

Sustainable soil stabilization: the use of waste materials to improve the engineering properties of soft soils

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Abstract

One of the biggest challenges of recent civil engineering is the need to make it sustainable by implementing environmentally friendly and cost-effective solutions. The search for new materials and technologies is an important and current issue also in the strengthening of soft soils. In the soft soil stabilization process, conventional materials (cement and lime) are being replaced by waste materials, such as stone slurry waste, spent coffee grounds, rice husk ash, crushed waste concrete and glass, natural fibers, sawdust, waste tire rubber and plastic waste materials. Appropriate waste admixture content contributes to soil reinforcement by reducing compressibility and increasing maximum density and shear strength. The application of waste as an admixture is an economically and ecologically beneficial method of soil improvement. It eliminates the cost of materials and helps to reduce the problem of waste disposal, which is sometimes very expensive and problematic. The study aims to analyze the effect of waste materials on improving the physical and mechanical properties of soils based on the research results presented in the literature.

Keywords: sustainability, circular economy, waste materials, geotechnical engineering.

1 Introduction

Due to the rapid development of civil engineering, areas characterized by difficult soil and water conditions with weak soils occurrence are increasingly being used for construction. Implementation of construction works on soft soils characterized by high compressibility, low bearing capacity, instability, slip failure and differential settlement is very problematic and limited (Vincevica-Gaile et al., 2021). In most cases, the weak subsoil should be improved so that it can be used as a base for various types of structures.

Nowadays, soil reinforcement methods should be based on a circular economy and solutions that minimize energy consumption, CO₂ emissions and use waste and recycled materials (Chittoori et al., 2012; Gomes Correia et al., 2016). Many suggestions on making soil stabilization more environmentally friendly can be found in the literature. However, the most common and widely described is the use of waste materials as an additive to weak subsoil. The application of waste material as an additive has many advantages, which include eliminating the cost of materials

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and helping to reduce the problem of waste disposal, which is sometimes very expensive and problematic. Appropriate waste material content reduces compressibility, increases maximum density and shear strength of soil.

The study aims to analyze the effect of waste materials on improving the physical and mechanical properties of soils based on the research results presented in the literature.

2 Methods of soil improvement

The methods of soil improvement have been classified in many different ways. Chu et al. (2009) divided them into five groups: ground improvement without admixtures in non-cohesive soils or fill materials, ground improvement without admixtures in cohesive soils, ground improvement with admixtures or inclusions, ground improvement with grouting type admixtures and earth reinforcement. The classification system and techniques are shown in Table 1.

Table 1. Classification of soil improvement methods (Chu et al., 2009)

Methods of soil improvement				
Ground improvement without admixtures in non-cohesive soils or fill materials	Ground improvement without admixtures in cohesive soils	Ground improvement with admixtures or inclusions	Ground improvement with grouting type admixtures	Earth reinforcement
<ul style="list-style-type: none"> • Dynamic compaction • Vibrocompaction • Explosive compaction • Electric pulse compaction • Surface compaction 	<ul style="list-style-type: none"> • Replacement/ Displacement • Preloading • Dynamic consolidation • Electro-osmosis or electro-kinetic consolidation • Thermal stabilization • Hydro-blasting compaction 	<ul style="list-style-type: none"> • Vibro replacement or stone columns • Dynamic replacement • Sand compaction piles • Geotextile confined columns • Rigid inclusions • Geosynthetic reinforced column • Microbial methods • Other methods 	<ul style="list-style-type: none"> • Particulate grouting • Chemical grouting • Mixing methods • Jet grouting • Compaction grouting • Compensation grouting 	<ul style="list-style-type: none"> • Geosynthetics or mechanically stabilized earth • Ground anchors or soil nails • Biological methods using vegetation

The selection of the method of soil reinforcement is influenced by: soil type, area, depth and treatment required, soil properties, availability of materials, availability of skills, local experience and local preferences, environmental concerns and economics (Harlten, 1996; Huat et al., 2014; Nicholson, 2015). However, the choice of the technique can be made for sustainability reasons as well (Gomes Correia et al., 2016).

