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Soil Stabilization using Ceramic Waste: an Experimental Study

Pankaj Rathore* and Suresh Kumar Tiwari

Civil Engineering Department, Malaviya National Institute of Technology, Jaipur, India

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Abstract

The main aim of this experimental analysis is to understand the effectiveness of ceramic waste (CW) in stabilizing the clayey soil. The effect of adding various CW percentages (5%, 10%, 15%, 20%, 25%, and 30%) on the geotechnical properties of clayey soil is evaluated by performing a series of laboratory tests like the Atterberg's limit test, compaction test, unconfined compressive strength (UCS) test, California bearing ratio (CBR) test, and swelling pressure test. Micro-structural analysis including scanning electron microscopy (SEM), energy dispersive spectroscopy (EDS), X-ray diffraction (XRD), and Fourier transform-infrared (FT-IR) spectroscopy are carried out on untreated and treated clay-ceramic composites. The results obtained indicate that the incorporation of 30% ceramic waste in clay soil increase the maximum dry unit weight (γmax) from 17.20 kN/m3 (CL + 0% CW) to 18.25 kN/m3 (CL + 30% CW). The unconfined compressive strength of clayey soil increases with the addition of ceramic waste. A maximum UCS of 217 kPa is obtained with 25% ceramic content, beyond which it starts decreasing. Similarly, increasing trend in CBR results is observed with an increase in the ceramic waste content. The increment in CBR is approximately 152% (unsoaked condition) and 142% (soaked condition). At the same time, the addition of ceramic waste in clay soil reduces the Atterberg limits, optimum water content (ωopt), and swelling pressure. "It can be concluded from the experimental study that CW can be used as a sustainable alternative soil stabilizer".

1. Introduction

Clayey soils create a lot of difficulty in construction activities due to their swelling and shrinkage behavior. These soils swell when in contact with moisture, while in a dry state, these soils start shrinkage. Due to this swelling and shrinkage behavior, clayey soils undergo considerable changes in their volume with changes in water content [1, 2]. The volumetric changes in clay soils are controlled by their water content, void ratio, clay mineral, and proportion present in the soil. However, the leading cause is the montmorillonite mineral present in clay soil [3]. These clayey soils can support enormous loads when dry but when moist, they become unstable and damage structures built on them [4]. Especially the lightweight structures built on clayey soils have been damaged in many countries like India, China, and United States of America. Considering all these issues, clayey soils are typically regarded as inferior materials for foundations, slopes, and pavement subgrade [6]. Therefore, construction activities on these problematic soils are a tough assignment and thus, an immense concern in the geotechnical engineering fraternity [7]. Thus clayey soils need stabilization before any construction activity is agreed upon to mitigate the effect of water on the clayey soil [5].

Industrialization, rapid growth in population on the one hand, and limited available land resources, on the other hand, forced the researchers to modify the engineering properties of existing problematic clayey soils so that we can carry out construction even on these soils [8]. Many researchers have developed numerous approaches to modify the geotechnical properties of clayey soils to solve the complications linked with these soils. Soil

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✉ *Corresponding author: 2019rce9060@mnit.ac.in (P. Rathore)*

stabilization is one approach to sort out the drawbacks associated with clayey soils by enhancing the geotechnical properties of these problematic soils [9].

Engineering properties of clayey soils might be enhanced chemically by using chemical additives as stabilizers [10, 11], mechanically by application of compaction energy [12, 13], by using a microbial bioenzyme [14, 15] electrokinetically by passing a current through the soil using electrodes [16–18]. The utilization of traditional stabilizers in soil stabilization, like fly ash, lime, and cement, is thoroughly discussed by various authors [19–22]. The high cost of chemical and traditional stabilizers and the depletion of natural resources forced the researchers to find alternative sustainable solutions for stabilizing clayey soils.

Various investigations have been dedicated to developing sustainable and eco-friendly soil improvement techniques to avoid the environmental issues of using traditional soil stabilizers like cement and lime [8, 23]. Using waste material in stabilizing weak soils is a cost-effective and sustainable method of improving the geotechnical properties of soils. Waste materials as soil stabilizers can be used alone or in combination with other additives. Sharma [6] used fly ash and ceramic waste to enhance the engineering properties of clay and concluded that the blends formed by the mixing of clay along with sand, fly ash, and ceramic waste improved the properties of clay and thus stated that the utilization of such waste materials in road construction is a sustainable practice of stabilization and disposing of the waste materials. Hassan et al. [24] used plastic waste material to stabilize the clayey soil. Bhardwaj et al. [25] used waste foundry sand and molasses to stabilize clayey soils and found waste foundry sand and molasses in soil stabilization enhanced the geotechnical properties of clay by increasing the γmax and UCS of clay.

Nowadays, ceramic materials are widely used for furnishing and ornamental purposes. However, after their useful life, these ceramic materials lose their utility and result in a waste material of no use. Due to the enormous accumulation of ceramic waste daily, it has become a topic of concern for industries to come up with practical solutions for its disposal. Materials containing high clay minerals are generally used in manufacturing ceramic products [26, 27]. These clay minerals obtain the characteristics of fired clay by dehydration and firing at temperatures ranging from 700 °C to 1000 °C [4].

Various studies have shown that throughout the process of production, handling, and transportation, 30% of the ceramic output goes waste [28]. Due to the absence of proper guidelines for the disposal of this waste, the considerable energy and power used in the manufacturing process are finally wasted. The disposed of CW also causes environmental problems. China is the world's largest manufacturer of ceramic products, estimated to be around 42.8% of global ceramic tile production. As per a study conducted in 2016, ceramic tile production was recorded to be 13056 million m2 with a standard growth rate of 5% [29]. The ceramic tiles market in India, which had a market of 4.9 billion Euros in 2017, dominates the ceramic sector, which is estimated to expand overall at a 9% CAGR to achieve 7.5 billion Euros by 2022 [30]

Nowadays, the utilization of discarded ceramic materials to enhance the geotechnical properties of clayey soils is a new research topic in the geotechnical community. Using ceramic waste as a soil stabilizer is a cost-effective and sustainable alternative for stabilizing clayey soils [6, 8, 27].

Previous studies suggested that some industrial and agricultural waste could improve the geotechnical characteristics of clayey soils or serve as a substitute for conventional soil stabilizers. However, only a few investigations have been carried out on incorporating ceramic waste as a soil stabilizer in clayey soil. The effect of ceramic waste on the microstructural characterization of clayey soil has also not been comprehensively analyzed in the past studies. This experimental study has thus been performed to evaluate the comprehensive mechanical and micro-structural behavior of clayey soil stabilized with ceramic waste. Atterberg's limit test, compaction, UCS, CBR, and swelling pressure test were evaluated to analyze the mechanical performance of ceramic waste-treated clayey soil. SEM, EDS, XRD, and FT-IR analyses were carried out to understand the micro-structural behavior on untreated and optimal ceramic-treated clayey soil. It is presumed that using an engineered combination of industrial waste as an alternative to traditional stabilizers would minimize the cost of stabilization and preserve the environment by saving natural resources and solving the disposal problem of industrial wastes.

