

Stabilization of soil with waste ceramic powder & calcium carbide residue for subgrade application

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ABSTRACT

The rapid depletion of natural resources and increasing industrial waste production underscore the urgency for sustainable soil stabilization strategies. This study presents a comparative evaluation of waste ceramic powder (WCP) and calcium carbide residue (CCR) as sustainable additives for enhancing the engineering properties of clayey soil. Reusing these industrial by-products not only mitigates landfill pressure and groundwater contamination but also conserves natural construction material. Soil samples treated with varying proportions of CCR and WCP were subjected to tests including Atterberg limits, Standard Proctor compaction, pH, Differential Free Swell (DFS), and Unconfined Compressive Strength (UCS) after 3, 7, and 28 days of curing. Test results revealed substantial improvement in soil characteristics, with CCR showing slightly superior results. The addition of CCR and WCP altered the soil classification from CH to MI and CL respectively. CCR addition reduced the Plasticity Index from 24.14% to 5.31%, making the soil suitable for subgrade applications. WCP increased MDD and reduced OMC, while CCR showed the opposite trend due to its fine particle size and pozzolanic nature. The swelling potential was significantly reduced, and after 28 days of curing, the UCS improved by 2.08 times with CCR and 1.81 times with WCP. Beyond stabilization, this study highlights the future potential of CCR as an alkali activator and WCP as a geopolymer precursor, supporting their application in sustainable and resource-efficient geotechnical and construction practices.

Keywords: Soil stabilization, WCP, CCR, Waste management, UCS.

1. Introduction

The growing demand for construction and limited availability of land have compelled researchers and engineers to modify the engineering properties of inferior soils, enabling construction on these challenging sites. Clayey soil is known for its challenging geotechnical characteristics, working with such soil can be difficult due to its low shear strength, high compressibility, and high swell and shrink properties. The majority of structures built over expansive soil suffer significant settlement due to volumetric changes brought by fluctuations in water content. Therefore, it becomes necessary to practice soil stabilization before construction to ensure the stability and durability of the structure built over it [1][3] [4] [5].

Stabilization through conventional methods like mechanical and chemical stabilization is often implemented to improve soil properties. However, the overwhelming reliance of these methods on natural resources poses a significant challenge for both society and the environment. Therefore, innovative solutions that emphasize the use of recyclable materials are being investigated more and more in response to environmental concerns caused by traditional techniques [2][7]. The increased production of industrial by-products has garnered significant interest in their utilization over traditional materials like cement, lime, and fly ash. Various researchers have examined the effect of different industrial wastes on soil properties [24-27]. This shift towards an eco-friendly approach has received a lot of attention towards sustainable development [7].

Each year, millions of tons of waste ceramic powder are generated globally from ceramic tile production, with estimates indicating that

around 3-5% of the world's ceramic production gets wasted daily. The significant production of ceramic waste, particularly in countries like India, highlights a pressing environmental issue. This waste not only poses disposal challenges but also causes soil, air, and water pollution [7]. India is among the top 10 countries, having a ceramic product production of over 0.6 billion square meters annually, the country generates around 100 million tons of ceramic waste [8][10]. The composition of this waste mainly includes silica, alumina, and iron oxides, accounting for about 89.1% of its makeup. Reusing ceramic powder presents a sustainable solution, particularly for soil improvement as it contains high quantity of silica and alumina oxides which makes it appropriate for pozzolanic reaction, which are further essential for soil stabilization. Its utilization can enhance the geotechnical properties of soil while simultaneously addressing the issue associated with its disposal. This approach not only ensures environmental safety but also offers a cost-effective solution for managing industrial waste, benefiting both the industry and the ecosystem [2].

Abdullah S. et. al. investigated two distinct sizes of ceramic dust that passed through Sieve No. 40 and Sieve No.10. The results of the study showed that with the increase in ceramic dust content Atterberg's limits and OMC of clay decreased whereas an increase in MDD, UCS, and CBR value was observed. Higher improvement is seen in the case of ceramic dust No. 10 as compared to No. 40. This suggests that soil stabilized with the appropriate type and proportion of ceramic dust could be viable for civil engineering applications [18]. Rajamannan et.

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al. investigated the effect of ceramic powder on index properties, compaction characteristics, swelling, shear strength, and CBR of clayey soil. Their observation shows that Atterberg's limits, swelling pressure, and OMC decrease with an increase in ceramic dust content. Whereas, UCS and CBR increase with the increase in ceramic dust content. Simultaneously, the soil classification is changed from high compressibility (CH) to low compressibility (CL). Further, the study suggested that up to 30% ceramic dust can be utilized for enhancing the soil strength for the subgrade of flexible pavement [19]. Kasehchi E. et. al. examined the effect of ceramic waste powder on inshore silty sand parameters such as UCS, failure strain, curing time, and curing temperature. The study indicates that the addition of CWP without an alkali activator (NaOH solution) did not affect the soil. However, with the addition of an alkali activator UCS value and failure strain value increase, at all curing times up to 15% and are further reduced by 24 %. Therefore, the study suggested the use of ceramic waste powder up to 15% with a concentration of 6M NaOH solution, which tends to be economical and environment friendly [7]. Therefore, the use of WCP as a soil stabilizer provides a sustainable and economical approach to enhancing soil characteristics. However, more research is needed to overcome the challenges associated with waste material and optimize its application across different soil types [33].

