively. However, Akinwumia and Boothb [50] found different results. They observed that increasing WSP by 2% and 6% caused a decrease in PL by 24% and 22.1%, but further increases in WSP by 10% caused an increase in PL by 38%. Hence, the results deduce that the change in the PL of problematic soils may depend on the soil types, as some research observed a slight change in the plastic limit [55].

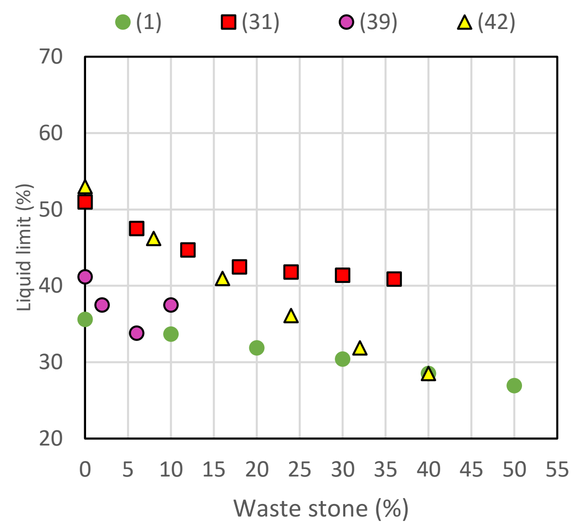

Figure 1 Effect of waste stone powder on liquid limit of treated soil: (1): [54]; (31): [39]; (39): [50]; (42): [45].

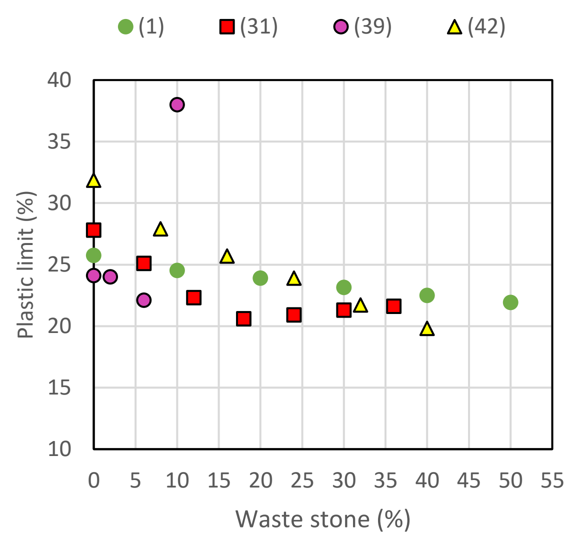

Figure 2. Effect of waste stone powder on plastic limit of treated soil: (1): [54]; (31):[39]; (39): [50]; (42):[45].

(c) Plasticity index (PI)

Figure 3 shows the effect of WSP on the PI of problematic soils. The figure shows that the PI of treated soil decreased with increasing WSP percentage. Akinwumi and Booth [50] found the effect of WSP on decreasing PI. The outcomes showed that increasing WSP by 2%, 6%, and 10% caused a decrease in the PI by 14.3%, 13%, and 10%, respectively. Ibrahim et al.[39] showed that as the percentages of WSP increased from 0% to 36%, PI decreased from 23% to 19.3%, which is equivalent to a 16% reduction in the PI of native soil. Blayi et al. [45] also studied that adding WSP by 8%, 16%, 24%, 32%, and 40% caused a reduction in PI by 18.5%, 15.3%, 12.3%, 10%, and 8.73%, respectively. Sivrikaya et al. [51] investigated the impact of WSP on the PI of clay soil. The results showed that increasing WSP by 50% caused a decrease in PI by 12%, equivalent to a nearly 67% reduction in the PI. Because WSP works as an inner material and its ability to absorb water is inferior to soil particles, this leads to decreases in the PI [45].

