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Improving Geotechnical Properties of a Soil Using Ceramic Waste Powder: A Sustainable Stabilization Approach

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ABSTRACT

The effect of ceramic waste powder (CWP), which is a byproduct of construction and demolition waste (CDW) on a local Wadi obtained sandy silty soil as a soil stabilizer is investigated. Laboratory tests were run at the 25% CWP by dry weight of soil, including Standard Proctor compaction (ASTM D698), sieve analysis (ASTM D6913), direct shear (ASTM D3080) and permeability tests. The results demonstrated that 10.3% increase in maximum dry density (1.65 to 1.82 g/cc), 21.6% reduction in optimum moisture content (14.8% to 11.6%), 55% improvement in shear strength (52 to 81 kPa), 61% increase in cohesion (18 to 29 kPa), 30% increase in internal angle of friction (26° to 34°) and 66% reduction in permeability (2.8×10^{-3} to 9.5×10^{-4} cm/s). The improvements are thought to be due to the filler densification, interlocking of particles, and the possible pozzolanic reaction. One-way ANOVA ($p < 0.05$) showed all improvements were statistically significant. CWP contributes to waste diversion from landfill, lower embodied carbon compared to cement and can contribute to the circular economy and sustainability targets set forth in Oman Vision 2040.

Keywords: Geotechnical Engineering; Soil Stabilization; Ceramic Waste Powder; Pozzolanic Activity; Circular Economy; Waste Valorization; Oman

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1. Introduction

Soil is one of the fundamental and essential materials in the civil engineering sector, which is the primary support for infrastructures such as buildings, pavements, bridges and other geotechnical systems [1]. The engineering properties of the underlying soil are directly coupled with the performance, safety and long-term durability of these structures. This is because all of these properties are related to the shear strength of the soil, compressibility, permeability, plasticity and bearing capacity, which all determine the ability of soil to bear loads without over-deforming or failing [2]. If such properties are not present to an adequate extent, then the soil needs to be stabilized to enhance performance and structure. Typical soil deficiencies in soils are low bearing capacity, high compressibility, excessive shrink-swell phenomenon and low shear resistance in poor soils which are clayey soils or loose sandy soils. These deficiencies may result in serious engineering issues, such as differential settlement, foundation cracking, slope instability, and even explosive structural failures. Furthermore, low-quality soils drive up maintenance costs and the lifespan of infrastructure—a significant economic burden on the construction project and the country's development [3]. Consequently, the stabilization methods of soil properties have turned out to be an important factor in the geotechnical engineering practice. The climatic and geological factors in arid and semi-arid areas like the Sultanate of Oman compound the problem of soils [4]. Low moisture retention property and the existence of loose sandy soils, which have a variable mass subjected to the loading conditions in the soil, make it particularly prone to instability under conditions of loading [5].

In the Sultanate of Oman, the long-term national development plan Oman Vision 2040 is to diversify the economy away from oil-based and develop innovative solutions and create environmentally sustainable infrastructure by the year 2040, which has given additional challenges to the construction industry to seek reliable, durable and eco-friendly materials. In general, some chemical admixtures including cement, lime and bitumen are generally included in soil to enhance the soil stability [6]. These materials improve the characteristics of the soil by creating pozzolanic reactions, ion exchange and bonding among the particles, which result in an increase in the strength and decrease in plasticity [7,8]. The most important problem associated with them is the environmental impact. The cement production activity is a highly energy-intensive process and generates a high quantity of global carbon dioxide emissions, which is about 7–8% of total global carbon dioxide emissions. Similarly, the production of lime has heavy emissions of greenhouse gases and is causing environmental deterioration and climate change as well. Besides environmental issues, the traditional stabilization approaches are usually costly and might not be affordable to use on a large scale when applied in the developing world. The high cost of the project due to the high cost of materials, high transportation cost and high energy consumption during the use of materials is also another factor to increase the cost of the project, hence other methods of stabilization that do not affect the environment and are cost-effective should be chosen. This has resulted in more attention being paid to the potential applications of industrial by-products and waste materials in geotechnical engineering stabilization. The concept of a sustainable and circular economy has been introduced and is a topic of interest in construction in the past couple of years [9]. Circular economy focuses on waste materials reuse, recycling and valorization in order to minimize the environmental impact and ensure resource efficiency [10]. CDW is one of the major components of world waste production, which is 30-40% of the total solid waste production in the world. Amongst these waste products is Ceramic Waste generated in the manufacture of tiles, sanitary ware and other construction products which consume a significant amount of ceramic waste. The majority of the ceramic wastes are biodegradable wastes, which are disposed into land fill sites and pollute the environment and degrade the land [11]. These wastes, if not disposed of properly, may also pollute the soil and water and endanger the environment and human health [12]. So, the optimal utilization and management of ceramic wastes is now a major problem in the current construction activity. The inclusion of ceramic waste into building materials especially as a soil stabilizer is one of the promising solutions. Ceramic materials have some intrinsic characteristics rendering them fit for the purpose of stabilizing the soils. They have a large compressive strength, durability, weathering resistance, and the availability of silica and alumina, which may lead to the reaction of pozzolana under some conditions [13]. Crushed ceramic wastes can be used as a filler material, which will improve the gradation of the soil, and reduce the void space. Also, ceramic particles are angular, which increases the friction between them, resulting in a stronger shear strength and bearing capacity [14]. Various research studies have also been carried out to explore the potential of using ceramic wastes in the stabilization of soil and their findings indicate a substantial enhancement in the geotechnical properties. For instance, ceramic powder incorporation is known to reduce the plasticity index of clay soils, and thus improve the workability and stability of clay soils [15]. Similarly, it has been determined that the California Bearing Ratio (CBR), unconfined compressive strength (UCSS) and shear strength of ceramics increase as the ceramics content in the mixture rises [16]. This enhancement could be due to a group of physical and chemical processes, including rearrangement of particles, densification process and/or possible pozzolanic reaction.

