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Stabilised Soil Properties Using Waste Marble Powder: A Review

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The increasing demand for sustainable construction materials has prompted the exploration of alternative solutions to enhance the engineering properties of soils, particularly in the context of road construction and foundation work. One promising approach is the stabilization of soil using waste marble powder (WMP), a byproduct from marble processing industries. This review aims to assess the effects of WMP on the physical and mechanical properties of soils, providing a comprehensive overview of recent advancements in soil stabilization techniques. The paper explores the impact of varying percentages of WMP on parameters such as compaction, plasticity, permeability, and shear strength. Additionally, the influence of WMP on soil's resistance to erosion and its long-term performance is discussed. Several case studies and experimental findings are presented, highlighting the potential of WMP to improve soil stability and durability while contributing to environmental sustainability by recycling waste materials. The review concludes by identifying key challenges and proposing future directions for research to optimize the use of waste marble powder in soil stabilization practices, aiming to address both technical and environmental concerns in construction engineering.

Keywords: Waste Marble Powder, soil stabilization, California bearing ratio, soil stabilization, Unconfined Compressive Strength.

1. Introduction

Stabilization of soils is a core element of geotechnical engineering, with the common objective of modifying or enhancing soil characteristics to be suitable for construction. Out of all the methods, the use of waste products in soil stabilization has attracted much economic and environmental interest (Ghanizadeh & Rahrovan, 2019). One such material is waste marble powder, derived from the industries involved in marble processing. Marble waste is produced to millions of tons per annum, utilization of this waste material in soil stabilization not only solves the problem of environmental pollution but also helps in solving the problem of management of waste (Obeta et al., 2019).

Some basic indices that are used for the determination of load-bearing capacity and strength of the soil are CBR- California Bearing Ratio and UCS- Unconfined Compressive Strength (Gurbuz, 2015). Most of the older approaches involve calculations of CBR and UCS which are very cumbersome, tiresome, and require a lot of time and resources for data collection in the field and laboratory. Currently, a significant effort has been made in the development of empirical models that could predict such values using accessible soil data properties and additive attributes(Kharade et al., 2014). Soil stabilization is an elementary practice in civil engineering, relating to the enhancement of mechanical characteristics of soil to be employed in executing construction (Dahale et al., 2012). The methods that are currently used to determine the efficiency of the current soil stabilization, especially CBR and UCS are often time-consuming, require more effort, and in most cases; require extensive field and experimentation. Such methods may be tedious and cost-intensive hence the need to produce more efficient accurate, precise, and predictive methods (Alazigha et al., 2018).

Soil stabilization means the improvement of the engineering characteristics of the soil to increase its strength, bearing capacity, and durability (Zumrawi & Abdalla, 2018). This is of special significance in construction and engineering activities where the quality of the ground determines structures' stability and useful lifespan. Improvement is the process of using various methods to improve the nature of soil as a material or base for construction projects, some of the problems that are solved by this practice include poor soil and erosion among other areas of a subgrade (Choksi et al., 2018; Minhas & Devi, 2016; Tamiru & Ponnurangam, 2019).

2. WASTE MARBLE POWDER IN CONSTRUCTION

Waste marble powder (WMP) is defined as the industry waste material that is produced from the different manufacturing processes of marble stones including cutting, shaping, and polishing. WMP was regarded as a waste product in the past, but the material has recently drawn much interest with potential usage in construction (Neeladharan et al., 2018). The utilization of WMP as a part of construction materials is helpful for industries in two ways – it solves the ecological issues associated with the disposal of marble wastes and improves the characteristics of the construction materials (Umar et al., 2023). WMP use in construction aids in containing the large volumes of marble waste generated thus cutting down the quantity of waste that ends up in the landfill hence the related impacts (Sufian et al., 2021). The integration of WMP into a construction project partially substitutes ordinary construction materials and thus saves on the depletion of natural resources like limestone, sand, and cement (Alnunu & Nalbantoglu, 2022). WMP can also reduce the total project cost of the construction materials necessary for building projects, hence enhancing the economy. Previous research showed that WMP can be used as a partial replacement for cement in concrete with a maximum of 25% replacement of WMP for cement in concrete, the physical properties of the concrete used in the study fulfill the standard requirements(Sivrikaya et al., 2020).

This not only helps to qualify the required amount of cement but also improves certain characteristics of the concrete, for example, workability or durability. WMP can replace fine aggregates (sand) in concrete mixes thus increasing their compressive strength while decreasing their water absorption (Julphunthong, 2015). The usage of WMP in mortar improves the mortar's bond strength, workability, and performance of the mortar. This then leads to the conclusion that by employing WMP in plastering applications, one is likely to achieve a smoother finish that can further prolong the life of the plaster. Hence, the application of WMP in the production of bricks and blocks for construction enhances the mechanical characteristics and at the same time offers a more sustainable solution than those currently existing (Yorulmaz et al., 2021).

A. Environmental impact

Environmental evaluation is an important process that includes the assessment of the environmental consequences of a project or activity before the implementation of the activity. This is due to the need to assess issues like the disposal of industrial waste as an aspect of controlling environmental impacts (Peretz et al., 2021). Marble powder which is produced from operations such as marble quarrying and processing poses a considerable inconvenience because of disposal and effects. This section focuses on the waste marble powder – from an environmental point of view and the possibilities as well as advantages of the material (Halliday, 2008).