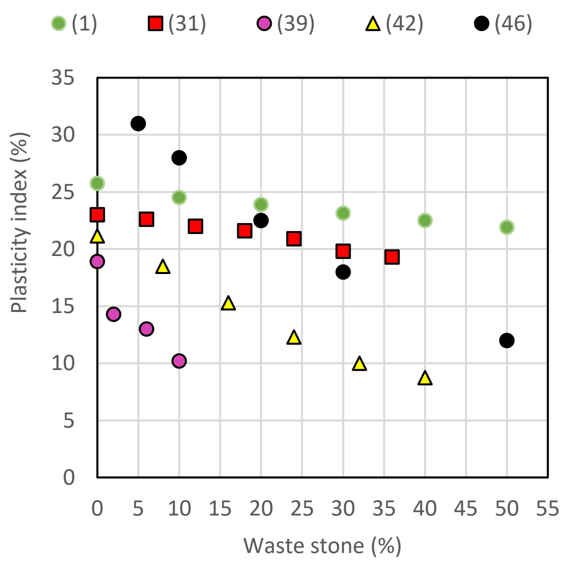

Figure 3. Effect of waste stone powder on plasticity index of treated soil: (1): [54]; (31):[39]; (39): [50]; (42):[45]; (46): [51].

(d) Linear shrinkage (LS)

Based on the reviewed studies, WSP affects soil's linear shrinkage (LS). As the percentage of WSP increased, the percentage of LS decreased. Ibrahim et al.[39] investigated that increasing the percentage of WSP by 36% decreased the percentage of LS by 29.1% (i.e., from 13.4% to 9.5%). Dang et al. [56] reported that adding 2.5%, 4.5%, and 6.25% of WSP clay soil, caused a decrease in LS by 12.7%, 9.4%, and 7.9%, respectively. This modification is equivalent to a 63.6% reduction in the LS of the soils when 6.25% of WSP is added, as shown in Figure 4. The same result was observed by Blayi et al.[45], they showed that adding 8%, 16%, 24%, 32%, and 40% of WSP caused a decrease in LS by 7.1%, 6.2%, 5.4%, 4.5%, and 2.61%, respectively. Figure 4 shows that the LS decreased with increasing WSP percentages in the soil mixture, and this may be due to the cation exchange between the soil particles and WSP particles, resulting in a decrease in the gaps and water content between the soil particles and, hence a decrease in the LS.

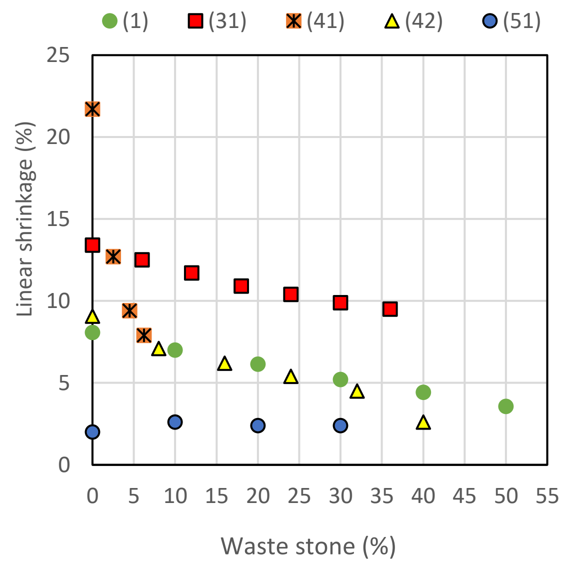

Figure 4. Effect of waste stone powder on linear shrinkage of treated soil: (1): [54]; (31):[39]; (41):[56];(42):[45]; (51):[52].