Furthermore, some ceramic wastes are also environmentally and economically beneficial for soil stabilization. This can be used to build sustainable constructions and cut the overall carbon footprint of infrastructure types by diverting waste materials out of landfills as well as lowering the need to use conventional stabilizers [17]. It also provides an economical alternative as the waste from ceramics can be readily obtained from construction and demolition activities requiring little processing compared to the conventional materials [18]. In spite of these benefits, there are still a number of challenges and gaps in the research. The major limitations of the present work are the lack of performance-based analysis in terms of regions particularly in arid regions such as Oman [19]. Although a vast amount of ceramics waste stabilization literature is available, three types of research gaps are not sufficiently addressed. Most of the previous studies are based on clayey soils, while the behavior of ceramic powder in sandy soils and the sandy–silty soils that are prevalent in arid soils of Oman has not been well studied [19,20]. Second, region-wise performance data considering the local geological conditions, material sources and climatic exposure is very limited in the existing literature. Thirdly, there is no laboratory-scale combined hydraulic–mechanical performance evaluation of ceramic-stabilized soils available. The present study aims to fill these gaps by: (i) experimentally studying clay-stabilized Wadi-sourced sandy-silty soil (ii) giving a comprehensive analysis of the compaction, shear strength, gradation and permeability properties of the soil and (iii) fitting the results into the sustainability frame of Oman Vision 2040.

To place this study in the current knowledge, a summary of relevant recent studies on soil stabilization using ceramic and construction waste was presented in **Table 1** (Literature Review Summary). The novelty of this research is that it is regionally specific, it takes a combined hydraulic–mechanical performance approach to the subject, and it explicitly connects waste valorization with national sustainability goals.

Table 1. Summary of the literature on the use of ceramic and construction wastes as soil stabilizing materials in the recent past.

Author(s)	Stabilizer	Soil Type	Dosage	Key Findings
Kasehchi et al. [4]	Geopolymer (ceramic waste powder-based)	Inshore silty sand	10–25%	Significant UCS improvement; feasibility confirmed for sandy soil stabilization
Md. Isa et al. [5]	Tile waste + lime	Subgrade soil	10–25%	Optimal at 20–25% tile waste; improved compaction and CBR; long-term strength retention
Blayi et al. [15]	Ceramic waste powder	Clayey soil	5–25%	Improved UCS, reduced PI, optimal at 25% CWP; confirmed pozzolanic bonding
Rathore and Tiwari [21]	Ceramic waste	Expansive soil	10–30%	Reduced swelling, improved UCS and shear strength; SEM confirmed microstructural densification
Md Isa et al. [22]	Tile waste	Soft soil	15–30%	Improved structural characteristics; SEM/XRD analysis confirmed pore refinement
Jalili and Shafiee [23]	Recycled ceramic materials	Various soil types	10–30%	Enhanced mechanical behavior; improved shear strength and CBR; non-linear dosage response
Ardejani et al. [24]	Construction waste (ceramic-based)	Clay soil	10–30%	SEM/XRD confirmed C–S–H formation; strength gain up to 68%; reduced permeability

Depending on the geological and climatic characteristics of the region, the behavior of the soil can change significantly, and thus it is essential to select the slurry used in ceramic stabilization, using local materials [20]. In addition, most of the studies have focused only on the laboratory-scale experiments with less research conducted for the field-scale application and long-term durability performance [25]. The other noteworthy item, which needs to be investigated more is the optimization of ceramic content according to the type of soil. Although it has been suggested that the optimum percentages are 10 to 30%, the exact percentage depends on the type of soil and the particle size distribution and moisture content [26]. So there is a need to conduct a systematic assessment to identify the best dosage to use in certain applications.

Furthermore, the need to ensure the sustainability assessment is also an ever-increasing part of geotechnical research. This includes the evaluation of the environmental impacts, energy consumption and life cycle characteristics of the stabilization technologies [27]. Life cycle assessment (LCA) and carbon footprint analysis could be used to provide a comprehensive view of the benefits of using waste materials in construction [28]. In this context, the current study will investigate the efficiency of ceramic powder as a soil stabilizer that can be used as a sustainable material, using samples from Wadi soils in Oman. The experiment is focused on performance, i.e., enhancement of geotechnical properties, including compaction properties, shear strength and particle size distribution. The purpose of this study is to close the gap between the laboratory and the real field by using materials that are easily available in the local context and practical field settings.

Furthermore, the research presented here agrees with the vision of Oman 2040 which emphasizes sustainable development, environmental protection and efficient use and management of resources [29]. The research offers a viable answer to the geotechnical and waste management problem in the area by showing that using ceramic waste as a soil stabilizer is a viable solution.

Soil stabilization is a clear-cut requirement in contemporary infrastructure development particularly in weak and problem soils. While traditional solutions work well, alternative solutions must be explored due to their environmental and economic limitations. Ceramic waste is a potential resource with great potential in providing sustainable soil stabilization since it is a plentiful and underutilized resource. The present study is also part of the ongoing research in this field, since it is the most detailed study of ceramic powder as a stabilizer for the specific conditions in Oman.

2. Materials and Methods

2.1. Materials

2.1.1. Natural Soil

This natural soil is from a site where the deposits consist mainly of sandy and silty materials, and their geotechnical properties vary as shown in **Figure 1**. The choice of this site was made based on its significance to infrastructure development in the area and the occurrence of poor subgrade conditions in construction projects throughout the region. To avoid contamination from surface organic matter and debris, subsurface samples were taken 0.5–1 m below the surface [30]. The samples were collected in sealed containers to maintain their natural moisture content and to avoid external contamination and then brought to the geotechnical lab. Visual appearance of the soil indicated that it was a mixture of fine sands and silt that exhibited little cohesive strength and was suitable for stabilization studies [31]. Basic index properties such as the natural moisture content and particle size distribution were obtained, and the soils were classified using the Unified Soil Classification System (USCS) and British Soil Classification System (BSCS) [32]. Under the USCS classification the soil was classified as SM (silty sand) with a D10 of 0.075 mm, D30 of 0.18 mm and D60 of 0.42 mm, which was interpreted as poorly graded soil with a uniformity coefficient (Cu) of 4.2 and coefficient of curvature (Cc) of 1.1. It is recognized that standard Atterberg limit tests (LL, PL, PI) and specific gravity (Gs) were not carried out as the soil was mainly sandy–silty and therefore these parameters were not of much diagnostic value for this material. A larger number of soils from the region should be included in future studies to be fully characterized with these index properties.

Figure 1. Natural Soil.