Sustainable soil stabilization aims to avoid traditional methods of soil improvement such as cementing or deep excavation and a single replacement of soils in favor of innovative techniques. An example of such a non-traditional method is the use of waste materials in soil improvement.

3 Waste materials used in in soil stabilization

Waste materials used as admixtures can be classified into the third group of soil strengthening methods presented in Table 1 – ground improvement with admixtures or inclusions. The implementation of the waste admixtures into the soil is often carried out by mixing and remolding to obtain the expected parameters of stabilized ground (Ilies et al., 2015). In some cases, the addition of traditional binders such as cement and lime is required.

Many possibilities for using waste materials in soil improvement have been presented in the literature, especially in the last three years (Devi et al., 2020; Vincevica-Gaile, 2021). Attom and El-Emam (2011) investigated the effect of using cutting stones slurry waste (SSW) in the stabilization of three types of clayey soils. The chemical analysis showed that the solid component of SSW is mainly composed of silica, alumina and calcium oxide. Regarding the grain size, the SSW material appeared to be silty sand with water content equal to 63%. Stone waste has an important role in a circular economy. It has a wide range of applications, not including soil stabilization. It is used in concrete production, clinker stabilization and porcelain production (Al-Joulani, 2014).

Spent coffee grains (SCG) are another waste material that can be used as an environmentally friendly source. Its potential use includes energy and construction materials (McNutt and He, 2018). Bedaiwy et al. (2019) found that the addition of spent coffee grounds may stabilize clayey soft soil.

Rice husk is a widely available waste material in all rice-producing countries. One of the methods of its utilization is the conversion into ash. The rice husk ash (RHA) comprises almost 90% of silica and is therefore a suitable material for soil stabilization (Brahmachary et al., 2019). RHA material is a carbon neutral product and its pozzolanic reactivity is used even in concrete mixes. The rice husk ash is used in soil stabilization as well (Brahmachary et al., 2019).

One method of limiting the extraction of natural aggregates, such as gravel, is the use of crushed waste concrete (CWC). Research analyses of Karkush and Yassin (2019) and Ibrahim et al. (2018) showed that adequately prepared waste concrete could be used in soil stabilization. However, the application of recycled concrete is much wider.

In recent years, much attention has been paid to crushed waste glass (CWG). In the form of glass powder, CWG material can be added to concrete or it could be used as fill material in the road pavement (Kazmi et al., 2019). Perera et al. (2022) investigated the effect of using crushed waste glass with a particle size of less than 5 mm in clayey soil stabilization. As the chemical analysis showed the CWG material is mainly composed of oxides of silicon, calcium, sodium, and aluminum comprise (Perera et al., 2022).

Natural fibers as an environmentally friendly material have a wide range of applications. They are used in building materials, particle and insulation boards and they can even replace synthetic materials (Sanjay et al., 2016). Bawadi et al. (2020) studied the influence of natural fibers on the properties of clayey soils. The researchers tested three types of natural fibers: banana, coconut and kenaf. All fibers were composed of calcium, potassium, iron and silica.

Sun et al. (2018) and Niyomukiza et al. (2020) investigated the effect of the sawdust on the properties of cohesive soils. The advantages of using sawdust as a stabilizer are the low cost of admixture material and the reduction of the problem of environmental pollution caused by its poor disposal.

Waste tire rubber is another material used in soil stabilization (Azam et al., 2020). However, the shredded tires can also be used as the lightweight fill of the road embankments and as drainage material (Edil and Bosscher, 1994). The search for methods to utilize used tires is an important issue due to the alarming amount of them worldwide.

Hassan et al. (2021) studied the influence of plastic waste materials on the geotechnical properties of clayey soils. The research program involved the use of shredded plastic bottles with fiber lengths of 1 and 2 cm. As the waste materials used in soil stabilization, Devi et al. (2020) also mention wet olive pomace, mushroom waste and marble dust.