4.1.2 Dry density-moisture content relationship

Adding WSP to the soil mixture affects the compaction parameters (maximum dry density (MDD) and optimum moisture content (OMC)). Figures 5 and 6 show the effect of WSP on MDD and OMC of soils, respectively. Ibrahim et al.[39] reported the determination of MDD and OMC of untreated and treated soil. They found that adding WSP by 36% increased MDD from 0.5 g/cm^3 to 1.5 g/cm^3, while decreasing OMC from 20.6% to 18.3%, equivalent to a 200% increase in the MDD and more than 11% reduction in the OMC. Ogila [18] studied the influence of WSP on the MDD and OMC of three types of soil (A, B, and C), which are a mixture of sand and expansive clay. Those three soil types are separated by different amounts of sand and expansive clay in their content. The results show that as percentage of WSP increased from 0% to 30% the MDD increased from 1.95 g/cm^3 to 2.12 g/cm^3, 1.97 g/cm^3 to 2.14 g/cm^3, and 1.9 g/cm^3 to

2.12 g/cm³, while OMC decreased from 13% to 11.2%, 14.2% to 11.6%, and 13.6% to 11.55% for all three types of expansive soils, respectively. Waheed et al. [6] also reported the effect of WSP on MDD and OMC of soil samples. They revealed that as WSP increased by 15%, the MDD increased by nearly 12% (from 1.6 g/cm³ to 1.79 g/cm³), while OMC decreased by 0.65% (18.35% to 18.23%). Mishra et al. [44] showed that an increase in the WSP from 0% to 30% caused an increase in the MDD from 1.94 g/cm³ to 2 g/cm³, while a decrease in the OMC from 13.1% to 11.1%. Additionally, Blayi et al.[45] studied the effect of various percentages of WSP on MDD of soil samples treated with WSP. They found that adding WSP by 0%, 8%, 16%, and 24% to soil caused an increase in MDD by 1.82 g/cm³, 1.84 g/cm³, 1.85 g/cm³, and 1.86 g/cm³. However, the MDD decreased to 1.84 g/cm³ and 1.83 g/cm³ when WSP was added by 32% and 40%. They also found that OMC decreased by 17.4%, 16.6%, 16%, 15.5%, 14.7%, and 13.5% when WSP was added to the soil by 0%, 8%, 16%, and 24%, respectively. Increasing MDD while decreasing in OMC when WSP was added to soil may be related to reducing the soil voids [45]. As consequently, adding WSP to the soil mixture causes an increased MDD while decreasing OMC. This change is because of the cation exchange reaction, which reduces soil particles voids and increases WSP-soil particle density [6].

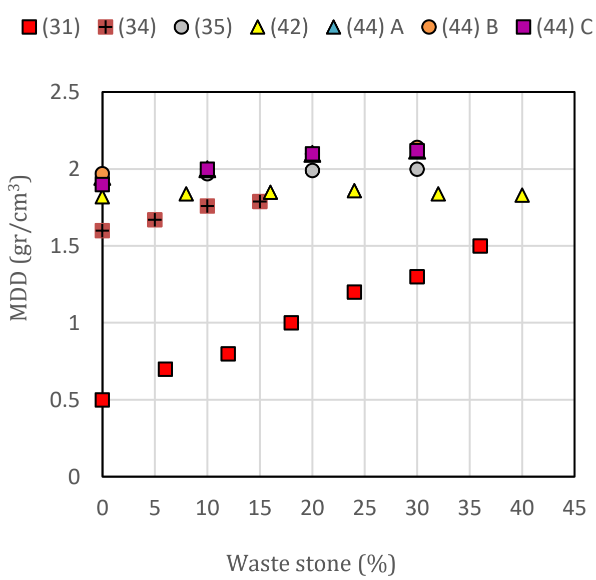

Figure 5. Effect of waste stone powder on MDD (g/cm3) of compacted treated soil: (31):[39];(34):[6];(35):[44];(42):[45];(44): [18].