Calcium carbide residue is a highly alkaline by-product generated during the acetylene production process through the hydrolysis of calcium carbide. Due to the highly alkaline nature of calcium carbide, it seriously damages both open and subsurface water. It contains a significant amount of $\text{Ca}(\text{OH})_2$ which makes it a potential alternative to be used as a stabilizing agent [14]. Recent research findings have shown that adding calcium carbide residue in expansive soil can yield higher strength while lowering its swelling potential. [11] [12] [14]. Therefore, CCR works well as a soil stabilizer. Its application not only enhances the geotechnical properties of soil but also offers significant benefits from environmental, engineering, and economic points of view [14], [31-32].

Although several studies have explored the use of industrial waste in soil stabilization, limited research specifically addresses the influence of such materials on soil pH, a factor that is crucial for long-term stability and chemical interactions. Moreover, no prior work has provided a direct comparative evaluation of waste ceramic powder (WCP) and calcium carbide residue (CCR) as soil stabilizers. To bridge these gaps, this study investigates the effects of WCP and CCR on the physical and mechanical properties of clayey soil through a comprehensive experimental program that includes Atterberg limits, differential free swell, pH, Standard Proctor compaction, and unconfined compressive strength (UCS) tests. The influence of each additive was critically assessed and compared to determine their relative performance. Their incorporation aims to reduce reliance on conventional stabilizers and mitigate ecological damage. Overall, the study promotes the circular use of industrial waste in sustainable geotechnical practices.

2. Material and methodology

2.1. Materials

2.1.1. Soil

The soil under study was procured from a depth of approximately 1-1.5m below the natural ground surface in the Bilaspur district of Himachal Pradesh. After extraction, it was carefully sealed and transported to the geotechnical engineering laboratory, at NIT Hamirpur. The soil was first dried under sunlight, then pulverized using a mechanical pulverizer, and finally stored in an air-tight bag. Various physical properties of soil were identified using relevant Indian standards and appropriate American Society for Testing and Materials (ASTM) procedures.

The particle size distribution curve (Fig. 1) shows that 90% of the soil passes through the 75-micron sieve, indicating a predominance of fine-grained particles, mainly silt and clay. This gradation is consistent with the high plasticity index observed, reflecting the soil's fine texture and

cohesive nature. Such composition typically results in high plasticity, low permeability, and susceptibility to volumetric changes. Additionally, the soil exhibits a high Differential Free Swell (DFS) value of 32.6%, indicating significant swelling potential. These characteristics make the soil unsuitable for construction without stabilization. The key physical properties of the soil, determined through laboratory testing, are summarized in Table 1. The key physical properties of the soil, determined through laboratory testing, are summarized in Table 1. The soil shows a plasticity index of 24.14%, classifying it as CH (highly compressible clay). It has a specific gravity of 2.63, a neutral pH of 7.3, a maximum dry density (MDD) of 1.75 g/cm^3 , and an optimum moisture content (OMC) of 17.1%.

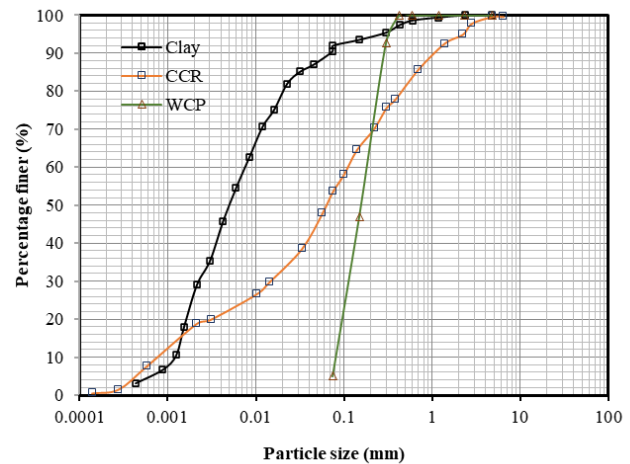


Fig. 1. Gradation curve of soil, CCR & WCP.

Table 1. Properties of soil.