This dust is exceptionally fine and can easily be suspended in the air during the process of production, during transport, or the disposal process and this may affect the health of the workers or people living near the industries by leading to respiratory diseases such as asthma. Discharge of marble powder to the environment without the application of an appropriate method will lead to polluting the soil and water systems (Lal, 2009). Marble is natural and the alkaline qualities can change the pH of the soil and influence water bodies. There may be a generation of massive quantities of marble powder, creating an immense problem at its disposal. Disposal means such as landfilling are not sustainable overall especially considering the present world trends (Poleto & Tassi, 2012).

Life Cycle Assessment (LCA) is another method of addressing the effects of marble powder production on the environment starting from production, usage of energy and resources, and ending with disposal (Scrivener & Favier, 2015). Environmental Impact Assessment (EIA) evaluates the effects of the disposal of marble powder on the environment by analyzing the effects likely to be incurred on the inhabitants, water, and air quality, and every other natural ecosystem (Baloi, 2003). Risk Evaluation summarizes the likelihood of danger to human health and the environment by identifying the proximity of exposure and possible preventative steps related to marble powder (Zhou & Lowe, 2003). Marble powder disposal causes pollution of air, water, and soil; however, utilizing it decreases its negative effects on the natural environment. Most marble slabs must be imported, with green marble originating from various parts of the world (Müller et al., 2014). By reusing the marble powder, the dependence on mined products like limestone and other raw materials is minimized thereby being good for the environment (Kibert, 2007). The use of marble powder in any production process can therefore reduce its costs making it a cheaper material to use as compared to other common ones. An environmental impact analysis of waste marble powder is important since this way the effects it might have on the environment can be prevented (Vishwakarma & Uthaman, 2020). The integration of marble powder in the construction sector to function as an aggregate in the construction of roads, as a part of soil stabilization, and in the agricultural sector utilizing it as a fertilizer will help in converting marble powder from waste material into one that has many uses (Indraratna et al., 2010). Apart from having positive environmental impacts, this is also an economic and resource-saving approach. As for further studies and developments, it will be crucial to disclose more information regarding the utilization of waste marble powder to support the concept of sustainable development and contribution to environmental protection (Huang, 2017).

B. Economic Benefits of using waste marble powder

The waste marble is wasted continuously due to construction and quarrying activities, making it a huge environmental issue. However, recent studies have revealed a promising potential solution: Turning waste marble into an effective reinforcement material for soil through soil stabilization. Thus, such an innovative approach has the advantage of not only solving the problem of waste disposal but also optimizing the potential economic benefits due to the virtual elimination of both the cost of soil treatment and waste. Based on the analyzed literature one of the key benefits of applying waste marble in the stabilization of soil is the improvement of its mechanical properties. Therefore, when marble waste particles are mixed with the soil the soil improves on its characteristics such as compaction, erosion, and settlement. This enhanced soil stability is highly desirable in parts of the world that are vulnerable to landslides, sinkholes, and other geotechnical risks. As such, improved structural stability of the soil using waste marble offers the potential to minimize such risks and, consequently, the costs of remedial measures. In addition, the incorporation of waste marble in the stabilization of soil also reduces the costs associated with waste disposal. Conventional methods that have earlier been used to dispose of wastes include landfill disposal and recycling of marble and these come with a lot of costs. Thus, when using waste marble as a soil stabilizer, these costs can be minimized or even eradicated. This means that not only is the impact on the environment reduced due to less waste being taken to the landfill but there is also a more cost-effective and sustainable approach to take. (Indraratna et al., 2010)

In conclusion, it is possible to argue that the employment of waste marble in the stabilization of soils is a highly effective way of providing a range of environmental and economic advantages on top of which the practice of utilizing waste marble optimizes the possibility of shaping more sustainable construction methodologies. The utilization of recycled elements in infrastructural projects can help to decrease the amount of virgin materials consumed and therefore play a role in decreasing the negative input to the environment. This approach, however, conforms to the rising trend in the adoption of sustainable development and circular economy strategies. The innovation of using waste marble in soil stabilization has the potential of providing substantial gains, but a detailed understanding of the treatment performance, and its effect on the environment needs to be explored in additional studies. Other considerations include the characteristics of the waste marble and other relevant properties, characteristics of the soil to be stabilized, and the use that the stabilized soil is to be put to. Instead, such questions can be answered based on sociological research; this approach would help to adopt this innovative solution correctly and for the long term. Therefore, incorporating waste marble into the stabilization of the soil is a viable and effective way to address problems of waste disposal and ensure sustainable construction materials in construction. From the view of increasing the stability of soil, decreasing costs, and supporting a circular economy, this proposal aligns to establish a more sustainability-driven and economically effective future. With further development in research in this technology, waste marble is expected to gain an even more significant role in the stabilization of soils and construction works in the future. (Golafshani & Pazouki, 2018)