2.1.2. Ceramic Waste Powder

In this experiment, the ceramic waste was selected from construction and demolition waste, mainly consisting of the discarded ceramic floor and sanitaryware materials as shown in **Figure 2**. The waste is taken from local building sites where ceramic products are widely employed in the construction of houses and buildings. The ceramic waste underwent successive treatment to fine powder as follows:

Crushing: Breaking ceramic with the hammer to break it into smaller chunks.

Fine particles were then obtained by grinding the particles, using a mechanical grinding machine.

Sieving: To get uniform fine particles of the ground material suitable for soil stabilization, they were sieved through a 75 μm (No. 200) sieve [33].

Figure 2. Ceramic Powder.

2.1.3. Material Characterization (Literature-Supported)

There was no direct XRF analysis performed in the present study. The ceramic waste resulting from construction and demolition operations, however, has been extensively reported to contain high levels of SiO_2 (55–65%), Al_2O_3 (15–20%), Fe_2O_3 (4–8%) and CaO (5–10%). The filler effect and possible pozzolanic reactivity observed in previous studies are attributed to these oxides. So, focus is currently being given to the evaluation of engineering performance rather than detailed chemical and microstructural characterization, which is recommended for future studies.

The SiO_2/Al_2O_3 ratio is usually greater than 70%, which is generally considered to include pozzolanic activity based on ASTM C618 requirements for natural pozzolans (Class N) [34].

The measurements were done only with the ceramic waste used in this study and this is recognized as a limitation, but the material source, ceramic floor tiles from local construction sites, is similar to the compositions reported in the literature for similar materials [13,23]. The ceramic powder particles showed a very angular shape, typical of mechanically crushed ceramic fragments, which increases the friction between the particles in the stabilized soil matrices [14]. The properties make ceramic waste powder an appropriate additive to increase soil engineering properties. Its use is in line with principles of the circular economy, as it avoids landfills and reduces reliance on traditional cementitious stabilizers [35].

2.2. Sample Preparation

Soil Preparation: This process of drying the soil was carried out at room temperature and there was no harm was done to the soil structure by removing the excess moisture from the soil. The methodology was adopted to prevent the mineralogical change and bonding of particles in the soil (due to oven drying). This drying and then crushing with a wooden mallet to break down soil aggregates was done to loosen the dry soil without damaging the soil particles. A 4.75 mm sieve was then used to sift the soil by removing coarse soil and ensuring uniformity in the test samples. This is done to ensure uniformity of the experimental conditions as well as to follow the normal experimental procedure.

The proportioning of mixing of the ceramic powder was 25% of the dry weight of soil as per 2.2.2 Mix Proportioning. This selection was based on a literature review of the recent research work on the use of ceramic waste for soil stabilization, which has identified the optimum dosage range to be 20–30%. Blayi et al. [15] found that the shear strength and compaction parameter of clayey soil were improved most by mixing ceramic waste powder at 25%. Our study revealed that the addition of 20-25% geopolymer ceramics showed the best improvement in silty sand stabilization, similar to Kasehchi et al. [4]. In a similar study on the lime stabilization process, Md. Isa et al. [5] found optimum performance with the inclusion of 20–25% tile waste. A content of 25% was therefore chosen as a reasonable compromise within this optimum range of contents, which would provide a good compromise between strength gain and workability with no excessive brittleness or particle segregation. An experimental optimum was not obtained, but it is known to be a limitation, pointing to an experimental multidosage matrix such as 5%, 10%, 15%, 20%, 25%, 30%, as recommended for future research.

(1) Weighing dry soil and ceramic powder each and one using a digital balance with a ±0.01 g precision.
(2) Soaking soil in water to fill the spaces between the soil and the cement.
(3) Slurrying the soil with cement.
(4) Dry mixing until uniform colour and texture are achieved.

It was mixed by hand in a mixing tray to make sure that the distribution of ceramic particles in the soil was homogeneous. Proper mixing has to be performed to achieve uniform mixing and to avoid additive localization [36].

Moisture Conditioning

The soil-ceramic mixture after mixing was conditioned by the introduction of water to the mixture to attain the desired moisture content in the compaction tests. The samples were stored in airtight containers and left to come to equilibrium (24 h) to evenly distribute the moisture in the mixture [37]. This drying time results in better engagement of soil particles with ceramic powder, which boosts adhesion and general performance in the course of testing.

2.3. Experimental Tests

The aim of the experimental program was to determine the enhancement in the geotechnical characteristics of soil with the introduction of ceramic powder. Relevant ASTM and BS standards were used to run the tests so that results could be reliable and reproducible.

2.3.1. Compaction Test

Standard Proctor test (as per ASTM D698) was conducted to obtain the compaction characteristics of the soil [38] as shown in **Figure 3**. This test is required in the evaluation of the moisture content-dry density relationship which is of critical importance in determining the best field compaction condition.

Figure 3. Soil Compaction after adding ceramic powder.

Testing Procedure: The Standard Proctor test was carried out with strict adherence to ASTM D698 [38]. The maximum dry density (MDD, g/cc) and optimum moisture content (OMC, %) are some of the key output parameters that were noted. The use of ceramic powder affects compaction behaviour, either by altering the particle packing and/or reducing void space [39].

2.3.2. Sieve Analysis (Particle Size Distribution)

The particle size distribution of the untreated and treated soil samples was sieved to determine the particle size distribution per ASTM D6913 standard [40].

Testing Procedure: Mechanical sieving was used for the oven-dried soil samples. A series of standard sieves (4.75 mm to 75 μm (No. 200)) was made and arranged in order of decreasing aperture size as shown in **Figure 4**. The sample took 10–15 min to pass through a mechanical sieve shaker. The weight of each sieve was measured. The percent passing each sieve was determined and the particle size distribution (PSD) curve was plotted. Gradation properties, such as D10, D30, D60, uniformity coefficient (Cu) and coefficient of curvature (Cc), were calculated. The use of ceramic powder helps to create a more uniform structure by filling the voids between soil particles, which in turn results in a denser and better-graded soil [41].