Properties	Soil
Specific gravity, G	2.63
pH	7.3
Liquid limit (%)	50.9
Plastic limit (%)	26.76
Plasticity index (%)	24.14
MDD (g/cm^3)	1.75
OMC (%)	17.1
Soil type	CH
DFS (%)	32.6

2.1.2. Waste ceramic powder

The ceramic tile industry generates waste ceramic powder as a byproduct during the final polishing stage of ceramic tiles which contains chemicals and heavy metals thereby harming the environment. Effective disposal of WCP is difficult due to its potential environmental hazards. Traditional disposal methods, such as landfilling, may not be suitable because of the risk of leaching harmful substances into the soil and water. To address these challenges and promote environmental protection, it is crucial to explore the use of WCP across different industrial sectors. Its application in the construction industry, in particular, can offer significant economic benefits by conserving natural resources. The waste ceramic powder used in this study was sourced from Logitech Company, which collects it from industrial suppliers. WCP is passed through Sieve No. 200 and particles passing through .075mm are used in the study. Table 2 presents the chemical composition of WCP, showing that it is predominantly composed of silica (SiO_2) at 94.6%, with smaller amounts of alumina (Al_2O_3) at 3.19% and calcium oxide (CaO) at 2.15%. The high silica content indicates strong pozzolanic potential, making WCP well-suited as a soil stabilizer and geopolymer precursor.

Table 2. Characteristics and chemical composition of WCP.

Characteristics	Value
Specific gravity	2.65
pH	7.46
Chemical composition	
SiO ₂ (%)	94.6
Al ₂ O ₃ (%)	3.19
CaO (%)	2.15
LOI (%)	0.04
MgO (%)	-
Fe ₂ O ₃ (%)	0.01
K ₂ O (%)	-

2.1.3. Calcium carbide residue

Calcium carbide residue (CCR) is a highly alkaline byproduct of acetylene gas production which leads to the contamination of surface and groundwater if not properly disposed of. Table 3 presents the chemical composition of Calcium Carbide Residue (CCR), which is predominantly composed of calcium oxide (CaO) at 86.15%. This high CaO content is crucial for soil stabilization, as it contributes to the improvement of soil by reducing plasticity and enhancement of cohesion. When a mixture of soil and calcium carbide residue comes into contact with water, a reaction occurs, producing calcium hydroxide, which aids in densifying and strengthening the soil. The presence of minor constituents like SiO₂ (2.23%), Al₂O₃ (1.94%), and Fe₂O₃ (1.06%) further supports potential pozzolanic reactions in the presence of moisture, aiding long-term stabilization. Overall, the composition highlights CCR as a highly effective material for improving the engineering behavior of problematic soils. Due to its alkaline nature, it may affect the pH of soil so its careful application becomes necessary. The calcium carbide used in this study was supplied from a hardware store in Hamirpur market, Himachal Pradesh. Before utilization material was crushed to powder and then passed through a 425-micron sieve.

Table 3. Characteristics and chemical composition of CCR.

Characteristics	Value
Specific gravity	2.25
pH	12.62
Chemical composition	
SiO ₂ (%)	2.23
CaO (%)	86.15
Al ₂ O ₃ (%)	1.94
Fe ₂ O ₃ (%)	1.06
MgO (%)	0.44
TiO ₂ (%)	0.10
Na ₂ O (%)	0.05

2.2. Methodology

2.2.1. Differential free swell test

The soil's differential free swell index is determined according to IS:2720-40 (1977). The Differential Free Swell (DFS) test measures the swelling potential of soil by comparing its expansion in water and kerosene. Equal amounts of dry soil are placed in a separate graduated cylinder; one filled with water and the other with kerosene. After 24 hours, the increase in the volume of water is recorded. The DFS value, expressed as a percentage, indicates the soil's tendency to swell.

2.2.2. pH test

An electronic pH meter is used to test the pH level by adding distilled water to a precise amount of soil. Before conducting the test, the pH meter is calibrated using a standard reference buffer solution having pH values of 4.0, 7.0, and 14. The pH test is performed following ASTM D

4972-13.

2.2.3 Atterberg's limit

The Atterberg limits of untreated soil and various mixes are determined according to ASTM D4318 (2004) standard. Atterberg limits define how fine-grained soil behaves at different moisture levels. They include the liquid limit, plastic limit, and shrinkage limit. These limits show when soil changes from liquid to plastic, plastic to semi-solid, and stops shrinking. They're key for classifying soils and predicting their performance.

2.2.4 Proctor test

The maximum dry density (MDD) & optimum moisture content (OMC) are obtained through a standard proctor compaction test, following the guideline specified in IS 2720 (Part-7) 1980. The hammer utilized in this test weighed 2.6 kg with 310 mm freefall height. The cylindrical mold utilized has an internal dimension of 100mm in diameter, 127.3 mm in effective height having 1000 cm³ capacity.