4 Influence of waste materials addition on engineering properties of soft soils

The most frequently reported parameters of waste-stabilized soils are maximum dry density, optimum water content, cohesion and friction angle. In all analyzed studies, both stabilized and untreated soil parameters were reported. The results presented in all the studies analyzed apply to cohesive and organic soils. The content of each additive was related to the dry weight of the soil.

4.1 Maximum dry density and optimum water content of waste-stabilized soil

The maximum dry densities (MDD) and optimum water content (OWC) analyzed in this study were determined under laboratory conditions using the Proctor compaction test.

Attom and El-Emam (2011) investigated that the addition of approximately 20% of stone slurry waste by weight of dry soil results in a 3-4% increase in maximum dry density and a 10-20% decrease in optimum water content in comparison with untreated soil, depending on the type of tested soil. The application of rice husk ash has the opposite effect on MDD and OWC parameters of clayey soil. Brahmachary et al. (2019) reported that the addition of 20% RHA resulted in a 25% reduction in maximum dry density and a 30% increase in optimum water content. Ibrahim et al. (2018) and Karkush and Yassin (2019) studied the effect of crushed waste concrete on the physical properties of organic and cohesive soils, respectively. A study presented by Ibrahim et al. (2018) shows that the maximum dry density increases with increasing CWC content (by a maximum of 25%), while the optimum water content decreases (by a maximum of 40%). Karkush and Yassin (2019) found the lowest maximum dry density for soil with the addition of 5% crushed waste concrete, which is even lower than determined for untreated soil. The maximum value of the MDD parameter was obtained with a CWC content of 15%. The maximum OWC was found at 10% CWC content, whereas it was the lowest at 15% CWC content. Perera et al. (2022) investigated that the maximum dry density of stabilized cohesive soil increases insignificantly with increasing crushed waste glass content (by a maximum of 5%), whereas the optimum water content decreases (by a maximum of 14%). Bawadi et al. (2020) reported that the MDD and OWC parameters depend not only on the content of natural fiber but also on their type. The researchers determined the highest maximum dry density at 0.5% banana fiber content. The lowest value of the MDD parameter was found at 1% kenaf fiber content and it was even lower than determined for untreated clayey soil. Bawadi et al. (2020) investigated that the optimum water content increases with increasing fiber content for all types of natural fibers added to clayey soils, however, the most significant change in OWC was observed with the addition of kenaf fibers. The addition of sawdust reduces the maximum dry density by 10% and increases the optimum water content by 10% at a sawdust content of 7% (Niyomukiza et al., 2020). Azam et al. (2020) reported that the addition of 20% waste tire rubber resulted in a 14% decrease in maximum dry density and a 30% reduction in the optimum water content of clayey soil. The addition of 4% plastic waste materials in the form of shredded plastic bottles resulted in a decrease in MDD by 4% and a reduction in OWC by 20% (Hassan et al., 2021). The investigation showed no significant effect of plastic fiber length on maximum dry density or optimum water content.

4.2. Cohesion and friction angle of waste-stabilized soil

Among the literature reviewed, only four research groups have analyzed the effect of waste additives on strength parameters. The reported cohesion and friction angle were determined under laboratory conditions in direct shear tests.

Attom and El-Emam (2011) investigated that the addition of stone slurry waste increased cohesion by 40%. The friction angle of soil stabilized with 20% SSW was the same as that determined for untreated soil. Bedaiwy et al. (2019) reported that the addition of 10% coffee grounds increased cohesion by 20%. The cohesion of soil treated with 5 and 15% SCG content was even lower than that determined for untreated soil. The highest friction angle of soil stabilized with coffee grounds was obtained for 5% SCG content. As Amiri et al. (2018) investigation showed, the addition of 50% crushed waste glass by weight of dry soil increased the friction angle by 50% and reduced cohesion by 45%. Sun et al. (2018) reported that sawdust increases cohesion and friction angle. The optimum addition of sawdust was found to be 7.5%.

4.3. Summary

The results of the addition of waste materials on the chosen physical and mechanical parameters of soils are summarized and presented in Table 2.