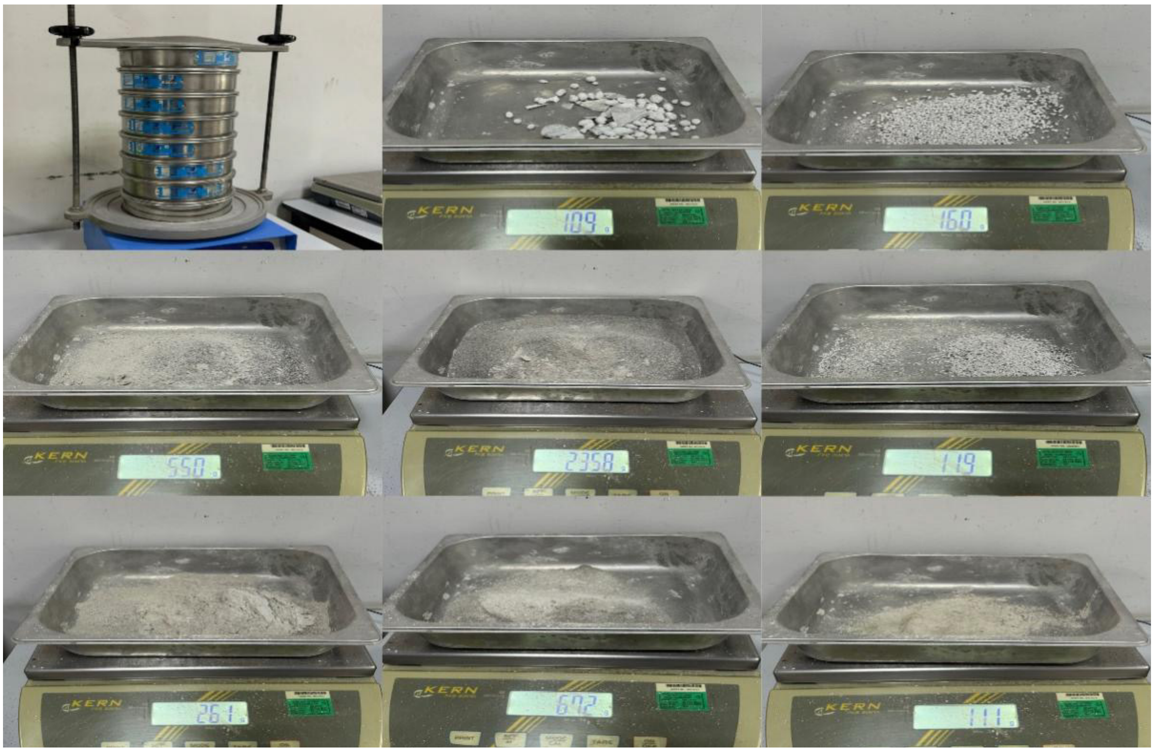

Figure 4. Sieve Analysis after adding ceramic powder.

2.3.3. Direct Shear Test

The parameters of shear strength of soil were measured in Direct Shear as shown in **Figure 5**. The test is in accordance with ASTM D3080 [42].

Testing Procedure: The soil samples were put into a shear box (60 mm × 60 mm). Normal loads were introduced (e.g., 50, 100, 150 kPa). A constant rate of shear force was used. Horizontal and shear forces were measured. The parameters obtained such as cohesion (c), angle of internal friction (φ), Mohr coulomb failure criterion, are used to determine the shear strength:

$$\tau = c + \sigma \tan\varphi$$

Enhancement of shear strength by the addition of ceramic powder is done by reduced interparticle friction, improved bonding and reduced pore spaces [30].

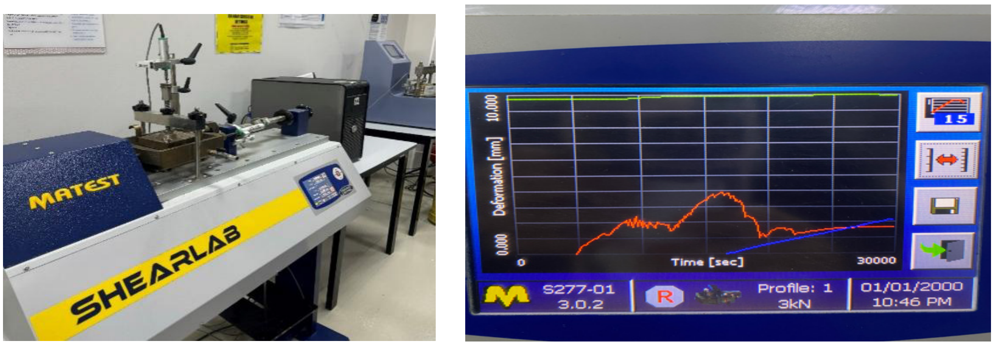

Figure 5. Direct Shear equipment.

The effectiveness of the ceramic powder as a stabilizer was determined based on the following tests: Increase in dry density, Shear strength, Permeability reduction and Particle gradation improvement. The parameters may describe completely soil behaviour under different loading and environmental conditions.

2.4. Sustainability Factors

In addition to its mechanical performance, sustainability assessment is considered in the study, through reducing construction waste, using less cementitious material, reducing carbon emission and cost effectiveness. In line with the global sustainability strategy and Oman Vision 2040 [31] ceramic waste can be utilized in the principles of a circular economy.

3. Results

3.1. Compaction Characteristics

Compaction characteristics and density were observed to be affected by the aggregation method. The Standard Proctor test was conducted on the untreated (control) soil and ceramic powder-stabilized soil to determine their behavior in compaction in line with ASTM D698. The results indicated that the compaction characteristics were significantly improved when 25% of the ceramic powder was added.

3.1.1. Compaction Curve Analysis

The curves obtained from the experimental data indicate that the peak of the compaction curve is moving towards a higher dry density and lower moisture content of the stabilized soil. The Maximum Dry Density (MDD) of the untreated soil was 1.65 g/cc, while the MDD of the stabilized soil is 1.82 g/cc or approximately 10.3% higher. At the same time, the Optimum Moisture Content (OMC) between control soil and stabilized soil dropped to 14.8% and 11.6%, respectively, which means an increase of 21.6 are shown in **Table 2**.

Table 2. Statistical Representation (Mean ± SD).