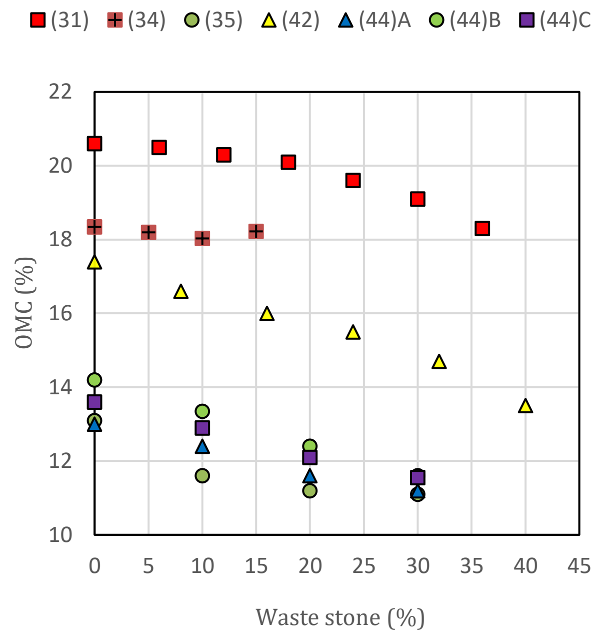

Figure 6. Effect of waste stone powder on OM (%) of compacted treated soil: (31):[39];(34):[6];(35):[44];(42):[45];(44): [18].

4.1.3 Swelling

Free swelling test is performed to determine the rate of change in the soil volume due to change in the water content [39]. Firat et al. [46] conducted a swelling test on two different types of soil (middle plasticity clay (CI)) and low plasticity clay (CL)) treated with WSP. They found that adding WSP from 0% to 15% caused a decrease in the percentage of swelling from 1.4% to 0.6%, and from 0.1 to 0.06 of CI and CL soil for 28 days of curing, respectively. However, adding WSP by 20% decreased the Swelling of CI soil to 0.4% and increased the Swelling of CL soil to 0.26% because 15% of WSP was determined to be an optimum percentage. Waheed et al. [6] reported the effect of WSP on the Swelling of silty clayey soil after 4 days of curing by using CBR molds with compacted samples subjected to 10, 30, and 65 blows, as shown in Figure 7.

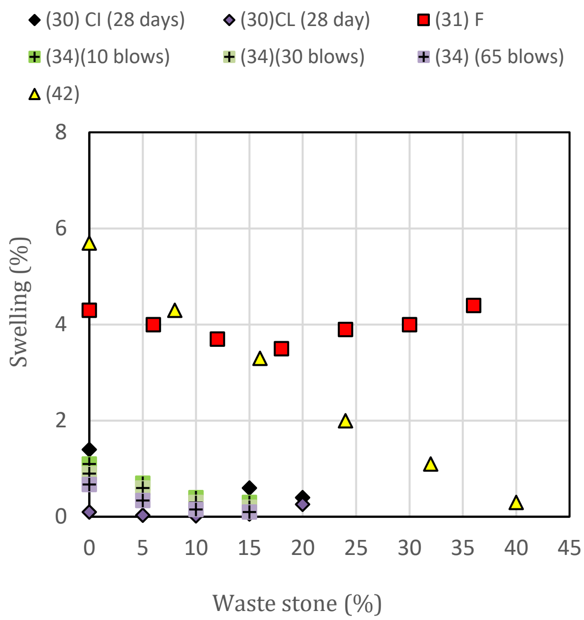

Figure 7 Effect of waste stone on Swelling of treated soil: (30): [46] ;(31): [39]; (34): [6];(42): [45].

The research showed that as the percentage of WSP increased by 15% the percentage of Swelling decreased by 72.7%, 77.8%, and 85.1% for samples with 10, 30, and 60 blows, respectively. Blayi et al.[45] found that adding 8%, 16%, 24%, 32%, and 40% WSP to soil decreased the Swelling by 4.3%, 3.3%, 2%, 1.1%, and 0.3 %. This reduction in Swelling is equivalent to 94.74% decrease when 40% of WSP was added. In contrast, Ibrahim et al.[39] studied the effect of various percentages of WSP on Swelling of clay soil at MDD. The research showed that as the percentage of WSP increased by 6%, 12%, and 18% the percentage of Swelling decreased to 4.3%, 4%, 3.7%, and 3.5%. However, further increasing in the percentage of WSP (i.e., 24%, 30%, and 36%) in the clay soil caused an increase in Swelling by 3.9%, 4%, and 4.4%. This change occurs because adding more WSP to expansive soils it might strengthen the forces that resist particles movement and consequently increase the Swelling.