2. Background

Considering the originality of the research into account, the research articles published in quality journals have been selected for the literature review. The type of soil, the form of ceramic waste, its amount, and additional additives utilized by various researchers are listed in Table 1. This experimental interpretation's prime objective is to explore ceramic content's influence on the engineering properties of clay soil, like Atterberg limits, compaction parameters, UCS, CBR, swelling pressure, and micro-structural behavior. Cabalar et al. [27] analyzed the use of CW in road applications by mixing CW in varying proportions from 5% to 30% at an increment of 5% and reported an increase in γmax and CBR. In contrast, a decrement in ωopt, UCS, and swelling potential was reported, and thus the authors suggested CW as an alternative soil stabilizer. Voottipruex [31] used ceramic waste to enhance the properties of laterite soil for the rural road by mixing CW from 0% to 21% at an increment of 3%. The authors reported a decrease in the liquid limit (LL), plastic limit (PL), plasticity index (PI), and swelling percent. In contrast, an increase in the CBR value and γmax was reported. Sabat [32] analyzed the effect of ceramic dust on Atterberg limits of locally available expansive soil of the Bhubaneshwar region. Ceramic dust was incorporated from 0-30% (at an increment of 5%). In expansive soil, ceramic dust was observed to have decreased both the LL and PL from 62% to 35% and 30% to 20%, respectively. The PI also reduced from 32% to 15%. Furthermore, the effect of adding CW in black cotton soil was analyzed, and a decrement in LL and PL was reported from 68% to 47% and 31.02% to 24.94%, respectively [33]. Neeladharan et al. [34] performed a series of experiments to analyze the engineering properties of weak clayey soil (CI) by treating it with tile waste and sodium hydroxide as a binder. The LL and PL values decreased with the addition of tile waste up to 35% and sodium hydroxide up to 17.5%. In another study, the strength and consolidation parameters of clay soil incorporated with ceramic dust were investigated, and the authors recommended the incorporation of ceramic dust up to 20% [35]. The increment in γmax with increasing ceramic content has been reported by various authors [26, 36–38]. The improvement in γmax is accredited to the higher specific gravity of ceramic waste.

Furthermore, increments in the UCS of clay by incorporating CW have been observed by various authors [5, 8, 39]. The combined effect of CW and cement was analyzed on the geotechnical properties of clayey soil; the authors reported maximum UCS at 90 days of curing in clay composite containing 6% cement and 30% CW [40]. The increase in UCS is accredited to cation exchange and formation of cementation compounds, which reduces the porosity of treated soil. Moreover, some studies have observed a decrement in the UCS of clay with the inclusion of CW [27].

3. Material and Testing Procedure

The soil used in this experimental study is clayey. The soil was obtained from Bassi near Jaipur, Rajasthan, India. The soil was manually dried and crushed into small particles, then plant residues and other unwanted substances were discarded. The soil was then sieved through a 1.18 mm sieve, and stored in air-tight containers. The particle size analysis of clay and ceramic waste is presented in Figure 1. Various engineering properties of clay soil achieved using Indian Standards are mentioned in Table 2. Figure 3 displays the EDS micrograph of untreated clayey soil in which higher peaks of silicon (Si), aluminium (Al), magnesium (Mg), calcium (Ca), oxygen (O), iron (Fe), potassium (K) were observed, which is congruent with the clayey nature of the soil [50]. XRD was used to investigate the mineral phases available in the clayey soil. Silica, montmorillonite, and illite minerals make up the clay sample used in this experimental study, as shown in Figure 15 (a). The aggregation of fine soil particles was noticed through SEM analysis, as shown in Figure 2 (a).

Table 1. Type of soil, the form of CW, and its amount, along with additional additives used by different authors.

Reference	Type of waste used	Soil type	Mix proportion	Other additive used
A. K. Sabat [32]	Ceramic tile waste (Sand size: 48%, Silt size: 31%, Clayey size: 21%)	Expansive soil	0%, 5%, 10%, 15%, 20%, 25%, 30%	-
Panwar *et al*. [42]	Ceramic tile waste (ϕ > 2.36 mm)	Fine sand (1.50 g/cc, 1.55 g/cc,1.58 g/cc)	2%, 4%, 8%, 10%, 12%	-
Akash *et al*. [43]	Sanitary ware (4.75> ϕ > 2.36mm)	Fine sand	0%, 2%, 4%, 8%, 12%	-
Cabalar *et al*. [27]	Ceramic tile waste	Clay (CL)	0%, 5%, 10%, 15%, 20%, 30%	-
Neeladharan *et al*. [34]	Ceramic tile waste (CTW) ((ϕ < 90 μm)	Clayey soil	5% CTW + 2.5% SH 10% CTW + 5% SH 15% CTW + 7.5% SH 20% CTW + 10% SH 25% CTW + 12.5% SH 35% CTW + 17.5% SH 30% CTW + 15% SH 40% CTW + 20% SH	Sodium hydroxide (SH)
Vootipruex *et al*. [31]	Ceramic waste	Lateritic soil	3%, 5%, 7%, 10%, 15%, 20%	-
Chukwueloka okeke A.U. [44]	Waste ceramic dust (C) (ϕ < 0.074 mm)	Expansive soil (S)	100% S 90% S + 10% L 95% S + 5% L 94% S + 4.5% L + 1.5% C 95% S + 3.5% L + 1.5% C	Lime (L)
Moreira *et al*. [45]	Roof tile waste (RT)	Silty soil (S)	RT- 5%, 15%, 30% C- 3%, 6%, 9%	Cement (C)
Onakunle *et al*. [26]	Ceramic waste dust	Laterite soil	0%, 5%, 10%, 15%, 20%, 25%, 30%	-
R. K. Sharma [46]	Ceramic tile waste (ϕ < 4.75 mm)	Clayey soil	0%, 2%, 4%, 6%, 8%	Sand, fly ash
Al- Baidhani *et al*. [5]	Crushed ceramic rubble (75 μm-425 μm) (1.3 μm-75 μm)	Expansive soil	0%, 10%, 30%, 40%, 50%	-
Adeboge *et al*. [47]	Pulverized ceramic waste	Laterite clay soil	5%, 7.5%, 10%, 12.5%	-
Balegh *et al*. [48]	Ceramic powder	Tuff soil	0%, 5%, 10%, 15%, 20%, 30%	Cement 2%, 4%, 6%
Sankar *et al*. [39]	Ceramic waste dust	Clayey soil	0%, 5%, 10%, 15%, 20%, 25%	-
Deboucha *et al*. [38]	Ceramic waste (Coarse aggregate)	Soft soils	0%, 5%, 10%, 15%	Marble dust (2%, 3%, 4%, 5%) Cement (1.5%, 2%) by weight of soil
Beyene *et al*. [49]	Ceramic waste (G_s = 2.81)	Clayey soil (CH)	0%, 5%, 10%, 15%, 20%, 25%, 30%	Lime (2-10%)