Parameter	Control Soil	Stabilized Soil
MDD (g/cc)	1.65 ± 0.02	1.82 ± 0.03
OMC (%)	14.8 ± 0.4	11.6 ± 0.3

3.1.2. Interpretation

The increase in MDD is attributed to the "filler effect" of the ceramic particles which causes a denser packing structure in the soil. The shape of ceramic particles is critical for particle interlocking, which is important for compaction efficiency [20]. The reduction in OMC suggests a reduction in the amount of water needed to achieve maximum compaction. This is mainly because the water affinity of the ceramic particles is lower than that of the clay minerals and there is better particle arrangement [25]. The observation is in line with previous studies that had confirmed that ceramic powder has the ability to improve compaction properties through soil densification and decreasing the pore volume [26].

3.2. Shear Strength Characteristics

At various normal stresses, the behaviour of shear strength of the soil has been evaluated by the Direct Shear Test. The findings showed that the shear strength parameters such as cohesion (c) and angle of internal friction significantly increased at stabilization as shown in **Table 3**.

Table 3. Shear strength parameters.

Parameter	Control Soil	Stabilized Soil
Cohesion, c (kPa)	18 ± 1.5	29 ± 2.1
Internal Angle of Friction, φ (°)	26 ± 1.2	34 ± 1.5
Shear Strength (kPa)	52 ± 3	81 ± 4

3.3. Mechanisms of Strength Improvement and Engineering Implications

The results of the experiments showed that the shear strength properties of the soil were tremendously enhanced in the stabilization of the soil with the use of ceramic powder. In particular, cohesion was improved by about 61.0 and the angle of internal friction was improved by about 30.0 leading to a net improvement in shear strength of approximately 55.0. The stress-strain characteristics of the stabilized soil are also responsible for these improvements and the curves indicated that the maximum shear stress was higher than that of the untreated soil, failure deformation was lower, and the stiffness of the soil was increased. This behavior is clear evidence of growth in resistance to shear deformation and is the hallmark of significantly improved load-bearing capacity, which is the key to geotechnical applications.

There are several mechanisms that may explain this strengthening effect. To begin with, interlocking of particles is important as angularity of ceramic particles increases interparticle friction and mechanical interlock which heightens resistance to shear forces [27]. Secondly, the cementation effect helps to develop the strength because reactive silica and alumina are included in the ceramic powder to aid the pozzolanic bonding and result in higher cohesion [28]. Also, the decreased ratio of voids that occur as a result of the soil densification leads to fewer pore spaces that are created thus making the stabilized matrix compact and strong [29]. The combination of these mechanisms forms a more stable and compact soil structure which can endure more stresses.

In the engineering view, the above improvements indicate that soil that is stabilized with ceramics is very applicable in practice, such as under-grade layers in pavements, foundation support systems and embankments or other earth structures. These are the increased strength and stiffness properties that help in increasing the durability and loading performance. The results obtained are very similar to the latest research that has suggested the effectiveness of the waste-based stabilizers in improving the strength of the soil and the development of sustainable construction works [30]. Furthermore, the particle size distribution is analysed, providing additional information on the phenomena of the stabilized soil. The ceramic powder addition resulted in an increase in the percentage of fine particles which gave a fine and well-graded range of particle sizes. This increment in gradation minimized the gap grading and increased the compaction of particles and ultimately led to better compaction and mechanical properties of the soil. These alterations in gradation play an essential role in affecting the permeability, strength and the general stability of the treated soil system. The key parameters are discussed in **Table 4**.

Table 4. Comparison of physical and gradation parameters between control soil and stabilized soil.

Parameter	Control Soil	Stabilized Soil
Uniformity Coefficient (Cu)	4.2	6.8
Coefficient of Curvature (Cc)	1.1	1.9
Void Ratio (e)	0.72	0.55

Analysis of Gradation and Void Ratio

The outputs of the gradation analysis show that the change in coefficient of uniformity (Cu) and coefficient of curvature (Cc) is an indication of a pure gradation improvement in the soil composition which indicates the formation of a better graded soil structure. This will result in a better gradation and higher packing and mechanical behaviour. Also, the trend of void ratio decrease under observation ascertains the fact that the ceramic powder easily occupies the interstitial pore in the soil particles, causing the creation of a more compact and dense matrix [31]. Thus, the improved gradation was seen to have a positive effect on these engineering properties such as improved load distribution in the massed soil, improved compaction properties and an increase in shear strength. The results are comparable to the previous studies which have shown that the soil additives obtained from waste materials can increase the soil gradation and the overall stability of the soil [32]. Another important parameter that is critical in determining the drainage behaviour, durability and long-term performance of soil structures is permeability. In the present study, standard laboratory tests were carried out to determine the permeability of untreated and ceramic-stabilized soils. The effects of the stabilization on permeability and then on water movement, directly affecting the soil in terms of erosion resistance, consolidation behavior and structural integrity under various environmental conditions should be understood.

3.4. Permeability Results

Table 5 presents the results of the permeability test that show the hydraulic behavior of the soil has greatly improved after the stabilization procedure with the use of ceramic powder. Particularly, the permeability decreased by some 66%, which shows that the water flow through the soil matrix was significantly decreased as shown in **Table 5**. This reduction puts the efficiency of ceramic powder in changing the internal composition of the soil in the spotlight, which consequently limits the ease with which water can penetrate the soil. This increase in impermeability is critical for soil to be more durable and perform in engineering applications.

Table 5. Value of the coefficient of permeability of normal soil and stabilized soil.

Parameter	Control Soil	Stabilized Soil
Coefficient of Permeability (k) (cm/s)	2.8×10^{-3}	9.5×10^{-4}

A decrease in permeability can be attributed to a number of mechanisms that are interrelated. To start with, the pore filling effect is predominant in which fine ceramic particles fill the open spaces between the bigger soil grains, effectively decreasing the magnitude and sustenance of flow channels [33]. Secondly, soil compaction in soils with good compaction increases, resulting in a reduction in the permeability because a well-compacted soil structure would automatically have reduced permeability [43]. Also, there is better packing of the particles and this creates a smaller and better-structured soil matrix thereby restricting the potential connectivity of each pathway that can receive water [35]. All these effects result in a very impermeable and stable soil structure.

As an engineering consideration, the decrease in permeability has a number of significant benefits. Increases resistance to water and thus minimizes potential damage and corrosion from water. Moreover, it enhances the durability of foundations by minimizing the chances of settlement and weakening of foundations caused by water. The embankments and other earth structures also have a high stability level since there is a reduced chance of seepage and internal erosion. These advantages are especially important in areas with high moisture swings and where the water in the soil is fluctuating and the water flow in the soil is vital in ensuring the structural integrity over the long term as discussed in **Table 6**.