2.2.5 Unconfined compression test

UCS test is done on both untreated & treated soil samples following the guidelines of IS 2720 part-10, 1991. The test aims to assess the influence of different additives on the strength characteristics of untreated soil. Specimens measuring 76mm * 38mm are prepared and cured for 3, 7, and 28 days in a desiccator. The strain rate considered for the testing of samples is 1.25mm/min.

3. Results and discussion

3.1. Differential free swell index test

The DFS test result reveals a high swelling characteristic of soil with a value of 32.6%, rendering it unsuitable for construction purposes. The differential free swell index fell steadily when waste ceramic powder was added: 25% at 4%, 18.6% at 8%, 11.78% at 12%, 5.04% at 16%, 0% at 18% (Fig. 2). The drop in DFS value may be observed due to the substitution of swelling clay particles by non-swelling ceramic particles. This is because the ceramic particles do not have the same water-absorbing properties as the clay particles [20].

Various proportions of Calcium Carbide Residue (CCR), ranging from 3% to 12%, are added to the soil to mitigate swelling. Remarkably, the inclusion of 9% CCR resulted in the complete elimination of soil swelling, reducing it to 0%. The reduction in DFS value upon the addition of CCR may be due to a cation exchange reaction between calcium ions and soil particles. However, there is a sudden rise in DFS value when the addition of CCR increases beyond 9%. This increase in DFS value may be attributed to a rise in the pH of the composite, which causes the breakdown of aggregates and disperses clay particles. This dispersion allows clay particles to adsorb more water, resulting in higher DFS values [9].

3.2.2. pH test

For pH testing of stabilized soil, different proportions of WCP & CCR are mixed with the untreated soil at 4%, 8%, 12%, 16%, 18%, 20% & 3%, 6%, 9%, and 12%, respectively. A pH range of 8 to 10 is frequently recommended for good stabilization, which ensures the soil's resilience to moisture changes and increases its stability. Understanding these pH effects is critical for customizing stabilizing approaches to specific soil types and project requirements, ensuring the best possible results in soil engineering initiatives. Figs. 3 and 4 illustrate the changes in pH values with the addition of varying proportions of WCP and CCR, respectively. Fig. 3 indicates that as the WCP content increases from 4% to 20%, a decrease in pH value is observed from 8.99 to 7.95 respectively. This indicates that the addition of WCP first transits the soil towards alkalinity, but as the percentage of WCP increases the alkalinity of the composite decreases. This decrease in alkalinity may be due to the presence of acidic oxides such as silica and alumina in WCP. These

oxides release hydrogen ions when they react with water, increasing soil acidity and causing a decrease in pH value. On the other hand, the pH increased from 12.22 to 12.62 as the CCR content increased from 3% to 12%. This rise in pH is due to the alkaline nature of CCR, which helps neutralize soil acidity. When CCR reacts with water, it forms calcium hydroxide, releasing hydroxyl ions that reduce hydrogen ion concentration and further elevate the soil pH.

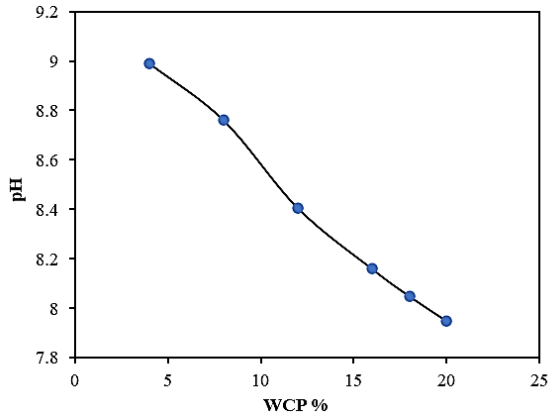


Fig. 3. pH value at varying %age of WCP.

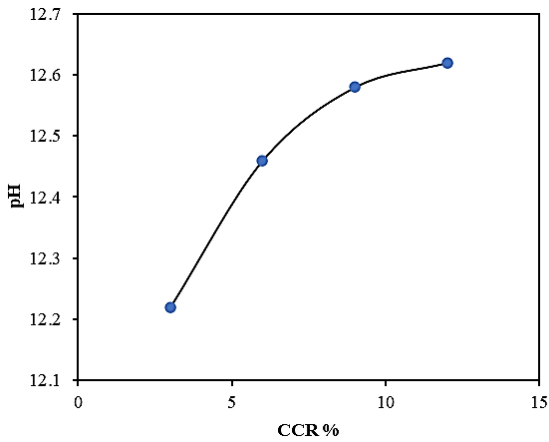


Fig. 4. pH value at varying %age of CCR.

3.2. Atterberg's limits

The test result shows that the liquid limit (LL) and plastic limit (PL) of untreated soil are 50.9% and 24.14% respectively. Therefore, as per the plasticity chart, the values of LL and PL fall within the range of high compressibility (CH) which highlights the need for stabilizing soil before it is subjected to any type of construction.