3. PROPERTIES OF WASTE MARBLE POWDER

3.1 Physical and Chemical Properties

A. Chemical Properties

One aspect of importance when applying waste marble chloride in soil stabilization is granulometry, which involves the determination of particle size distribution. The particle size distribution of waste marble has the potential to affect both the textural and compaction properties of the stabilized soil hence influencing its performance in various engineering applications. These characteristics of waste marble particles can help in the enhancement of soil texture which comprises of fine particles. When incorporated in a coarser grain size waste marble particles then the pores among the larger particles can be filled up hence reducing the porosity of the soil and hence increased stability of the soil. This increased interlock is particularly useful in instances where the soil is expected to experience shear forces, like in sloping sites or those with potential foundation projects. While some effects may be beneficial, such as enhancing the fertilizer efficiency due to its fine particle size, there are negative impacts in terms of the compaction of the waste marble. Such increased cohesion helps to enhance the soil's resistivity to deformation or what may be referred to as, improved resistance to compaction to the required density. This can be particularly difficult if the substrate must be compacted to provide adequate bearing capacity or prevent future settlement.

Table 1. Chemical Composition of Waste Marble Powder (Firat et al., 2017)

Constituents	Chemical Composition (%)
CaO	50.87
SiO_2	7.27
MgO	0.84
SO_3	0.37
Fe_2O_3	0.45
Al_2O_3	0.11

Materials containing WMP have shown increased strength specifically in the aspect of abrasion and wear therefore making it ideal to produce paving blocks meant for areas that experience high traffic (Tingle & Santoni, 2003). In other aspects, WMP in the self-compacting concrete (SCC) formulation can be used as an aid to enhance the viscosity of the SCC to get better flowability and filling ability without segregation.

B. Physical Properties

Based on these properties, WMP can be added to the process of manufacturing ceramic tiles since it can improve the aesthetic value while making the product lighter to fire and therefore reducing energy consumption (Karim et al., 2018).

Table 2. Physical Properties of Waste Marble Powder (Karim et al., 2018)

Property	Value
Color	Light gray

Form	Powder
Fineness (kg/m²)	350
Odor	Odorless
Particle Size Distribution (µm)	< 59
Specific Gravity	2.63
Water Absorption	0.97%

WMP can enhance the strength, toughness, functional characteristics, and appearance of construction materials to a greater extent (Firoozi et al., 2017). By implementing the WMP, problems concerning marble waste disposal, such as transportation and disposal costs, are minimized; the frequency of quarrying is decreased; and the CO_2 emissions related to construction projects are reduced (Khan et al., 2020). Waste management is an essential practice of sustainable construction to avoid mining of construction resources and the utilization of WMP is sustainable construction by recycling waste.

3.2 Impact on the Soil Properties

3.2.1 Improved Soil Texture and Structure

This study showed that the process of incorporating waste marble into soil affects some of its physical and chemical properties. Due to the changes in texture and structure of the soil and change in soil pH level waste marble can be used to enhance the use of the soil in engineering and agriculture. The proportion of sand, silt, and clay in a soil is known as soil texture and influences many aspects of the soil including its compaction, permeability, and water-retaining capacity. Waste marble particles are often of fine particle size and when incorporated into the soil bring changes in the texture of the soil by contributing to increased silt and clay fraction. This may be beneficial for altering the compaction characteristics of the soil and/or increasing the shear strength, thus making the soil more suitable to withstand deformations or erosion.

Moreover, incorporating waste marble can also influence the change in the structure of the soil. Soil structure thus defines how particles in the soil are grouped to form interconnected aggregates or peds. It has been observed that wastes such as marble particles are also present in the matrix, and these can behave as binders by agglomerating to form big aggregates. This better soil structure may promote water penetration, aeration, and root penetration resulting in better fertility and productivity of the soils. (Rane et al., 2023).

3.2.2 Improved pH of Soil

Besides textural and structural soil properties, waste marble can also affect one of the most significant soil attributes, which is pH. Calcium carbonate, which is usually found in waste marble, is mildly alkaline and improves the soil pH. With this, although the pH of seven may be slightly alkaline which is good for the growth of some plant species, it will favor the growth of plant species that require acidic environments. Hence, assessment of the target soil pH and type of plant that is grown in each area should be of vital concern when introducing waste marble into agricultural soils.

Waste marble influences inhomogeneous nutrient distribution in the soil, and soil pH also impacts on the chemistry of the soil. For example, with an increase in pH the concentrations of some elements like iron and manganese are decreased while that of phosphorous and potassium are increased. This can have potential benefits of increased nutrient availability to plants and improved overall health of the soil.

The impacts of waste marble on the texture, structure, and pH of the soil may be influenced by the attributes of the waste marble and the type of soil used for treatment. This means that the particle size distribution of the waste marble, the initial properties of the soil, and the application rate of waste marble can affect both the amplitude and the direction of the changes that occur in the physical properties of the soil after its amendment with waste marble. (Milburn & Parsons, 2004)

Therefore, it can be concluded that the use of waste marble mixed with soil affects the physical and chemical characteristics of the soil. Due to the influence on the physical and chemical properties of the soil such as texture, structure, and pH, waste marble can positively affect the compaction, shear strength, permeability, and nutrient availability of the soil. But at the same time, it is necessary to adequately assess the specific properties of the waste marble and the soil that is being treated to provide the expected positive results and exclude negative effects.