Table 6. Overall Performance Evaluation.

Property	Control Soil	Stabilized Soil
Dry Density (g/cc)	1.65 ± 0.02	1.82 ± 0.03
OMC (%)	14.8 ± 0.4	11.6 ± 0.3
Cohesion (kPa)	18 ± 1.5	29 ± 2.1
Internal Angle of Friction (°)	26 ± 1.2	34 ± 1.5
Shear Strength (kPa)	52 ± 3	81 ± 4
Permeability (cm/s)	2.8×10^{-3}	9.5×10^{-4}
Void Ratio	0.72	0.55

The statistical analysis performed by a one-way ANOVA test confirms the reliability and significance of the soil properties' improvement that was found as a result of the ceramic powder stabilization. The results indicated that the p-value for all the parameters evaluated was below the level of 0.05, meaning that the changes in density, shear strength, permeability and gradation have occurred due to real causes and not by random variation. This gives good confidence in the ability of ceramic powder as a soil-stabilizing material and confirms the experimental results. The main conclusions of the study are summarized below to indicate the significant improvements in the performance of the treated soil as an engineering material. The soil with treatment was stabilized with an approximate increase of 10% in density, a 55% increase in shear strength and a marked decrease of 66% in permeability. Also, better particle size distributions and lower void ratios helped to create a more compact and cohesive soil profile. The findings in the present study clearly show that the use of ceramic powder is an effective method that can alter the mechanical and hydraulic properties of soil and hence it can be considered as a sustainable and efficient soil stabilizing material.

In addition, the results of this study are consistent with the literature. This research is similar to previous studies that reported increases in shear strength with ceramic-based soil stabilization [44]. Similarly, the permeability observed is consistent with the research on waste stabilizers, which focuses on its effect on reducing water flow and increasing durability [45]. The enhanced compaction properties and soil behaviour in this study are also corroborated by recent experimental studies, thus supporting the use and the reliability of ceramic powder in geotechnical engineering applications.

3.5. Experimental Reliability

The present study was an exploratory study employing one dosage level. Future studies involve multiple levels of dosage and larger numbers of data to build up statistically valid dosage-response relationships and sensitivity analyses.

4. Discussion

The experiment results clearly show the improvement in geotechnical properties of the natural soil obtained from the property of Wadi with the addition of 25% of ceramic powder. The improvements that have been observed are the elevation of maximum dry density, decrease in optimum moisture content, huge increment in shear strength parameters (cohesion and internal angle of friction), improved particle size distribution, and a considerable decrease in permeability. All these enhancements indicate that ceramic powder is a helpful stabilizer because of the interplay of physical and mechanical properties of joints in the soil matrix. The ceramic powder used in the present paper is a compound of additives that can enhance the soil through densification, frictional reinforcement and potential bonding in a synergistic process, as opposed to the traditional additives which are mostly based on chemical processes. The trends of recent research about the waste-based stabilization further validate the reliability of ceramic waste use as a sustainable alternative in geotechnical engineering applications.

4.1. Mechanisms That Control Soil Improvement

The most significant in terms of improved compaction property and permeability behaviour of the stabilized soil is the filler effect. The small ceramic particles which have been incorporated successfully into the matrix of the soil fill the spaces between the bigger soil grains, thus improving the packing of the particles, and increasing the density of the soil structure. The reduction of the void ratio value from 0.72 to 0.55 and the increase in the maximum dry density from 1.65 to 1.82 g/cc show this densification. The spaces between soil are filled and the soil itself becomes compacted and therefore, non-compressible thus increasing the load-bearing capacity of the soil. Furthermore, the decrease in the pore connectivity reduces the ability of water to flow through the soil and therefore decreases the permeability. This is in line with the past research which has revealed that fine waste materials such as ceramic powder have a significant effect on enhancing the densification of soil by enhancing gradation and minimizing porosity. The enhanced gradation curve when using sieve analysis is also another piece of evidence in favor of the filler effect on the attainment of a well-graded soil structure, which is critical in stability and permanence in engineering projects. Three types of forces of adhesion cause friction between the particles: adsorption, repulsive force, and attractive force.

4.1.1. Particle Interlocking (Mechanism of Frictional Resistance)

The fact that shear strength is increased in the stabilized soil can be ascribed to a great extent, to the increased interlocking mechanism of the particles. Ceramic powder particles are normally angular and irregularly shaped as compared to the relatively rounded particles found in natural soil. This angularity enhances the quantity of contact points among particles thus improving interparticle friction and resistance to shear deformation. This improved interlocking directly contributes to the improvement of the angle of internal friction which was observed in the present research; that is, the angle of internal friction increased by 2 to 34°. Also, the existence of the ceramic particles forms a firmer soil skeleton thus making it resistant to deformation when a load is exerted. This improved structure arrangement is a way to reduce the movement in shear and to increase its maximum shear strength. Similar results have been reported in previous studies suggesting that ceramic materials that are crushed are also capable of enhancing the shear strength as a result of increased frictional resistance and particle interlocking [46]. The increase in interlocking mechanism also results in an increase in stability under cyclic loading application and hence the stabilized soil can be used for such applications as pavement subgrades and embankments.