4.2. Effect of WSP on the mechanical properties of soil

4.2.1 Unconfined Compressive Strength (UCS)

Unconfined compressive strength (UCS) is the strength of soil to resist the applied load. Bayesteh et al. [47] studied the effect of WSP on clay soil, as shown in Figure 8. They observed that increasing WSP by 40% caused an increase in the UCS from 2000 kPa to 2391 kPa. Waheed et al. [6] noticed that the UCS of native soil increased from 101 kPa to 146.1 kPa, 202 kPa, and 187.3 kPa by adding 5%, 10%, and 15% WSP, respectively. Adding WSP by 5%, 10%, and 15% caused an increase in the UCS by 146.1 kPa, 202 kPa, and 187.3 kPa. This improvement in strength is equivalent to a 100% increase when 10% of WSP was added. Ibrahim et al. [39] also evaluated the effect of WSP on UCS of clay soil with various curing periods. The study showed that adding 36%, of WSP increased UCS of the treated soil by 90.5%, 99%, and 101% for 1, 14, and 98 days curing, respectively. Blayi et al.[45] studied the influence of various percentages of WSP (i.e., 0%, 8%, 16%, 24%, 32%, and 40%) on an expansive soil subjected to 0, 7, 14, and 28 days curing. Adding WSP from 0% to 40% caused an increase in UCS from 185.3 kPa to 324.5 kPa, from 222.5 kPa to 563.7 kPa, from 264.1 kPa to 671.6 kPa, and from 279.4 kPa to 818.6 kPa for immediately, seven, fourteen, and 28 days of curing, respectively.

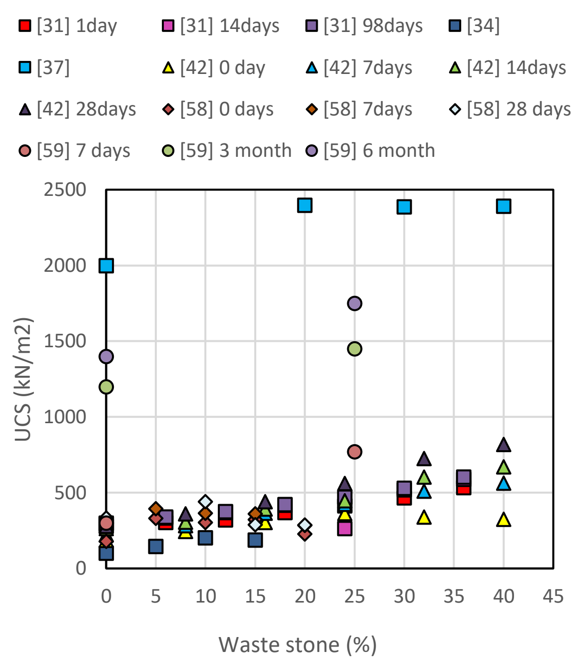

Figure 8 Effect of waste stone on UCS of treated soil: (31): [39];(34): [6]; (37):[47]; (42): [45]; (58): [43], (59):[53].

The results showed that UCS increased significantly after 28 days of curing, equivalent to a 193%

increase. Ural et al. [43] revealed that increasing the percentages of WSP in the WSP-soil mixture caused an increase in UCS of expansive soil. The study showed that adding WSP by 5%, 10%, 15% and 20% caused an increase in UCS by 332 kPa, 305 kPa, 324 kPa, and 229 kPa, for immediately tested samples. Pastor et al. [53] studied that the UCS clay soil increased with an increasing percentage of WSP. The study shows that increasing WSP by 25% with lime by 9% (the percentage of lime was fixed at 9%) cause an increase UCS of clay soil by 131%, 334%, and 424% for 7 days, 3 months, and 6 months of curing, respectively. This increase in the UCS value with the addition of WSP to the soil mixture is due to the present of calcium carbonate in WSP [6].