3.3.1 Effect of WCP on Atterberg limits

The variation in Atterberg's limit with different proportions of WCP is shown in Fig. 5. It shows that when waste ceramic powder (WCP) is added to the soil at amounts ranging from 4%, 8%, 12%, 16%, 18% and 20% the liquid limit progressively decreases, with values of 45.4%, 41%, 35.9%, 32.445%, 30.5% & 29.99% respectively. At the same time, the plastic limit decreased to 26.76%, 25.50%, 23.72%, 22%, 19.75%, 18.46% & 18.06% respectively. The PI value also shows a notable reduction, dropping from 24.14% to 11.8%, as WCP content increases from 4-20%. These changes indicate the shift of classification of soil from high compressibility (CH) to low compressibility (CL). This may have occurred due to the substitution of soil particles by the particles of WCP. Similar behavior is observed in a previous study involving WCP-stabilized clay [11].

3.3.2 Effect of CCR on Atterberg limits

When CCR is mixed with the soil composite at 3%, 6%, 9%, and 12% the liquid limits are lowered whereas the soil plastic limits are considerably raised (Fig. 6). A potential reason for the higher PL value could be the increased viscosity of pore fluid, which enhances shear resistance between the particles. On the other hand, a decrease in PI value was seen as the CCR content increased. The flocculation of soil particles and the cation exchange phenomenon are two possible reasons for the decrease in PI value. The flocculation of soil particles causes bigger and stiffer aggregation of clay particles which is a result of absorption of Ca²⁺ during the cation exchange process. Up to 9% CCR, the PI shows a considerable decline from 24.14% to 5.31%, which means that 9% CCR is the point at which Ca²⁺ adsorption reaches its maximum. As per IRC SP 89 (2010) 5.31% PI suggests its suitability as a subgrade material [40]. A few researchers observed a similar behavior of CCR-stabilized soil in the past [12] [14] [15] [31].

Figure 7 demonstrates that the initial liquid limit of soil is 50.9% and the plasticity index of soil is 24.14%, so as per the PI chart this value indicates the classification of soil as clay with high compressibility (CH). When 4% to 12% of WCP is added, the liquid limit drops from 45.4% to 35.9% and the plasticity index drops from 19.9% to 13.9%, which lies in the range of clay of intermediate compressibility (CI). However, as the percentage of addition of WCP increases from 16% to 20% the liquid limit & plasticity index decrease further from 32.445% to 29.86% and 12.695% to 11.8% respectively changing the classification of soil to clay with low compressibility (CL). Whereas, with the addition of a varying proportion of calcium carbide residue from 3% to 12%, the liquid limit decreases from 44.028% to 38.99% and the plasticity index of soil composite decreases from 13.88% to 5.311%. This shift in values leads to a change in the classification from clay with high compressibility (CH) to clayey silt with intermediate compressibility (MI).

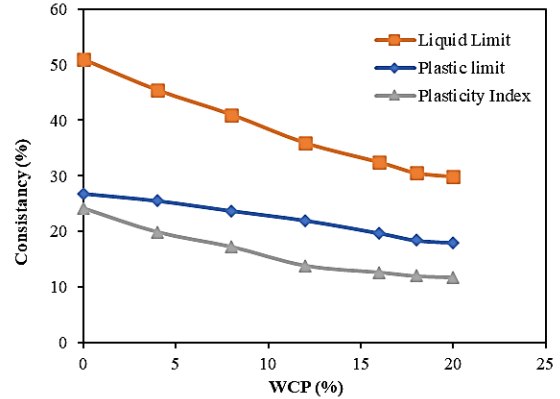


Fig. 5. Consistency of soil with varying % of WCP.

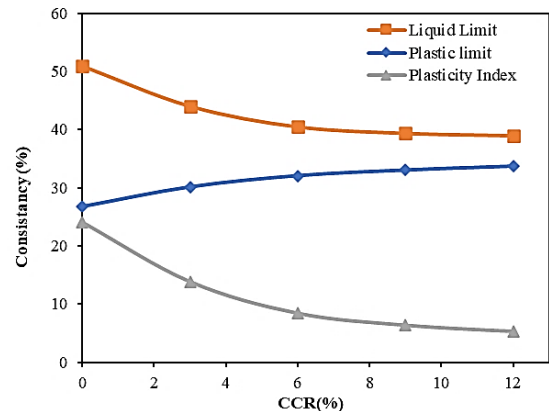


Fig. 6. Consistency of soil with varying % of CCR.