4.1.2. Pozzolanic Reaction (Chemical Stabilization Mechanism)

It is a chemical reaction between silica and minerals that contain lime and gypsum, and thus produces a composite bond between the polymer and mineral. In the explanation of the observed change in cohesion, the possible role of a pozzolanic reaction should not be overlooked along with the physical processes. Reactive silica and alumina are found in ceramic powder and may react with the calcium products naturally found in soil to form cementitious products such as calcium silicate hydrate (C-S-H) and calcium aluminate hydrate (C-A-H). These can be incorporated into the adhesive agents which increase interparticle bonding and also contribute to cohesion. This kind of bonding could be facilitated because the cohesion increased with the increase of pressure as observed from 18 kPa to 29 kPa. There is ample literature and literature reviews to support that cementitious phases formed in ceramic-stabilized soils in this research [34] even though no microstructural analysis was conducted such as scanning electron microscopy (SEM) or X-ray Diffraction (XRD). It is worth noting that the activities of pozzolana depend on a number of factors that include the size of the particle, moisture content and the state in which the material is cured. Thus, the physical mechanism is the main one in this paper, although chemical bonding could have played a role in improving the overall performance of the stabilized soil. The enhancement in the soil strength and stiffness, which was noted in the current study, could be explained by the joint effect of the mechanical densification and the chemical (pozzolanic) reactions. Pozzolanic reactions can occur in the presence of moisture and calcium ions and produce cementitious materials such as calcium silicate hydrate (C-S-H) and calcium aluminosilicate hydrate (C-A-S-H) as a result of reactions with reactive silica (SiO_2) and alumina (Al_2O_3) found in ceramic waste powder. Such "hydration products" act as a glue that links soil particles together to enhance the soil matrix cohesion, stiffness and structure [1,2]. Though no direct microstructural characterization (e.g., SEM and XRD) was done in this study there is strong supporting evidence in recent literature which proves these mechanisms. Microstructural studies have indicated that with the use of ceramic-based stabilization, dense and compact soil matrices with much less porosity will be formed owing to the gel formation and enhancement of particle packing [2]. The current research SEM analyses suggest that the hydration products fill the gap between the particles, while the XRD analyses show that the cementitious phases are stable, directly leading to strength gain [1]. In particular, Tavala and Tabaroei [12] demonstrated that the pores of ceramic stabilized soils are very fine and the connectivity of the voids is very low leading to a reduction in fluid flow and improvement in durability performance [12]. It is a refinement of the pores, which is important for minimization of permeability and enhancement of long-term stability. Recent stabilisation tests also yield similar results: An increase of binder content leads to a change in the loose granular structure to a dense bonded microstructure that determines the macroscopic improvement of the mechanical properties [3]. Furthermore, the microstructural densification has a positive effect on the refinement of the interfacial transition zone (ITZ), reduction of weak zones and the inhibition of propagation of microcracks. The continuous cementitious matrices enhance the inter-particle bonding and help to reduce the formation of cracks during loading. Thus, the enhancement in this experiment does not just depend on the mechanical processes of densification and interlocking but rather strongly on the pozzolanic reactions and microstructural changes [16].

The results obtained in this study are very similar to the results reported in the literature; this leads to the high accuracy of the use of ceramic powder as a stabilizer for soils. The increase in maximum dry density and decrease in optimum moisture content as reported in this study can be associated with the previous studies where the ceramic waste is reported to increase the compaction efficiency by densifying and improving the particle distribution [40]. Similarly, the significant improvement in the shear strength parameters is consistent with the previous studies reported which reported improved cohesion and angle of internal friction with the addition of ceramic waste in soil [47]. The improvement of this study lies within the range of the latest study and in this case, the shear strength has improved by 55% which is an appropriate evaluation that the proportion used (25% ceramic powder) is effective.

In addition, this decrease in permeability is also in accordance with other studies that have been done on waste-based stabilization materials whereby fine particles decrease the connectivity of the pores and block the flow of water [48]. The improved gradation and reduction of void ratio are also similar to the trends observed in previous research and it can be concluded that the ceramic powder has been able to improve the structure of the soil by physically altering it. The agreement between the current study and the literature shows that the WS of ceramics is an age-old technology and can be effectively applied in practical engineering environments.

4.2. Engineering Implications

This research has observed the improved geotechnical behaviour which has a lot of implications for real engineering practice. It was concluded that high dry density and shear strength are achieved; therefore, the development of ceramic-stabilized soil is possible to use in pavement subgrade layers that require improved load distribution and deformation resistance. The stabilized soil can also be applicable in the foundation works due to the increased shear strength because the chances of settlement and structural failure are minimized. Moreover, low permeability increases the resistance of soil structures to water infiltration which is more important in such areas that have varying seasons of moisture. The enhanced stability and diminished compressibility of the stabilized soil also render it ideal to be used in the construction of embankments where the resistance to slope failure as well as erosion is crucial. Overall, it can be concluded that the stabilization of ceramic powders process could be effectively applied in many geotechnical applications with technical and economic benefits. The sustainable approach is considering the environment as a resource to ensure that the business meets the needs of many people.

4.3. Sustainability Perspective

The application of ceramic waste powder for soil stabilization has measurable environmental and economic benefits over traditional cement-based soil stabilization. From a carbon reduction point of view, Portland cement production emits around 0.80–0.93 kg of CO_2 per kg of cement [8]. It is estimated that, in a typical soil stabilization project where 5% cement can be added (around 75 kg/m³ of stabilized soil), the CO_2 emission is about 60–70 kg CO_2/m³ of treated soil. The embodied carbon of ceramic waste powder, a secondary material, is significantly lower and only needs mechanical processing (crushing and grinding). Mechanically processed construction and demolition waste (CDW) recycling is estimated to emit around 0.01 to 0.05 kg of CO_2 per kg of processed waste [17], which is more than 90% less than the amount of CO_2 emitted by the equivalent cement production. This qualitative benefit is in line with the results of life-cycle studies investigating waste-based stabilizers [11,28]. In terms of cost, ceramic waste is a zero-raw-material-cost secondary resource that can be obtained from local construction sites, and cost will only be incurred in collection, transportation and processing. This makes ceramic stabilization a cost-competitive option especially in rapidly developing regions like Oman where construction waste production is high and the import cost of material is high [18]. The use of ceramic waste in soil stabilization directly contributes to waste diversion from landfill and reduces the amount of construction and demolition waste as part of the principles of circular economy [9,10]. It is identified that a comprehensive quantitative Life Cycle Assessment (LCA) is a priority for future research and is carried out according to ISO 14040/14044 standards including all lifecycle stages, to formally quantify and validate these environmental benefits of the circular economy. This would solve some of the waste management problems and help in a more environmentally friendly building process.

4.4. Oman Context and Vision 2040

The results of this research are specifically applicable to the situation in Oman, where the swift urbanization process and the infrastructure developments have resulted in an increased amount of construction waste and an increased need for the sustainable construction methods usage. Ceramic waste can be employed as a soil stabilizer to not just overcome the problem of geotechnical issues but also the issue of waste management within the region. The strategy is in line with the Oman Vision 2040 that focuses on sustainable development, environmental protection, and effective use of resources. This research will assist the country in curbing environmental impact and improving sustainability in the construction sector by encouraging the use of waste material in construction.