4. Methods of using waste marble in soil Stabilization

4.1 Mixing Techniques

There is a problem with the quality and properties of WMP that depends on the source and therefore requires quality testing and regulation (Zuber et al., 2013). Another requirement that needs to be met is the compatibility of WMP with other construction materials to fulfill the performance characteristics of the constructions. It is necessary to apply certain processing and handling methods that will allow the incorporation of WMP into construction materials while preserving the quality of the latter (Zuber et al., 2013). Compliance with the local and international standards and regulations in the use of material in construction is highly vital when using WMP.

Since waste marble powder is generated in a large quantity in the marble processing companies, it can offer a good chance of improving the sustainability and the characteristics of the construction materials (Ingles & Metcalf, 1972). Thus, the integration of WMP in different construction applications can lead the industry to solve environmental issues, overcome operational costs, and encourage the conservation of resources. That is why further scientific investigation of the effects of WMP and research of the factors that contribute to or hinder its functioning in the construction industry will enhance the optimization of the application of WMP for making the construction industry eco-friendly as well as efficient (Milburn & Parsons, 2004).

4.2 Application Techniques

The efficient use of waste marble in soil stabilization shall involve the consideration of several methods. There are two broad categories of soil stabilization namely in-situ stabilization and pre-soil treatment. In-situ stabilization of waste marble requires the incorporation of waste marble into the soil at the construction site. It is especially appropriate for use in large-scale engineering activities that would be uneconomical, to transport this soil to another site for treatment. Since waste marble can indeed stabilize the soil when blended and incorporated into it, this could mean that waste marble can be mixed directly with the soil to be stabilized, further cutting the costs of transportation and handling. Nonetheless, there are some drawbacks to implementing in-situ stabilization: it can be difficult for areas with restricted access, or in areas that are geographically complicated. It may also take special means to make sure that waste marble mixes well on the soil in the zone where it will be applied as well as also disperse the waste marble evenly amid the entire mass of soil To avoid these issues, better planning and coordination is advisable. Soil stabilization of construction involves exposure of samples of soil to waste marble in regulated conditions before use. This technique is less flexible than the previous one, but it provides much better control over the flow of waste marble and allows for sharper adjustments to the relative amounts of materials. Depending on the nature of the black cotton soil and the type of construction work in construction, it is made possible to ensure that the desirable level of stabilization has been accomplished before the incorporation of the soil into the construction project. (Yorulmaz et al., 2021).

Pre-treatment can be used more extensively in the conditions of less extensive construction, or when important quality requirements are expected. They also enable the determination of the most suitable waste marble-soil mixture for a given application through the testing of different mixtures. But pre-treatment is comparatively more costly and takes more time than in-situ stabilization particularly if larger quantities of soil are expected to be treated. The selection of in-situ stabilization and pre-treatment will therefore depend on some of the factors such as the size and type of project and the extent of rehabilitation needed as well as cost and time. At times, it is possible to apply both techniques and manage to get the intended outcomes, an aspect that is evident when compared to the traditional methods. Another aspect that needs to be taken into consideration is the correct application method and the correct handling of the soil mix and compaction. Proper mixing is vital so that the waste marble particles are evenly distributed throughout the soil mass of the specimen, and compaction is also important to obtain the required density and stability of the stabilized soil. With a proper understanding of the correct application technique, the application of waste marble in soil stabilization, therefore, comes with the associated benefits of environmental and economic value.

Mechanical methods include compressing the soil down with rollers, tamper, or other vibrating equipment which would help to compact the soil. Using materials such as geotextiles, geogrids, and fibers in reinforcing an existing soil to increase the strength it possesses (Saygili, 2015). Moisturizing the surface and then adding cement into the soil and creating a strong mass that can better bear loads than the soil (R. Ali et al., 2014). An example of soil improvement is the use of lime which is applied to minimize instances of plasticity while at the same time enhancing the strength of the soil, especially soils that are highly composed of clay. Utilization of fly ash as a soil alteration material aimed at improving the physical and mechanical characteristics of the soil to satisfy durability requirements (Kusuma et al., 2023). Adding filler materials, such as bitumen or asphalt enhances the cohesiveness and at the same time decreases the permeability of the mix. Filling up vacant lands or degraded areas with plant cover to anchor the soil through root structures that interlock the soil mass and hinder erosion(Soni & Singh, 2019). Microbial-induced calcite Precipitation (MICP) is defined as using microorganisms like bacteria that help to form calcium carbonate that can improve the strength of the soil by binding the particles of the soil together (Abdulla & Majeed, 2021).

Figure 1 refers to soil stabil9ization methods.