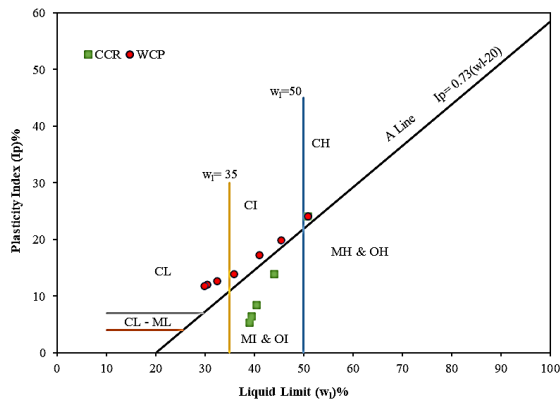


Fig. 7. Liquid limit V/s Plasticity Index chart with varying percentages of WCP&CCR.

3.3. Compaction characteristics

The compaction test results of untreated soil shows that the MDD is 1.75g/cc, while the OMC is 17.1%.

3.4.1 Effect of WCP on compaction characteristics

Figure 8 Compaction of soil with varying percentages of the waste ceramic powder. In clayey soil, adding WCP in different percentages of 4%, 8%, 12%, 16%, 18%, and 20% resulted in an increase in MDD from 1.75 to 1.83 g/cc and a decrease in OMC from 17.1% to 13.2% (as shown in Fig. 8). The rise in MDD may be attributed due to the replacement of WCP, which has a slightly higher weight and specific gravity than clayey soil. The rise in the MDD of soil upon the addition of WCP can be due to a higher SG of WCP than that of clayey soil. Whereas a decrease in OMC may be attributed to the absorption of water molecules by the additive i.e. WCP. This shows the higher value of WCP impacted positively on the strength when it was added to clayey soil. The results showed an increase in MDD and a decrease in OMC on adding WCP are in good agreement with previous research [18].

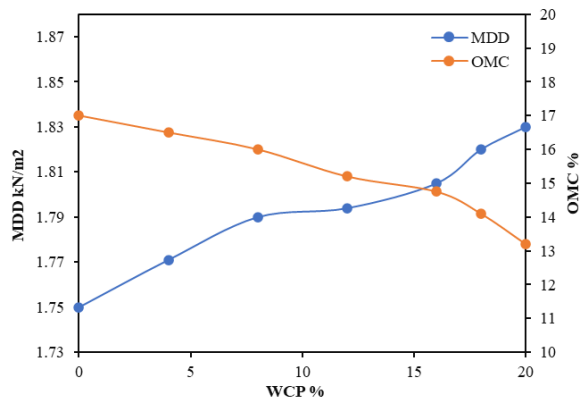


Fig. 8. Compaction of soil with varying % of WCP.

3.4.2 Effect of WCP on compaction characteristics

When calcium carbide residue is added to the untreated soil at varying percentages of 3%, 6%, 9%, and 12%, it results in notable changes to the soil's optimum moisture content (OMC) and maximum dry density (MDD), as shown in Fig. 9. As CCR content increases because overall weight of mixture lowers due to lower specific gravity of CCR than soil. Conversely, the pozzolanic reaction between soil particles & CCR caused the OMC to rise to 19.1%. The rise in OMC is attributed to the addition of CCR which leads to the adsorption of

Ca²⁺ ions onto the surface of clay particles, promoting flocculation. Similar trends have been observed in previous researchers [12] [19].

3.4. Unconfined compressive strength tests

The observed UCS values of untreated soil after 3 days, 7 days, and 28 days of curing were 227.686 kPa, 278.726 kPa & 334.52 kPa respectively. Since the 28-day UCS value is only 334.52 kPa, the soil is considered weak and unsuitable for subgrade use. This indicates a clear need for stabilization to improve its strength and durability.

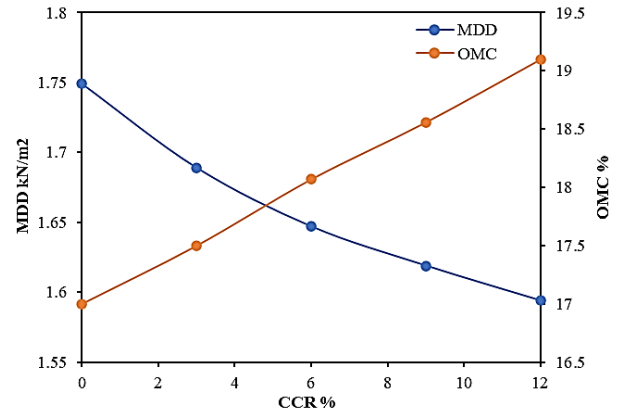


Fig. 9. Compaction of soil with varying % of calcium carbide residue.