4.2.2 California bearing ratio (CBR)

The CBR values are a crucial factor in assessing the pavement design's subbase and subgrade thickness [45]. Various percentages of the additive were investigated in the literature to increase CBR values, as shown in Figure 9. The effect of waste stone powder (WSP) on the strength properties of clay soils with zero and 28 days of curing was evaluated by Firat et al. [46]. The study showed that increasing WS from 0% to 15% caused an increases in CBR value from 8.1% to 16.2%, and from 8% to 14.1% for 0 and 28 days of curing, respectively. However, after increasing WS by 20%, the CBR value decreased to 12.3%, and 12.25% for CI soil of zero and 28 days of curing, respectively. Additionally, the maximum CBR value of the uncured sample was 15.2% when 10% of WSP was added to CL soil; however, the CBR value decreased to 14.2% by adding 15% and more of WSP after 28 days of curing. Furthermore, Waheed et al. [6] studied the effect of WSP on soaked CBR values of expansive soil.

The results showed that when the percentage of WSP increased from 0% to 10%, the CBR values increased from 2.1% to 5.3%, from 3.2% to 6.3%, from 4.3% to 7.9% of samples with 10, 30, and 65 number of blows after 96 hours of curing, respectively, while adding WSP by 15% reduced the CBR value to 4.6%, 5.3%, and 6.2% with 10, 30, and 65 number of blows, respectively. Mishra et al. [44] also studied that adding 10%, 20%, and 30% of WSP caused an increase in CBR value by 6.3%, 8.4%, and 9.7%. This improvement in CBR is equivalent to a 136.6% increase when 30% of WS was added.

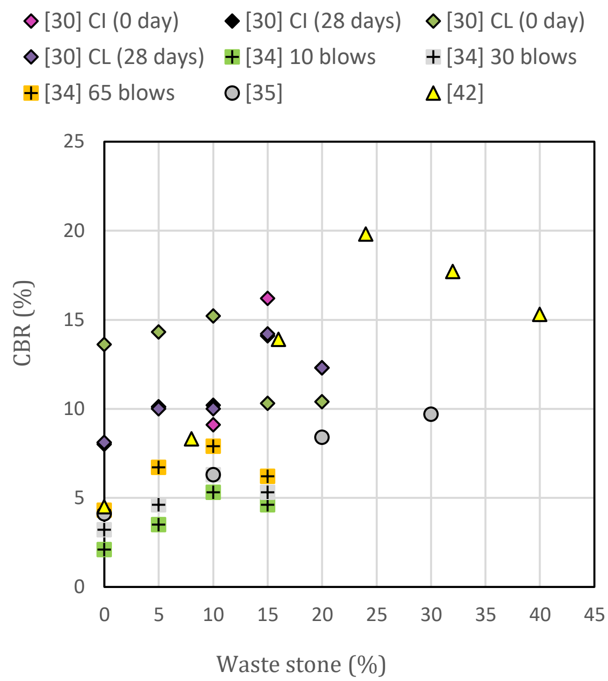

Figure 9. Effect of waste stone on CBR values of treated soil.(30): [46] ;(34): [6]; (35): [44]; (42): [45].

Blayi et al.[45] showed that increasing WSP from 0% to 24% caused an increase in the CBR value from 4.5% to 19.8%; however, the CBR value decreased to 15.3% after increasing WS by 40%.This increase in CBR value with the addition of a certain percentage of WSP occurs because the main component of WSP is carbon dioxide, which increases cementing reactions between WSP and expansive soil, thereby increasing the CBR value. Sometimes, if WSP is not heated, calcium carbonate (CaCO3) doesn't transform into calcium oxide (CaO). Therefore, the cementing reaction doesn't occur, leading to a decreased CBR value when more WSP is added.