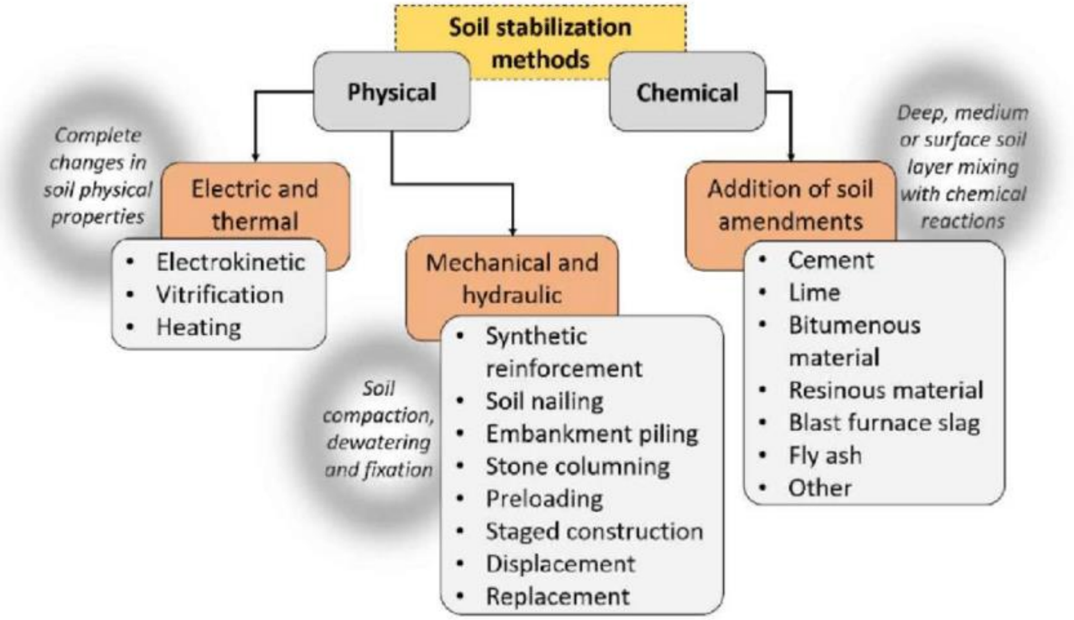

Figure 1. Soil Stabilization Methods through Various Techniques

Improving the base course capacity and stability to bear heavy loading and avoid distortion of pavements is a significant application in road construction (Bhavsar & Patel, 2014). Building foundations is important to have stable foundations and support for the residential, commercial, and industrial building foundations. Protecting vulnerable land from being washed away by water or blown away by wind, for instance in riverbanks, slopes, and coastal lines. Building containment structures to minimize the mobility of leachate and its effects on the groundwater(Zorluer & Gucek, 2014). There are distinct types of soil, requiring various methods of stabilizing such and therefore the need for tests on the soil type to be stabilized. Despite this, chemical stabilizers have undesirable impacts on the environment, and this necessitates the need to select environmentally friendly products. Several authors state that the price of work methods in soil stabilization techniques may differ depending on certain factors related to the project. It is critical not only to achieve the desired stabilization outcomes in civil construction projects but also to ensure their durability into the future.

5. Challenges Encountered while using Waste Marble Powder

5.1 Variability in Soil and Additive Properties

The marble industry discharges a lot of waste materials; if the waste is not managed well, it will only compound the problem of pollution (Gray & Sotir, 1996). Among the sustainable solutions include the modification of using waste marble powder in the stabilization of the soil which in the process also enhances the value of waste by reusing rather than disposing. Still, basic relations between the amount and type of waste marble powder and the improvement of

CBR and UCS are observed, however, the relations are not strictly progressive (Fawaz et al., 2024).

5.2 Long Term Durability

It may seem that in many cases, traditional bivariate and multivariate analysis procedures may not properly capture such linkages, which is why one must look for more complex computational algorithms. In this regard, it can be argued that ANNs can indeed be seen as solving this problem because the networks can capture the nonlinearity that might be present in the relations between the input variables and the output responses. MATLAB-developed ANN models will assist in the development of a useful tool to estimate the CBR and UCS of the required stabilized soils with waste marble powder and hence, assist in increasing the efficiency of the evaluation of soil stabilization (Elahi et al., 2022).

6. Previous Studies on Soil Stabilization with Waste Marble Powder

Some researchers have stated that by incorporating WMP, there is an improvement in the strength of the soil with a decrease in the plasticity of the soil. The treated soils are packed with marble powders and most of the angular particles fit into the interstices to minimize the swell/shrink ability of the soil (Yao et al., 2023). This, in turn, translates to better performance indicators including the UCS and the CBR. When incorporated into a particular WMP, it tends to lower the overall OMC of the soil. This means that at this stage, soil specimens can achieve the maximum compaction with the least water content; this could be regarded as being of benefit, especially in construction sites that experience variable rainfall intensity (Mozumder & Laskar, 2015). In the previous research, most of the researchers observed that as the quantity of WMP in the mixture increases, the workability of the mixture as indicated by the Plasticity Index (PI) decreases. This would imply less variation in the contraction and expansion of the soil and therefore give better control of the volume of the soil available (Bilim et al., 2009). Thus, it can be stated that the usage level of WMP seems to have a level of maximum importance, beyond which its importance is lower. For instance, in the given work, it has been suggested that for obtaining optimal conditions in terms of the higher strength combined with the workability of the final composite material, the content of WMP can constitute the range of 15 to 20% of the total weight (Bilim et al., 2009).