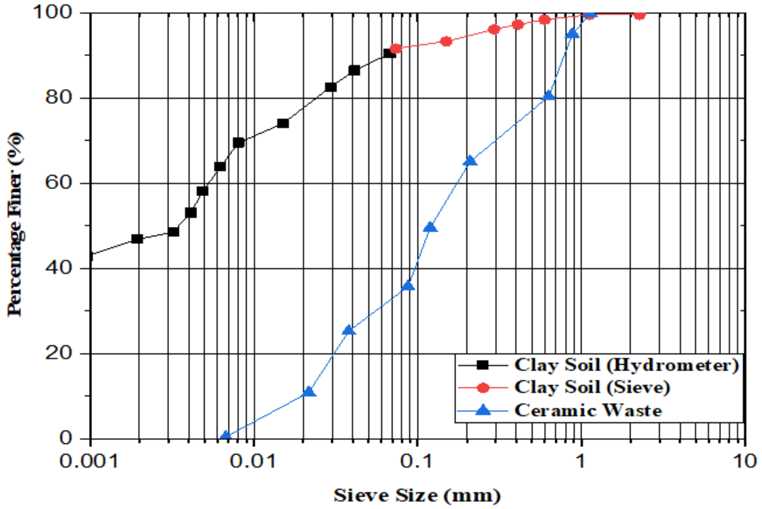

Figure 1. Particle size analysis.

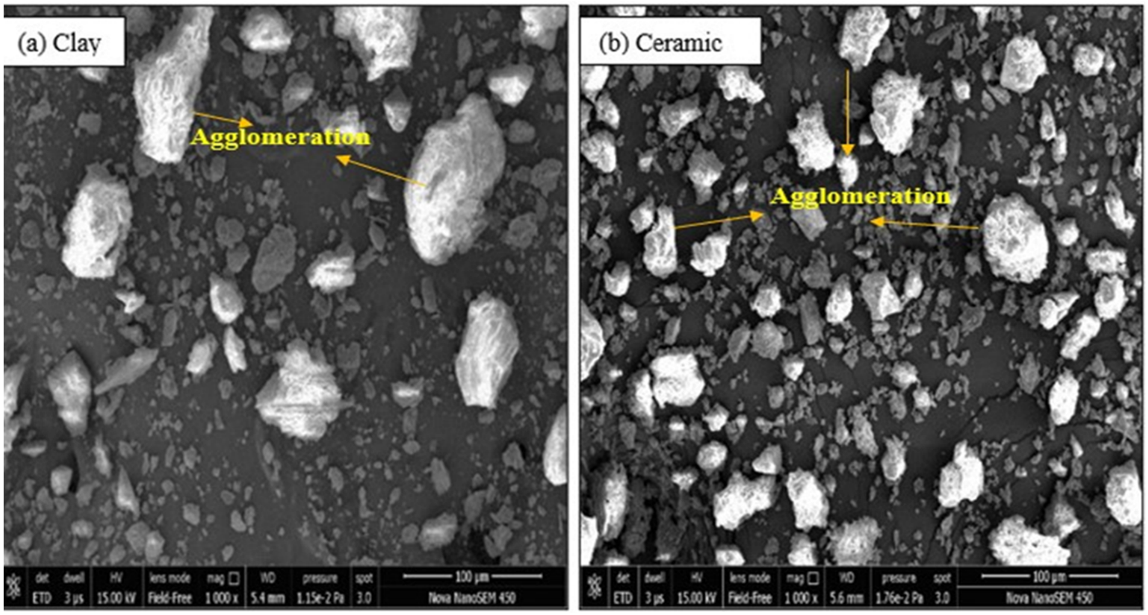

Figure 2. SEM images of (a) clay, (b) ceramic waste.

Table 2. Geotechnical properties of clay.

Property	Values	Standard used
Specific gravity	2.65	IS: 2720 (III) 1980
Liquid limit (LL)%	34.0	IS: 2720 (V) 1985
Plastic limit (PL)%	25.2	IS: 2720 (V) 1985
Plasticity index%	8.8	IS: 2720 (V) 1985
Soil type	CI	IS: 1498-1970
γ_{max} (kN/m^3)	17.2	IS: 2720 (VIII) 1983
ω_{opt}%	18.0	IS: 2720 (VIII) 1983

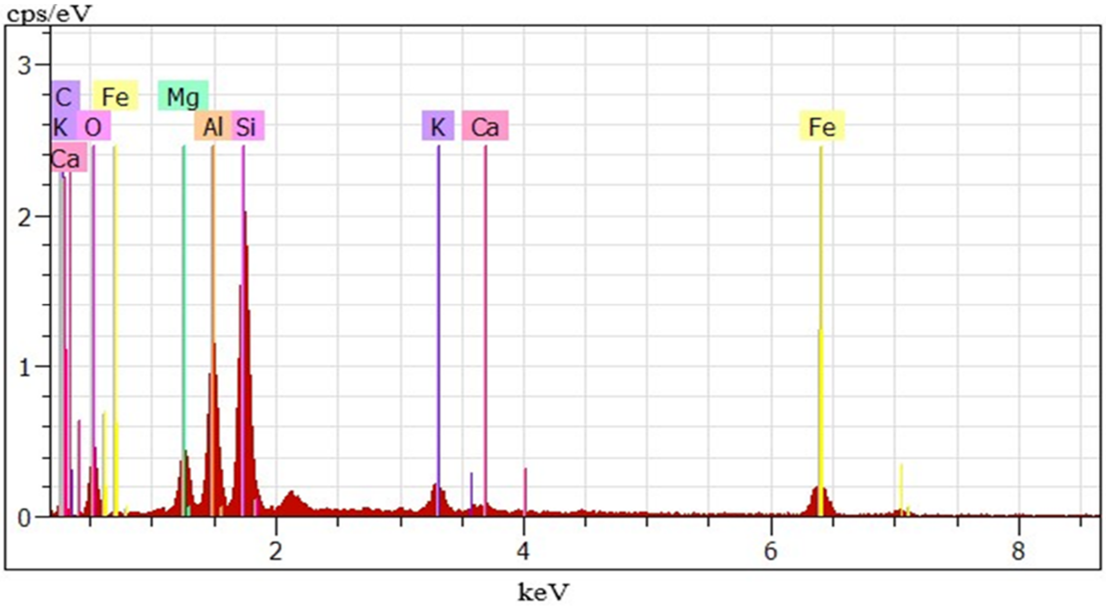

Figure 3. EDS spectra of clay soil.

CW of specific gravity 2.70 and size finer than 1.18 mm obtained from the mechanical grinding of waste ceramic tiles, as shown in Figure 4, has been used as a stabilizing agent. The gradation curve of

CW is shown in Figure 1. To determine the compatibility of CW together with the clay, microscopic analysis was done. The EDS and SEM analysis of CW was carried out in the material research center at Malaviya National Institute of Technology Jaipur, Rajasthan, India. The EDS and SEM analysis results reveal the CW compatibility to be used with the clay. Table 3 illustrates the chemical composition of CW. Figure 5 represents the EDS analysis of CW, and it can be noticed from the micrograph that CW used in this study mainly consists of silicon (Si), oxygen (O), aluminium (Al), calcium (Ca), iron (Fe), potassium (K), magnesium (Mg), titanium (Ti), carbon (C), and sodium (Na). Agglomeration in finer ceramic particles was noticed through SEM analysis, as shown in Figure 2 (b)

Table 3. Chemical composition of CW.