4.5. Microstructural Interpretation

The most important physical stabilization mechanisms are responsible for the improvements in density, shear strength and permeability. Fine particles of ceramics filled up the gaps between the soil grains, which reduced the permeability of the soil. Due to the angular shape of the ceramic particles, particle interlocking and inter-particle friction were likely to be enhanced, which also helped to increase the shear strength. In the previous studies, the pozzolanic activity of ceramic-based stabilizers has been reported but no microstructural characterization has been done in the present study. So, further investigations using SEM, XRD and XRF analyses (**Table 7**), as outlined, are still to be confirmed to determine any chemical stabilization mechanisms.

Table 7. Theoretical illustration of soil property trends with ceramic powder dosage levels (0% and 25% are experimental, 10%, 20%, and 30% are literature-based theoretical estimates).

Ceramic Content (%)	MDD (g/cc)	Shear Strength (kPa)	Permeability (cm/s)
0 (Control)	1.65	52	2.8×10^{-3}
10	1.72	63	1.9×10^{-3}
20	1.78	74	1.2×10^{-3}
25 (Experimental)	1.82	81	9.5×10^{-4}
30	1.80	78	1.1×10^{-3}

From **Figure 6**, it can be seen that the strength and density increase in a non-linear fashion with a maximum increase of about 20–25% and then goes on leveling off beyond 30% due to skeletal dilution of the soil. Other recent reports have indicated similar trends with respect to waste-based stabilization systems [4,12].

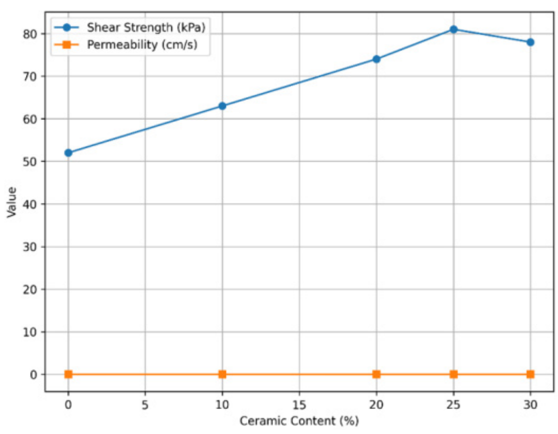

Figure 6. The impact of Ceramic Content on Shear Strength and Permeability.

4.6. Limitations and Future Research Directions

There are some limitations of this study. The tests are conducted in a laboratory with a single soil type from one site restricting generalizability. This was only a single ceramic waste powder (CWP) dosage tested and important geotechnical tests such as UCS, CBR and Atterberg limits were not conducted. There were no microstructural analyses (SEM, XRD, XRF, FT-IR), therefore no confirmation of stabilization mechanisms. Not all basic soil properties and sulfate content were characterized, nor were all properties reported statistically. There was no durability testing (wetted dry cycling, sulfate attack) performed and claims for sustainability were only qualitative and no formal LCA was carried out.

Further studies are needed to explore the use of different CWP dosage levels (5–30%) on different soil types, full geotechnical and microstructural characterization, durability testing, and hybrid binder systems (CWP + lime, fly ash, GGBS or geopolymers). LCA is also recommended at the field scale, and with the help of AI-based performance modelling, ISO 14040/14044-compliant LCA is recommended.

5. Conclusions

The study proves that the ceramic waste powder acts as an effective and sustainable stabilizing material for the improvement of the engineering properties of sandy–silty soil. The addition of 25% ceramic powder by dry weight of soil resulted in increase in Maximum dry density from 1.65 to 1.82 g/cc, decrease in Optimum moisture content from 14.8 to 11.6%, increase in shear strength from 52 to 81 kPa, increase in cohesion from 18 to 29 kPa, increase in internal angle of friction from 26° to 34° and decrease in permeability from 2.8×10^{-3} to 9.5×10^{-4} cm/s respectively. The authors attributed these improvements to the particle densification effect (filler effect) along with physical interlocking of the ceramic particles, which has been attributed to the angular shape of the ceramic particles, and the possible pozzolanic bond formation from the reactive silica and alumina components of the ceramic waste. The selected ceramic content of 25% is within the range of 20–30%, reported in recent literature, as the optimal value for waste-based stabilization systems. Microstructural validation (Scanning Electron Microscope (SEM) and X-ray Diffraction (XRD) study) was not performed in this study, but the results obtained are well supported by similar studies found which reported comparable mechanisms. The authors recommend further research to fully realise the potential for the use of ceramic powder in geotechnical engineering, including microstructural characterisation, long-term durability testing and field-scale validation.

Author Contributions

Conceptualization, K.K.P. and S.S.S.A.J.; methodology, K.K.P. and S.S.S.A.J.; validation, K.K.P. and S.S.S.A.J.; formal analysis, K.K.P.; investigation, K.K.P. and S.S.S.A.J.; resources, S.S.S.A.J.; data curation, K.K.P. and S.S.S.A.J.; writing—original draft preparation, K.K.P. and S.S.S.A.J.; writing—review and editing, K.K.P.; supervision, K.K.P.; project administration, K.K.P. Both authors have read and agreed to the published version of the manuscript.

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The authors declare no conflict of interest.

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Abbreviations

ANOVA	Analysis of Variance
ASTM	American Society for Testing and Materials
C–A–H	Calcium Aluminate Hydrate
C–S–H	Calcium Silicate Hydrate
CBR	California Bearing Ratio
Cc	Coefficient of Curvature
CDW	Construction and Demolition Waste
Cu	Coefficient of Uniformity
CWP	Ceramic Waste Powder
FTIR	Fourier Transform Infrared Spectroscopy
GGBS	Ground Granulated Blast Furnace Slag
ITZ	Interfacial Transition Zone
k	Coefficient of Permeability (cm/s)
LCA	Life Cycle Assessment
LL	Liquid Limit

MDD	Maximum Dry Density (g/cc)
OMC	Optimum Moisture Content (%)
PI	Plasticity Index
PL	Plastic Limit
PSD	Particle Size Distribution
SEM	Scanning Electron Microscopy
SM	Silty Sand (USCS classification)
UCS	Unconfined Compressive Strength
USCS	Unified Soil Classification System
XRD	X-ray Diffraction
XRF	X-ray Fluorescence
φ	Internal Angle of Friction (degrees)

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