3.5.1 Effect of WCP on UCS

The effects of different WCP percentages on the soil UCS variation are shown in Fig. 10. After 28 days of curing, the UCS value of WCP-stabilized soil was 378.269 kPa for 4%, 427.569 kPa for 8%, 605.75 kPa for 12%, 577.955 kPa for 16%, 529.29 kPa for 18% and 496.951 kPa for 20% WCP content, respectively. The inclusion of WCP improved the UCS of the composite due to the presence of reactive silica and alumina, which interact with the available calcium in the soil to initiate pozzolanic reactions. These reactions lead to the formation of cementitious compounds such as calcium silicate hydrate (C-S-H) and calcium aluminate hydrate (C-A-H), which enhance particle bonding and contribute to matrix densification. Additionally, the improvement in strength is also attributed to cation exchange processes that promote closer particle arrangement and stronger interparticle bonds [3, 36]. The UCS values show an increasing trend with WCP content up to an optimal level of 12%, beyond which strength begins to decline. This suggests the importance of optimizing WCP dosage to achieve maximum performance in soil stabilization applications. The UCS of clayey soil increased greatly by 1.81 times upon the addition of 12% WCP. This showed that WCP could increase the strength of clayey and can be used as a stabilizer for the purpose of constructing sub-base layer of the road. Similar behavior was observed in previous studies [3, 36-37].

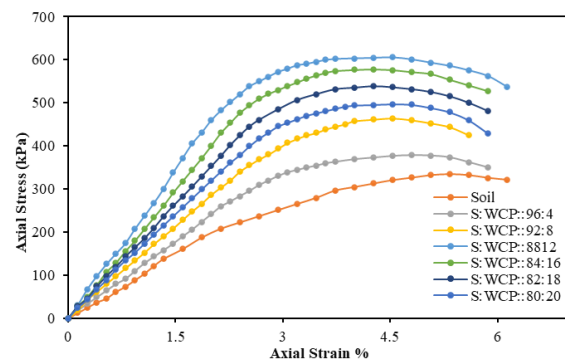


Fig. 10. UCS variation with varying % of waste ceramic powder after 28 days of curing.

3.5.2 Effect of CCR on UCS

As shown in Fig. 11, the addition of CCR in varying proportions (3%, 6%, 9%, and 12%) increases the UCS value of the soil with an increase in curing duration. The UCS values for a 28 days curing period for different percentages of CCR are 424.795 kPa for 3%, 495.739 kPa for 6%, 624.726 kPa for 9%, and 697.726 kPa for 12%. This shows the UCS value rises by 2.08 times the untreated soil after 28-days of curing. This rise in UCS with higher CCR content is observed due to the introduction of calcium hydroxide into the soil, which reacts with the pozzolana (i.e. silica and alumina) present in the soil, leading to a pozzolanic reaction. The pozzolanic reaction forms a cementitious compound (such as C-S-H and C-A-H), significantly improving the binding characteristics and overall strength of the soil. Also, longer curing time allows the pozzolanic reactions to develop more cementitious compounds resulting in a progressive increase in UCS value. Results from the previous study on the effect of CCR on clayey soil have also shown that adding CCR to untreated soil enhances its strength characteristics [12-15].

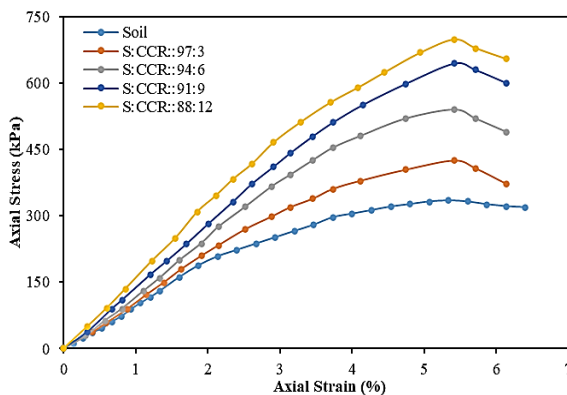


Fig. 11. UCS variation with varying % of calcium carbide residue after 28 days of curing.

3.5.3 Effect of WCP and CCR with curing period

The relationship between the curing period (days) and UCS of soil mixed with varying percentages of WCP and CCR is shown in Fig. 12. The graph shows that for all compositions, the UCS values steadily rise as the curing period increases, suggesting that the addition of CCR and WCP improves soil strength as the pozzolanic reaction between the additives and soil develops over time. Different percentages of CCR and WCP show varying levels of strength gain. The unconfined compressive strength (UCS) of the soil increased significantly with the addition of CCR and longer curing durations. At 3 days of curing, UCS rose from 227.69 kPa for untreated soil (S:100) to 397.13 kPa for the S: CCR: 88:12 mix i.e. an increase of approximately 74.5%. After 7 days, the strength increased from 278.73 kPa to 451.73 kPa (62.1% increase), while at 28 days, the UCS reached 697.73 kPa, more than doubling the initial value of 334.52 kPa and highlighting a remarkable 108.5% increase in strength. These findings clearly show that both CCR concentration and curing duration have an important impact in increasing soil strength, making stabilized soil much more suitable for subgrade application.