In conclusion, with all the above findings, Table 3 and figures 2 and 3, it is recommended that waste marble powder can indeed serve as a viable and sustainable option as a soil-stabilizing material. However, one must clarify that it is possible to make the following statement that the use of WMP depends on the type of soil that can be used to obtain the appropriate engineering characteristics (Uddin et al., 2022). These results can be several types of soil, with future research utilizing much higher values, which have not been considered in this study (Rajeshwari & Mandal, 2019).

Recent advancements in the field of deep learning reveal them as useful in estimating the characteristics of stabilized soil containing waste marble powder. Research has established that deep learning techniques like multi-expression programming, gene expression programming, Artificial Neural Networks (ANNs), and Extreme Gradient Boosting (XGB)can accurately predict the CS and other characteristics of WMP-stabilized soil. The input variables that are always reported to have a major influence on the models include the amount of WMP, moisture content, and curing time(Rane et al., 2023).

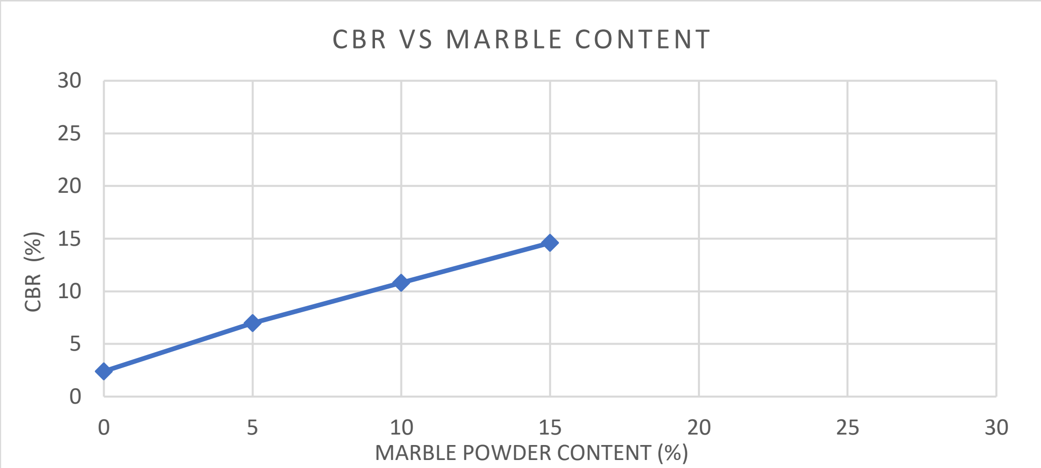

Figure 2.CBR vs Marble Content (Plotted from previous data table)

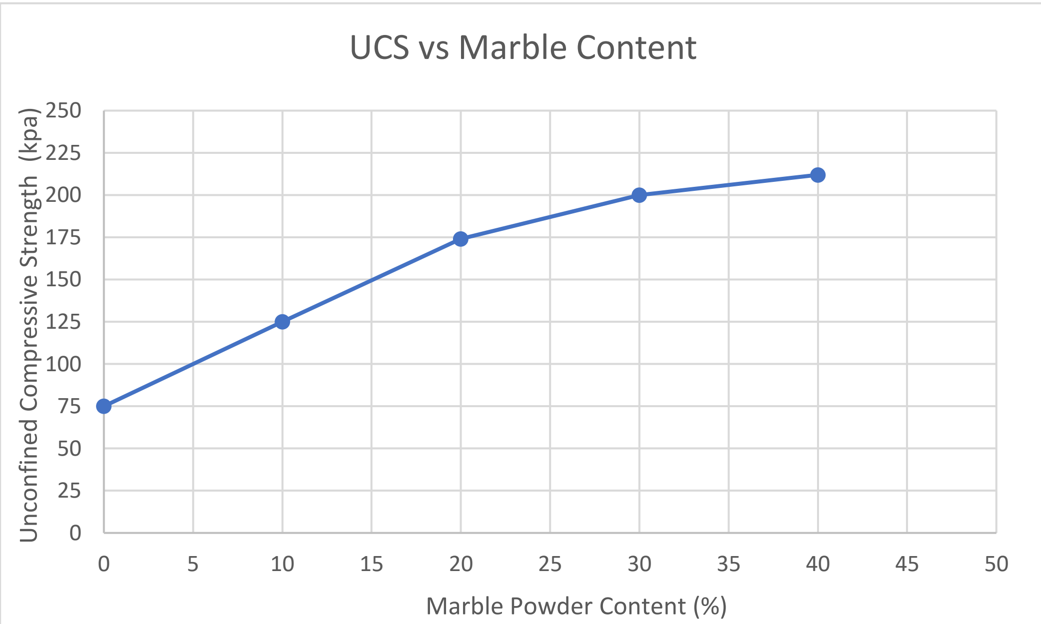

Figure 3.UCS vs Marble Content (Plotted from previous data table)