Chemical composition	**Si**	**O**	**Al**	**Ca**	**Fe**	**K**	**Mg**	**Ti**	**C**	**Na**
Content (%)	39.54	23.78	16.14	6.95	3.85	2.72	2.35	2.26	1.90	0.50

Figure 4. Ceramic waste used in the study.

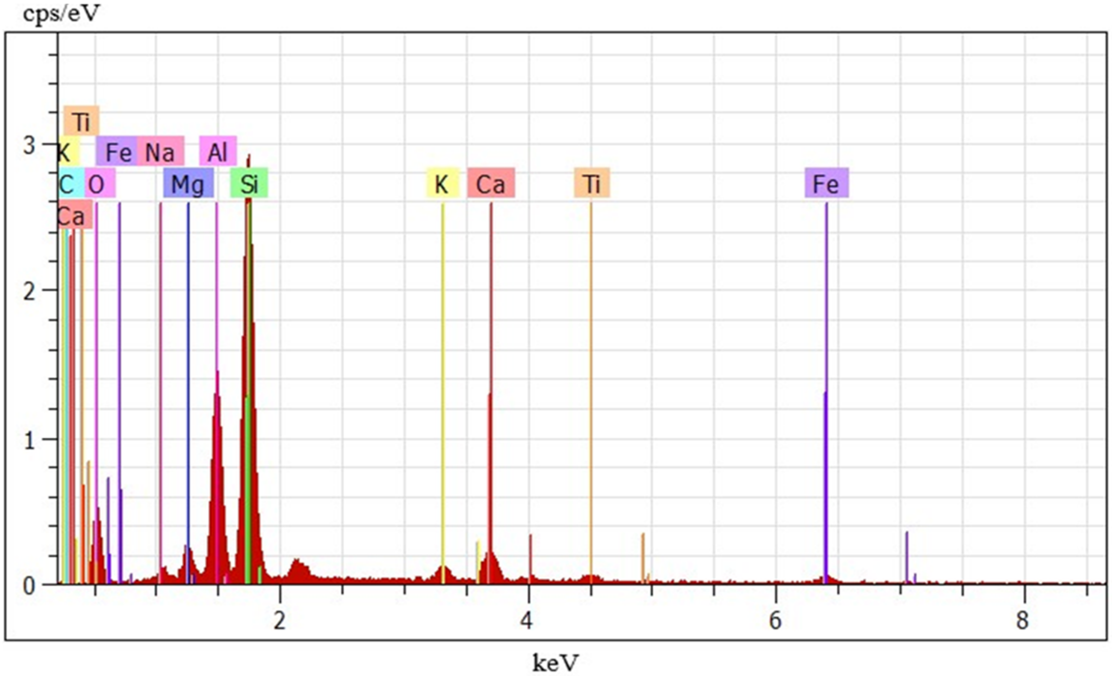

Figure 5. EDS spectra of ceramic waste.

4. Experimental Methodology

The effect of CW inclusion on the basic engineering behavior of clay was analyzed by treating the clay soil with 5%, 10%, 15%, 20%, 25%, and 30% CW and performing various tests, namely the Atterberg limit test, compaction test, UCS test, and CBR test. EDS, SEM, XRD, and FTIR were the micro-structural tests performed in the study. The procedure mentioned in standard codes was used to prepare the samples and perform the tests mentioned. This section reports the experimental methods used in the study.

The clay procured from the site was crushed and dried in an oven. Then the clay composites containing CW were mixed in the dry state till a homogeneous mix was achieved. The optimum water content of the mix was added to the homogeneous mixture during the sample preparation. The composites were coded, so that the results could be analyzed precisely. The composite code and the clay and ceramic proportion are mentioned in Table 4. For example, the code CL + 5% CW represents 95% clay and 5% ceramic waste.

Table 4. Composite code and proportions of clay and cement.

Composite code	Clay soil (%)	Ceramic waste (%)
CL + 0% CW	100	0
CL + 5% CW	95	5
CL + 10% CW	90	10
CL + 15% CW	85	15
CL + 20% CW	80	20
CL + 25% CW	75	25
CL + 30% CW	70	30

4.1. Atterberg limit test

To find the LL and PL, Atterberg's analysis was conducted on the different combinations of clay-CW, as mentioned in Table 4. The standard procedure mentioned in the IS 2720 part 5-1980 was followed for performing this test.

4.2. Compaction test

To find the γmax and ωopt modified proctor, compaction test was performed on various compositions of clay-CW. As discussed in IS 2720, part 8-1983, the standardized procedure was followed. Clay and CW were appropriately mixed in the dry state. Then water was added, and the mixture was remixed to obtain homogeneity. The composite consisting of clay and CW was placed in a mold of 1000 cc volume in 5 successive layers each successive layer in the mold was tamped 25 times using a rammer of 49 kg, and the drop height of the rammer was adopted as 450 mm. γmax and ωopt were obtained from the compaction analysis graph. The γmax and ωopt obtained were further used to prepare the specimens of different tests performed in this experimental study.

4.3. Unconfined compressive strength test

UCS test was performed on different combinations of clay and CW, as per IS 2720 part 10-1991. The cylinder-shaped specimens of 38.1 mm diameter and 76.2 mm height were prepared from each combination. The samples were prepared at γmax and ωopt obtained by the compaction analysis. The prepared samples were kept in plastic bags and were cured for 7, 14, and 28 days. The testing was performed on the samples placed axially between the plates of the UCS testing machine with a strain rate of 1 mm/minute.

4.4. California bearing ratio test

CBR test was performed on various combinations of clay-CW mixtures as per the standard procedure mentioned in IS 2720 part 16-1987. The soaked and unsoaked CBR samples for every combination were prepared as mentioned in Table 4 at their corresponding γmax and ωopt. The unsoaked CBR analysis was done on freshly prepared samples using a strain-controlled CBR machine, and soaked CBR test was done after soaking the sample in water for 96 hours.

4.5. Swelling pressure test

Standard specifications mentioned in IS 2720 part 41-1977 were used to analyze the effect of mixing CW on the swelling pressure of parent clay soil. Composite consisting of clay and CW from 0-30% at an increment of 5% were prepared at γmax and ωopt in compaction mold. After this, the sample of 20 mm thickness and 60 mm diameter was extracted using a cutting ring. After curing the sample for 28 days, the sample was kept in a consolidation cell, and swelling pressure was evaluated using a constant volume procedure.

4.6. Micro-structural analysis

To understand the micro-structural behavior of treated and untreated clay samples, SEM, EDS, XRD, and FIR tests were carried out. SEM and EDS were used to analyze the morphological changes. The morphology of various clay and CW combinations was analyzed using Nova Nano Sem 450. Testing was done on a 1 cm cube sample obtained from 28 days of cured samples. The sample was coated with gold in a sputter coating machine before performing the SEM analysis to prevent charge accumulation during the experiment. The elemental changes following ceramic incorporation are known through the EDS test. However, the modification in soil fabric after ceramic incorporation can be easily seen with the SEM image.