5. Effect of WSP on pavement thickness design

The road thickness can be determined by knowing the value of CBR demonstrated by the Design Manual for Roads and Bridges [57]. The thickness of the sub-base and capping layer are obtained based on the CBR values that were found under the effect of WSP by several researchers, in this section effect of WSP on sub-base thickness will be discussed, as shown in Figure 10. Firat et al. [46] investigate the influence of WSP (i.e., 0, 5, 10, 15, and 20 %) on the CBR of clay soils. They observed that adding 15% WSP increased CBR value from 8.1% to 16.20% for uncured medium plasticity clay, decreasing sub-base thickness from 190 mm to 150 mm. Mishra et al. [44] observed that, as the percentage of WSP increased from 0% to 30%, the CBR value increased from 4.1 % to 9.7 %, causing a significant decrease in sub-base thickness from 232 mm to 173 mm. Blayi et al. [45] also found that adding 40 % of WSP increased the CBR value from 4.5% to 15.3%, resulting in decreased sub-base thickness from 240 mm to 150 mm. Those results show that WSP has a positive influence on reducing road thickness, thereby reducing the cost and required materials for road construction.

6. Conclusion

In this study, the effect of WSP on problematic soils has been reviewed. According to the literature, the effect of WSP on the geotechnical characteristics of the soil has been determined as follows:

- The maximum percentage of WSP used to tabilize weak soil was 50%.
- Calcium oxide is a main constituent of WSP that prevents water intake. When it is mixed with soil by 40%, it causes a decrease in Liquid limit, plastic limit, plasticity index, linear shrinkage, and Swelling of the mixture ranged (44% to 46%), (19% to 38%), (59% to 74%), (67% to 71%), respectively.
- Due to the cation exchange between WSP and soil, the voids between soil-WSP mixture particles decrease. Thus, the density of the WSP-soil mixture increases by 3% to 11%, while OMC decreases by 7% to 18% by adding 30% of WSP.
- Because of the high content of calcium oxide in WSP, adding WSP to the soil mixture causes an increase in the soil's strength (i.e., unconfined compressive strength and California bearing ratio). The unconfined compressive strength and California bearing ratio increased by (19% to 76%) and (137% to 320%) when 30% of WSP was added, respectively.
- Adding WSP content in the subgrade soil mixture reduced the sub-bases thickness due to the increased strength of the subgrade soil.

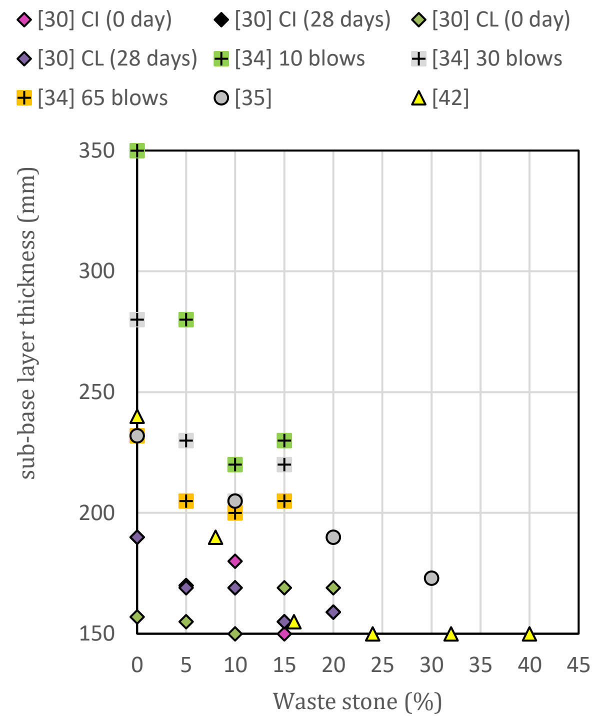

Figure 10. Effect of waste glass on sub-base layer thickness (mm):(30):[46];(34):[6];(35):[44];(42):[45].

7. Suggestions for future research

The waste stone powder was used to improve the geotechnical properties of problematic soils by numerous studies in civil engineering. Additional tests like settlement, directed shear, and freezing-thawing tests could be reviewed to understand better the effect of waste stone powder on the physical, durability, and mechanical properties of problematic soils. Moreover, there is a gap in utilizing various particle sizes and compositions of waste stone that could influence the soil type properties.

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