Table 2. Soil improvement by different methods

Admixtures	Percentage content	Author(s)	Results
Stone slurry waste (SSW)	approx. 20	Attom and El-Emam (2011)	<ul style="list-style-type: none"> • 3-4% increase in the maximum dry density and 10-20% reduction of the optimum water content • increase in cohesion by up 40%
Spent coffee grounds (SCG)	5, 10, 15	Bedaiwy et al. (2019)	<ul style="list-style-type: none"> • 20% increase in cohesion at 10% SCG content • 40% increase in friction angle at 5% SCG content
Rice husk ash (RHA)	5, 10, 15, 20	Brahmachary et al. (2019)	<ul style="list-style-type: none"> • 5% and 25% decrease in maximum dry density at 5% and 20% RHA content, respectively • 15% and 30% increase in optimum water content at 5% and 20% RHA content, respectively
Crushed waste concrete (CWC)	10, 20, 30, 40, 50	Ibrahim et al. (2018)	<ul style="list-style-type: none"> • 25% increase in the maximum dry density and 40% reduction of the optimum water content at 50% CWC content
	5, 10, 15	Karkush and Yassin (2019)	<ul style="list-style-type: none"> • 3% increase in the maximum dry density and 11% reduction of the optimum water content at 15% CWC content
Crushed waste glass (CWG)	10, 20, 30, 40, 50	Amiri et al. (2018)	<ul style="list-style-type: none"> • 50% increase in friction angle at 50% CWG content • 45% decrease in cohesion at 50% CWG content
	5, 10, 15, 20	Perera et al. (2022)	<ul style="list-style-type: none"> • 5% increase in the maximum dry density and 14% reduction of the optimum water content at 20% CWG content
Natural fibers	0.3, 0.5, 1	Bawadi et al. (2020)	<ul style="list-style-type: none"> • 7% increase in the maximum dry density at 0.5% banana fiber content and 30% increase in the optimum water content at 1% banana fiber content
Sawdust	7.5	Sun et al. (2018)	<ul style="list-style-type: none"> • increase in cohesion and friction angle
	3, 5, 7	Niyomukiza et al. (2020)	<ul style="list-style-type: none"> • 10% decrease in the maximum dry density and 10% increase in the optimum water content at 7% sawdust content
Waste tire rubber	5, 10, 15, 20	Azam et al. (2020)	<ul style="list-style-type: none"> • 14% decrease in the maximum dry density and 30% reduction of the optimum water content at 20% tire rubber content
Plastic waste materials	1, 2, 3, 4	Hassan et al. (2021)	<ul style="list-style-type: none"> • 4% decrease in the maximum dry density and 20% reduction of the optimum water content at 4% plastic material content

Conclusions

Most of the additives analyzed in the study had a positive effect on the properties of the soil-waste material mixtures.

The addition of stone slurry waste, crushed waste concrete and glass and banana fibers increased the maximum dry density of the stabilized soil. Crushed waste concrete has the most significant effect on MDD. However, the CWC content was as high as 50%. The addition of rice husk ash, sawdust, waste tire rubber and plastic waste materials decreased the maximum dry density and reduced the compactability of the soil-waste material mixtures.

The increase in friction angle of the stabilized soil was caused by the addition of spent coffee grounds, crushed waste glass and sawdust. The increase was most significant in stabilization with SCG, even at low SCG content. None of the additives decreased the friction angle.

The addition of stone slurry waste, spent coffee grounds and sawdust increased the cohesion of soil-waste material mixtures. A more significant increase in cohesion with a lower additive content was found for stone slurry waste. However, the percentage of SSW was significantly higher than SCG. The addition of crushed waste glass decreased the cohesion of stabilized soil.

The analysis confirmed the relevance of investigating the effect of the addition of waste materials on improving the engineering properties of soft soils.

It has to be underlined that consideration and analyses presented in this study should be treated only as a proposition of the potential use of waste materials in soil stabilization. Before the waste admixtures implementation, laboratory and field tests should be provided. The study did not analyze the influence of each waste material on the environment (underground water, organisms etc.). The long-term effect of the use of waste admixtures should be considered as well.

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