The Rigaku powder diffractometer equipment was used for the XRD examination of treated and untreated samples. This test was performed to determine the mineral phases in the treated and untreated samples. The test was performed on powder samples smaller than 90 µm prepared by crushing and sieving 28-day-cured UCS specimens. The data was obtained at an angle of 2θ with a step size of 0.02 and a range of 5° to 80°. The acquired data was analyzed using the X'pert high score plus software [51, 52].

FT-IR test detects the functional groups in the soil sample by absorbing the spectrum under independent vibrations. Perkin Elmer instrument was used for FT-IR analysis with a scan range of 400-–4000 cm-1. The powdered sample used in this test was the same as in the XRD analysis.

5. Results and Discussion

5.1. Atterberg limit tests

The outcomes of the Atterberg limits are shown in Figure 6. It is evident from the figure that the increasing amount of CW content caused a reduction in LL and PL of CW-treated soil. LL and PL values reduced from 38% and 22% to 23%, and 14%, respectively. This reduction in LL and PL is due to replacing swelling clay particles with non-expansive CW particles [26, 48].

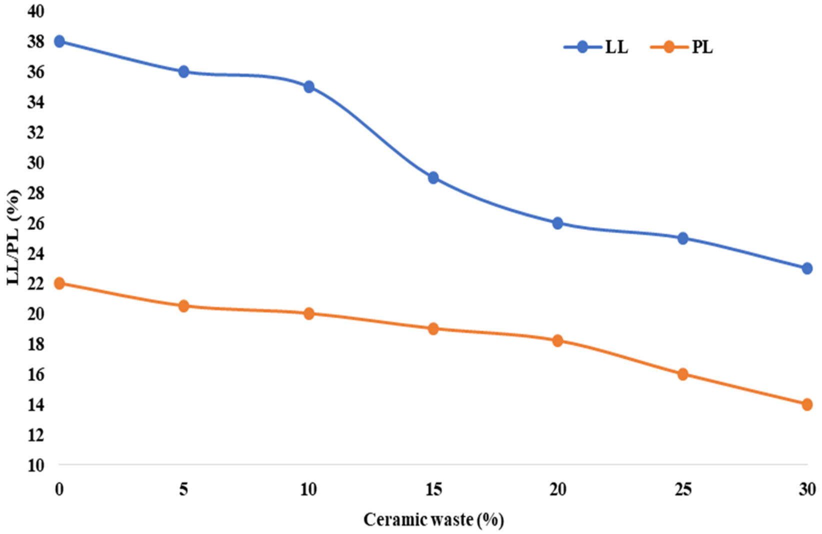

Figure 6. Variation of LL and PL with ceramic waste.

5.2. Compaction

The outcomes of the modified Proctor test on different composites of clay and CW are presented in Figure 7. It may be analyzed that on increasing the ceramic content, the γmax of clay increases while the ωopt of clay decreases. The replacement of 5%, 10%, 15%, 20%, 25%, and 30% CW increases the γmax of clay from 17.2 kN/m3 to 17.35kN/m3, 17.75 kN/m3, 17.92 kN/m3, 18.0 kN/m3, 18.15 kN/m3, and 18.25 kN/m3, respectively. In contrast, ωopt of clay decreased from 18.0% to 17.75%, 15.5%, 15.52%, 14.60%, 13.80%, and 13.0%. The increase in the γmax of clay-CW mixtures is attributed to replacing clay soil with CW of higher specific gravity. In contrast, the decrease in ωopt is attributed to ceramic waste's comparatively lower moisture absorption capability. This tendency of increase in γmax and decrease in ωopt is consistent with the outcomes mentioned by some other researchers [5, 8, 31].

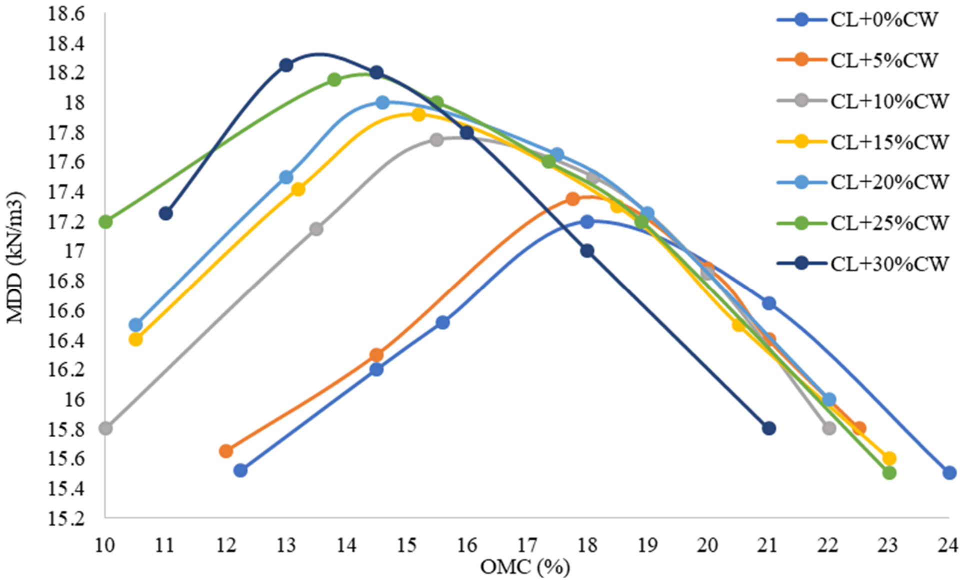

Figure 7. Compaction curves for clay-ceramic composites.

5.3. Unconfined compressive strength

The UCS test was used to analyze the improvement in the strength of untreated and treated clay by mixing CW in percentages 5%, 10%, 15%, 20%, 25%, and 30%. The improvement in the strength of untreated clay and clay treated with CW at different curing periods is shown in Figure 8. It can be analyzed that the UCS of untreated clay was increased from 58 kPa to approximately 217 kPa at 25% CW content. Further increment in CW resulted in a decrement in strength. In this experimental study, 25% CW content was supposed to be the ideal CW content. Moreover, It was observed that CW was able to enhance the strength of clay for all curing periods. The remarkable improvement in the UCS of ceramic-treated clay is attributed to the exchange of cations and the development of pozzolanic compounds. Micro-structural analysis in the later section also confirms the formation of the pozzolanic compound (CASH). Similarly, an improvement trend in UCS due to the formation of pozzolanic compounds by incorporating CW is reported by [8, 53].