Table 3. Previous studies on soil stabilisation using WMP

Author Name	Testing Types	Type of Material	Percentage of Material used	Conclusive Remarks
Saygili, 2015	MDD/OMC and Unconfined Compressive strength	Marble Dust	5%, 10%, 20%, 30%	The optimum moisture content decreased from 16.5% to 15.5% with the addition of marble dust, while the maximum dry unit weight increased from 17.1 to 18.0 kN/m³. Unconfined compressive strength also improved, ranging from 55 kPa to 200 kPa as the

				marble dust content increased.
Krichphon Singh, V.K.Arora, 2017	Unconfined Compression Strength	Rice husk ash, fly ash and Marble dust	Rice husk Ash- 10% Fly Ash- 8% Marble dust- 20%	The soaked unconfined compression strength of rice husk ash-stabilized expansive soil increased with the addition of marble dust up to 20%, after which further addition reduced the strength. However, incorporating fly ash content led to a 14% increase in unconfined compression strength of the soil.
Narendra Marukaa Ravi Kant Pareek,2023	California Bearing Ratio	Marble Dust	10%, 15% and 20%	The CBR values of the soil increased significantly with the addition of marble dust, starting from 1.61% at 0% marble dust. At 10%, 15%, and 20% marble dust, the CBR values improved to 8.25%, 11.19%, and 10.43%, respectively.
F. Yilmaz and M. Yurdakul, 2016	Unconfined Compressive Strength at 7 Days and 28 Days	Marble Dust	5%, 10%, 15%, 20%, 25%, 30%, 35%, 40%	The 7-day unconfined compressive strength ranged from 100 to 210 kPa, while the 28-day compressive strength ranged from 115 to 255 kPa, both increasing with higher marble dust content.
Chen, James A. & Idusuyi, Felix O, 2015	California Bearing Ratio, Atterberg Limit and Unconfined Compressive Strength.	Waste Ceramic Dust	10%, 15% and 20%	The UCS increased from 55 kN/m² to 98 kN/m² as the waste ceramic dust (WCD) content rose from 0% to 30%. Additionally, the soaked CBR value improved by 150% with 30% ceramic dust, while the swell percentage decreased from 71% to 35%.
Sachin N. Bhavsar , Ankit J. Patel, 2012	MDD/OMC, Atterberg Limits, Linear Shrinkage	Marble Dust	Black cotton soil- 50% Marble powder- 50%	Replacing 50% of soil with marble powder reduced the liquid limit by 15.55%, the plastic limit by 7.597%, and the plasticity index by 7.956% compared to black cotton soil. Additionally, marble powder increased the maximum dry density by 14.05%, reduced the optimum moisture content by 6.8%, and decreased the linear shrinkage by 19.7%.
Ibrahim Haruna Umar, Hang Lin, Awaisu Shafiu Ibrahim, 2023	Specific Gravity, Atterberg Limit	Marble Dust	45%	Increasing the percentage of marble powder in clay soil to 45% raises the specific gravity from 2.73 to 2.83, with no further change beyond this level. Additionally, the plasticity index significantly decreases from 32.6% in clay soil to 22.6% with the addition of waste marble powder.
Najwa Wasim Jassim, Hanan Adnan Hassan, 2022	MDD/OMC, Plasticity Index	Marble Dust	0 - 15%	The plasticity index decreased by about 22% with the increase in the Marble dust content from 0% to 12%.The maximum dry density of the treated soil mixture increased by about 14% whereas the optimum moisture content OMC of the mixture decreased by about 26% with the addition of 15% marble dust content
Hassan A. M. Abdelkader, Mohamed M. A. Hussein, Haiwang Ye, 2021	California Bearing Ratio, Atterberg Limit, MDD/OMC and Unconfined Compressive Strength.	Marble Dust	5-25%	The addition of up to 25% marble dust significantly reduced the liquid limit, plastic limit, and plasticity index, while increasing the maximum dry density (MDD) from 18.42 kN/m³ to 20.2 kN/m³. The unconfined compressive strength (UCS) rose from 417 kPa to 600 kPa, and the soaked CBR improved by 108%, from 6.19% to 12.9%, compared to untreated soil.
Osman Sivrikaya, Firdevs Uysal, Aysegul Yorulmaz & Kemal Aydin, 2020	Plasticity Index, Expansion Index, Linear Shrinkage	Marble Dust	0-50%	The marble powder ratio which gave the best results was determined as 50% for both MH samples and CH samples. The laboratory test results showed that the waste marble powders were effective in soil stabilization by reducing the plasticity index from 49 to 26 for the CH samples and from 21 to 9 for the MH sample.
KMN Saquid Wani, B. A. Mir	California Bearing Ratio,	Marble Dust	0-14%	The addition of 21% waste marble dust increased the un-soaked CBR from 6% to 18% and the soaked CBR