The unconfined compressive strength (UCS) of soil samples increased notably with the addition of waste ceramic powder (WCP) and longer curing periods. At 3 days, the UCS improved from 227.69 kPa for untreated soil (S:100) to a maximum of 377.21 kPa for the S:WCP::88:12 mix, representing a 65.7% increase. After 7 days, the UCS rose from 278.73 kPa to 406.23 kPa for the same mix i.e. a 45.8% improvement. By 28 days, the strength showed a substantial increase, rising from 334.52 kPa to 605.75 kPa (81.1% increase). However, beyond 12% WCP, the strength began to decline slightly, indicating that the optimal WCP content is around 12%. These results demonstrate that WCP effectively enhances soil strength, especially at moderate replacement levels and with longer curing durations, thereby improving its suitability for subgrade applications.

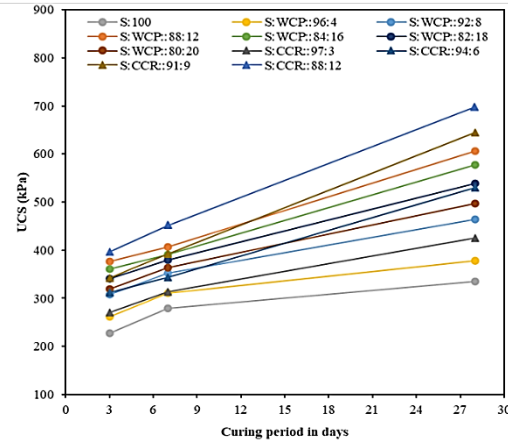


Fig. 12. UCS for clayey soil improved using various proportions of admixtures for different curing periods.

When comparing CCR and WCP, both additives significantly improved the UCS of the soil, particularly at 12% replacement and with increased curing time. However, CCR consistently produced higher strength gains across all curing durations compared to WCP. At 28 days, for instance, CCR-enhanced soil reached a UCS of 697.73 kPa, while WCP-enhanced soil peaked at 605.75 kPa. Furthermore, CCR showed a steady increase in strength with no performance drop-off, unlike WCP, which exhibited declining strength beyond 12% content. This indicates that while both materials are effective stabilizers, CCR offers superior strength improvement and reliability, making it the more effective option for enhancing subgrade performance.

4. Conclusion

This research explores the potential of utilizing WCP and CCR for stabilizing clay. Results indicate that adding WCP and CCR significantly impacts the engineering properties of clayey soil, with optimal contents determined to be 12% for WCP and 9% for CCR. Based on laboratory investigations, the following conclusions are made:

- The differential free swell index decreased significantly from 32.6% to zero with the addition of 18% WCP and 9% CCR, improving the soil's suitability for construction. This enhancement in volumetric stability makes the soil more reliable and suitable for use as a subgrade material.
- The alkaline nature of CCR led to an increase in soil pH, while the addition of WCP caused a slight reduction, reflecting their contrasting chemical influences on the soil environment.
- The Plasticity Index (PI) was reduced by 5.311% with the addition of CCR and by 11.8% with WCP, resulting in a PI less than 10 for CCR-treated soil, which meets the suitability criteria for subgrade material as per IRC SP:89 (2010).
- The reduction in the Plasticity Index due to the addition of CCR and WCP resulted in a soil classification shift from CH (high-plasticity clay) to MI and CL (low-plastic clay), indicating enhanced soil properties and greater suitability for subgrade applications.
- The compaction test revealed that with the addition of CCR, MDD of soil decreases whereas OMC increases. However, with WCP addition MDD of soil increases whereas OMC reduces. These changes indicate that WCP enhances the soil's compactability, improving its suitability as a subgrade material in pavement construction.

In terms of strength, CCR proved to be more effective than WCP in enhancing the strength of the soil, reaching a peak UCS of 697.73 kPa at 28 days, which is about 15.2% higher than the maximum strength of 605.75 kPa achieved with WCP. The steady increase in strength with CCR across all curing periods, without any drop-off, suggests it offers more consistent and reliable performance. These results indicate that

CCR is a more suitable choice for improving soil properties and ensuring better subgrade performance in road construction.

This study explored and compared the effects of CCR and WCP on soil stabilization through laboratory testing, highlighting their potential use in improving subgrade soils. Future research should investigate the long-term durability of these materials under real environmental conditions, supported by sustainability assessments and field testing. Since WCP contains high silica and alumina content while CCR is rich in calcium hydroxide, their combination could enhance pozzolanic reactions, leading to improved stabilization performance. Furthermore, this synergistic approach may provide a sustainable and cost-effective alternative to traditional soil stabilizers.

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