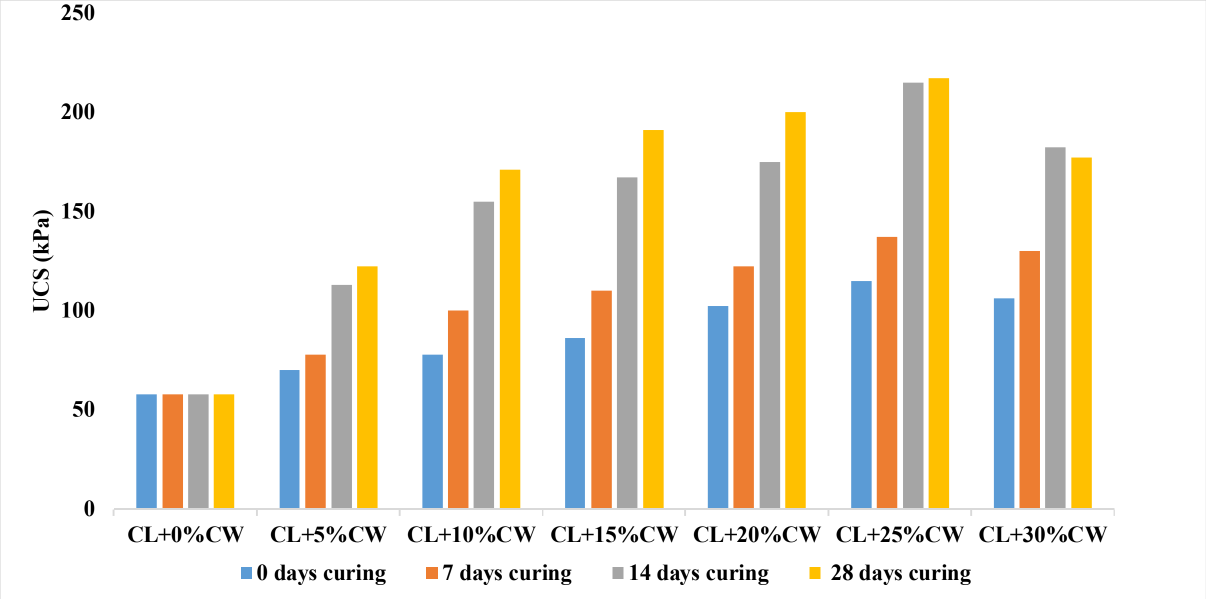

Figure 8. Variation in UCS of clay-ceramic composites.

The axial stress-strain behavior of 28 days cured untreated and clay treated with CW is represented in Figure 9. The failure strain of clay treated with higher CW content (CL + 20% CW, CL + 25% CW, CL + 30% CW) is lesser than the failure strain of untreated clay (6.58%). The ceramic-treated clay specimen CL + 20% CW shows instant loss of post-peak resistance after gaining peak strength, which indicates brittle failure. These findings are similar to the results reported by [54, 55].

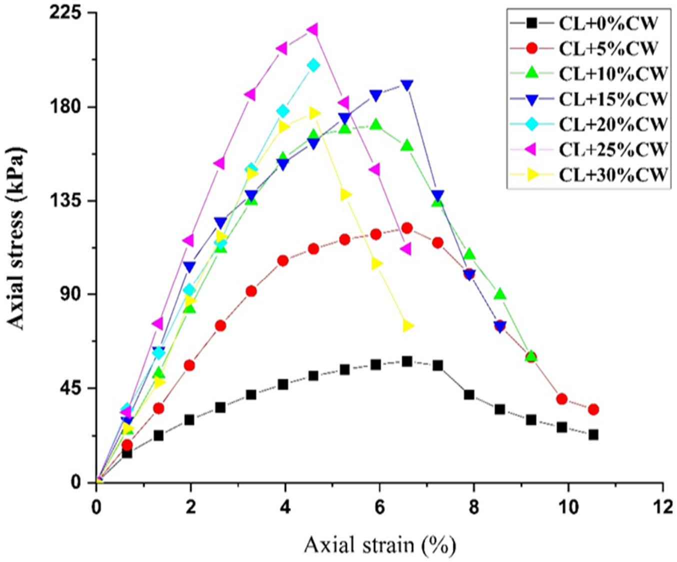

Figure 9. Axial stress-strain behavior of ceramic treated clay (28 days of curing).

Figure 10 portrays the pattern of failure in specimens subjected to the UCS test. Except for CL + 10% CW and CL + 20% CW, almost all the samples exhibit a similar failure pattern through the shear plane, indicating the brittle nature of clay-ceramic composite. Specimen CL + 10% CW primarily depicts bulging failure along with microcracks, which could be accountable for the increase in the axial strain, as seen in Figure 9, while in specimen CL + 20% CW, failure along vertical crack has been noticed, which is due to the instant collapse of the sample and negligible post-peak strength, which is also validated through the results shown in Figure 9.

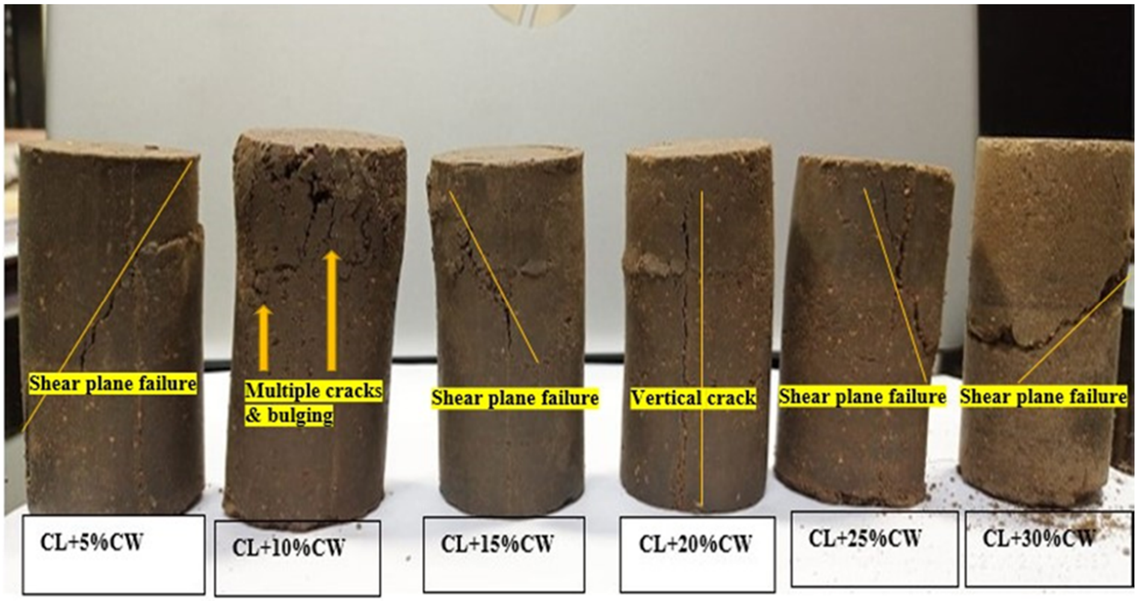

Figure 10. Failure pattern of UCS samples at various percentages of ceramic content.

5.4. CBR test

Figure 11 represents the soaked and unsoaked CBR analysis of clay mixed with various percentages of CW. The inclusion of CW in clay increased the CBR value. The unsoaked CBR value of clay increased from 9.5% to 24% by incorporating 30% CW; the increase in CBR value in unsoaked condition at 30% ceramic content is almost more than 150%. Soaked CBR test was performed to simulate the worst conditions during the rainy season. From the results shown in Figure 11, it can be inferred that the CBR value of clay-CW composite at 30% ceramic content is approximately 140% more than the untreated soaked CBR value. The increasing trend in the CBR analysis by mixing the CW is attributed to various reasons like (i) higher γmax of composites, (ii) higher specific gravity of CW, (iii) interaction between ceramic grains and soil sample, (iv) due to pozzolanic property of CW. The significant increment in soaked CBR value is attributed to pozzolanic activities in clay-ceramic composites in the presence of moisture content. The results of the CBR analysis thereby represent improved mechanical strength of clay-CW composites [27, 31].