& Ishfaq Rashid Sheikh, 2021	Unconfined Compressive Strength.			from 3% to 12%, showing improvements of 200% and 400%, respectively, making it beneficial for pavement construction. Additionally, UCS values rose significantly, from 65 kPa to 490 kPa with 14% marble dust after 7 days of curing.
Sumit Shringi, Vishvendra Singh, Dr. B. Acharya, 2018	Plasticity Index, Linear Shrinkage	Marble Dust	30%, 40%, 50%	Reduction in plasticity index for 30, 40, 50 % marble powder are respectively 15.63, 23.63, & 30.48 %. With increasing marble powder content the linear shrinkage is reducing.
Ismail Zorluer and Suleyman Gucek	California Bearing Ratio, Unconfined Compressive Strength.	Marble Dust & Fly Ash	Marble Dust - 10% Fly Ash- 20%	CBR test showed an increase of 60–75%, in parallel with the increase in amount of additive material. Unconfined compressive strenth shows an increase of 40% when conducted after 56 days curing.
Anukant Lohia, Er. Sunil Kumar and Er. Vikram	California Bearing Ratio	Marble Dust	10%, 15%, 20%	The CBR value of the soil is increased with increasing order of marble dust percentage. The optimum results were found when soil was stabilized with 15% marble dust. The CBR value is increased from 2.40 % to 14.6. %
Parte Shyam Singh and Yadav R K	Plasticity Index, Shrinkage Limit	Marble Dust	0-40%	The addition of up to 40% marble dust reduced the liquid limit from 57.67% to 33.90% and lowered the plasticity index from 28.35% to 16.67%. Additionally, the shrinkage limit of the black-cotton soil increased significantly from 8.06% to 18.39% with 40% marble dust.
A. B. Muhiddin, T. Harianto, A. Arsyad and Indriyanti	California Bearing Ratio, Unconfined Compressive Strength.	Marble Dust	0-30%	Maximum CBR value occurs in mixture with 30% marble powder with an increase of 168.2%. With the addition of 30% marble to the original soil and with 7-day curing, the mixture gain UCS strength up to 354.54%
Shelema Amena, 2022	California Bearing Ratio,	Marble dust and Plastic strips	Marble dust - 20% Plastic Strips- 0.25%	The values of CBR increased from 1.5 to 6.2% in addition to 20% marble dust and 0.75% plastic strips.The CBR swell of the expansive soil decreases with the addition of marble dust and plastic strips.
P. Meenakshi, Y. Sai Krishna 2023	Unconfined Compressive Strength, Shear Strength	Marble dust, Calcium Chloride	Marble Dust- 9%, Calcium Chloride- 2%	The addition of 9% marble dust and 2% CaCl2 significantly increased the unconfined compressive strength and cohesion of the soil. Marble dust improved strength by 128.8%, while CaCl2 further boosted it by 235.5%, with cohesion increasing by 80% and 165% respectively. Overall, the combination of marble dust and calcium chloride enhanced the soil's shear strength and stability.
Başer, O. 2009	swelling percentage, and rate of swell	Marble dust	0-30%	Waste limestone dust and waste dolomitic marble dust were applied to expansive soil at 0–30% stabilizer. As the stabilizer percentage increased swelling percentage reduced and the rate increased.
Ranjit Singh Vinod Kumar Sonthwal, 2021	MDD/OMC and California Bearing Ratio	Marble dust and Polyproplyne Fibre	Marble dust- 10-30%, Polyproplyne- 0.1 to 0.3%	The optimal CBR results were achieved with a combination of 30% marble dust and 0.1% polypropylene fiber. The highest MDD was 2.15g/cc with 30% marble dust, while the lowest was 1.8g/cc with 30% marble dust and 0.3% polypropylene fiber.

Its advantage comes in handy by giving a precise relationship of non-homogeneous variables like WMP content with soil properties, than the conventional techniques (Khademi et al., 2017). These models can be employed to identify the optimal percentage of WMP to fulfill the requirement of strength and performance for the stabilized soil mixtures (Golafshani & Pazouki, 2018). From a broad perspective, therefore, the literature reveals deep learning as a useful tool for the assessment of how the WMP-stabilized soil is likely to behave. This makes the construction industry better in terms of efficiency and sustainability as waste is recycled and put into use and at the same time ensures the construction's stability (Najigivi et al., 2013).

Future studies may be conducted to understand the applicability of these conceived models in other types of soil and conditions with other WMP characteristics (Kovačević et al., 2022). By using the findings from the geotechnical engineering domain, it is possible to promote the stability and efficiency of deep learning models. Thus, in the future, researchers could explore the possibility of using long Short-time Fourier Transform for the prediction of other properties like flexural strength and durability (Hanandeh et al., 2020).

Analyzing these points, it is possible to bring out the ideas of how deep learning can make the more powerful tool for utilization of the WMP in soil stabilization in longer terms.

7. CONCLUSIONS

In conclusion, the use of waste marble powder (WMP) for stabilizing soil has emerged as a promising and sustainable solution for enhancing the engineering properties of soils, particularly in the construction and geotechnical sectors. The review highlights that the incorporation of WMP significantly improves various soil properties, including compaction characteristics, plasticity index, shear strength, and durability. Waste marble powder not only enhances the structural performance of soils but also provides an effective means of recycling industrial byproducts, contributing to environmental sustainability.

However, despite the positive results from numerous experimental studies, challenges remain in optimizing the correct dosage of WMP for different soil types and understanding its long-term effects on soil behavior. The variability in results suggests the need for further research to develop standardized guidelines for its application, as well as to assess the environmental impact and cost-effectiveness of large-scale implementation.

Future studies should focus on the development of more comprehensive and detailed investigations, including long-term field trials, to better understand the durability and performance of WMP-stabilized soils under diverse environmental conditions. With continued research and refinement, waste marble powder has the potential to become a valuable resource in soil stabilization, offering both technical advantages and ecological benefits in the construction industry.

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