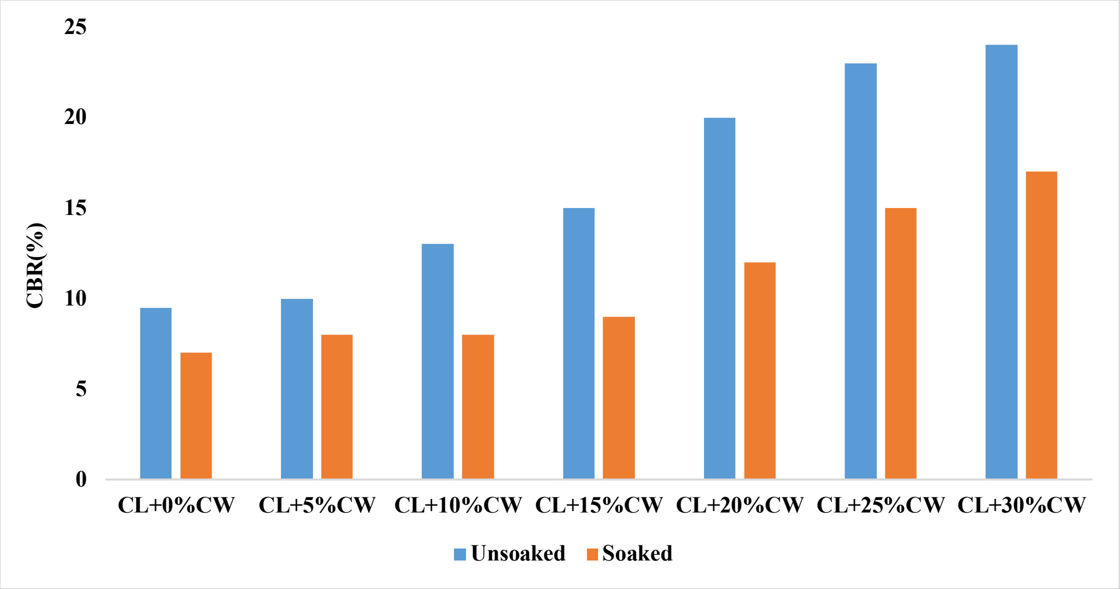

Figure 11. Variation in CBR value with ceramic waste.

5.5. Swelling pressure

The changes in the swelling pressure of clay-ceramic composites are represented in Figure 12. It can be analyzed from the results that the inclusion of CW in clay has resulted in a decrease in the swelling pressure of clay-ceramic composites. The replacement of 5%, 10%, 15%, 20%, 25%, and 30% CW decreases the swelling pressure from 75.25 kPa to 74.50, 70.00, 66.50, 62.00, 55.25, and 42 kPa, respectively. The inclusion of 30% CW in clay soil decreased the swelling pressure by approximately 44%. The decrement in swelling pressure is attributed to the replacement of expansive clay particles by non-expansive CW particles and pozzolanic reactions between ceramic and clay particles in the presence of available moisture.

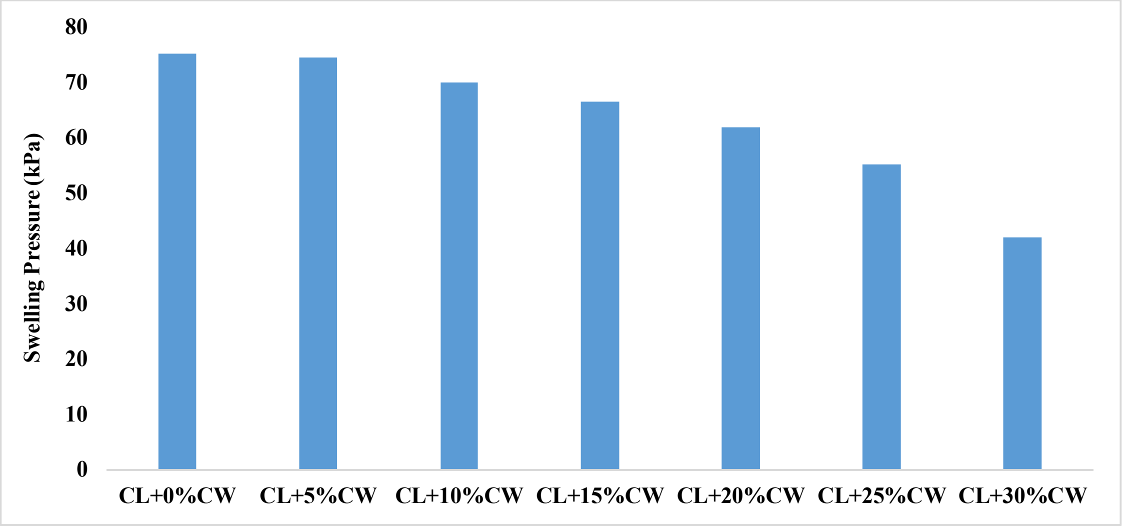

Figure 12. Variation of swelling pressure in clay-ceramic composites.

5.6. Micro-structural analysis

5.6.1. SEM analysis

SEM analysis was done to examine the changes on the surface of the treated and untreated clay-ceramic samples. The morphological changes on CW-treated samples after 28 days of curing are shown in Figure 13. The untreated sample has a porous surface, whereas in the case of the treated samples, due to the reaction between clay and ceramic particles, white lumps of cementitious products can be seen. These cementitious gel products are responsible for better interlocking within soil particles, ultimately accountable for the compact and denser matrix of treated samples. Similar white patches of cementitious products were noticed by [21, 50, 53, 56]. The improvement in the surface morphology of ceramic-treated clay soil samples is attributed to the presence of a higher percentage of silicon (Si) and aluminium (Al) in CW and clayey soil, as observed through EDS analysis. In higher proportion, the presence of these elements Si and Al led to the formation of calcium-alumino-silicate-hydrate (CASH) [56, 57]. The appearance of CASH is also validated through the results of XRD analysis.

5.6.2. EDS analysis

EDS analysis of soil samples was performed to analyze the chemical composition of clayey soil before and after treatment with CW. Figure 14 represents the EDS analysis of clay treated with optimal ceramic content at 28 days curing period. The percentage weight (Wt%) of key elements available in the soil before and after optimal ceramic treatment is presented in Table 5. The Wt% of Si and Al in CW-treated clay was found to reduce. In addition, the EDS spectrum of CW-treated clay shows the significant presence of Ca. The reduction in Wt% of major elements and presence of Ca in CW-treated soil confirmed the possible formation of cementitious compound CASH due to the pozzolanic activities [50].

Table 5. The weight percentage of elements present in clay before and after treatment.

Element (Wt %)	(CL + 0% CW)	(CL + 25% CW)
Si	28.82	26.54
Al	17.37	9.30
O	16.99	22.39
Fe	14.93	2.57
C	8.94	26.60
Mg	8.72	2.75
K	3.28	1.37
Ca	0.95	6.07
Na	-	0.43

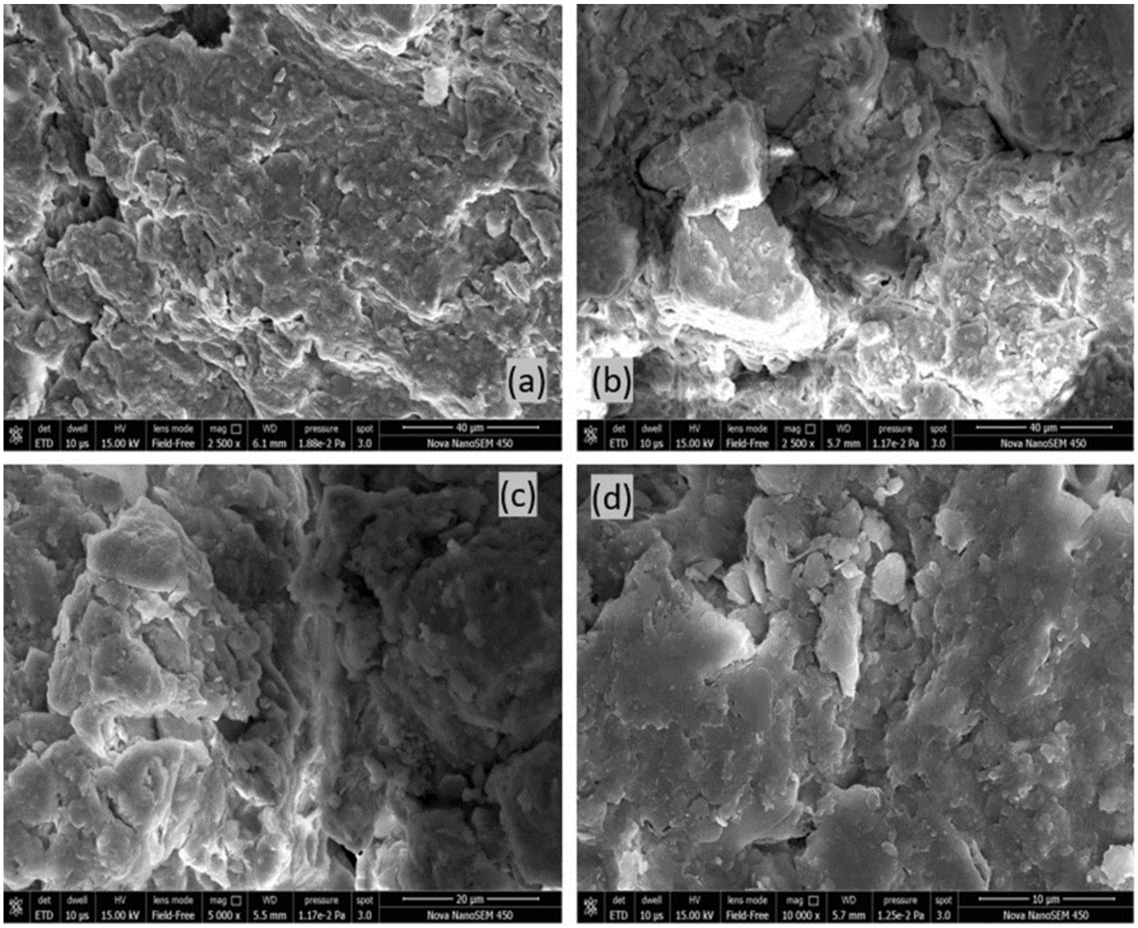

Figure 13. SEM micrographs (a) CL + 0% CW (2500x magnification), (b) CL + 25% CW (2500x magnification), (c) CL + 30% CW (5000x magnification), (d) CL + 25% CW (10000x magnification).

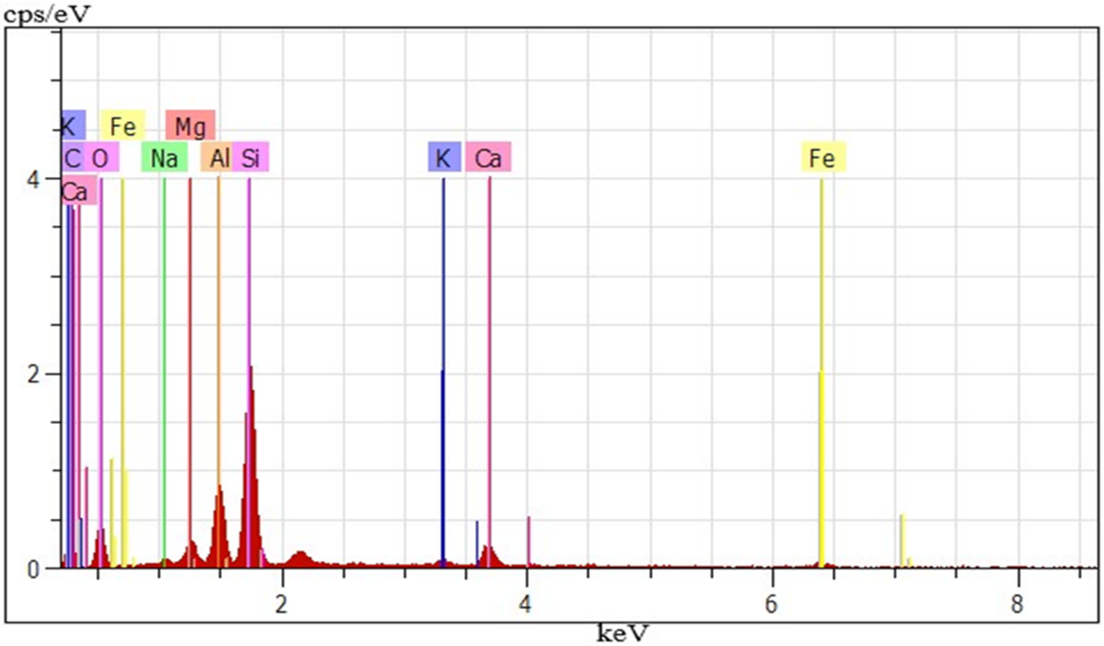

Figure 14. EDS spectra of clay treated with 25% ceramic waste (CL + 25% CW).

5.6.3. XRD analysis

As per Figure 15, which shows the X-Ray Diffraction patterns of the untreated clay and clay treated with 25% CW (by dry weight), it was found that the untreated clay showed a significant proportion of the clay minerals like silica, montmorillonite, and illite. After the stabilization of clayey soil by different doses of CW and a curing period of 28 days, a reduction in the peak intensities related to silica and montmorillonite was noticed, while peak intensity corresponding to Illite mineral almost disappeared in composite stabilized with 25% CW. These variations in the XRD patterns of untreated and CW-treated clayey soil are attributed to the cementitious reactions between the primary clay minerals and ceramic material. Furthermore, the XRD pattern of the stabilized specimen shows an additional intensity peak of CASH, which is developed due to the pozzolanic reactions.

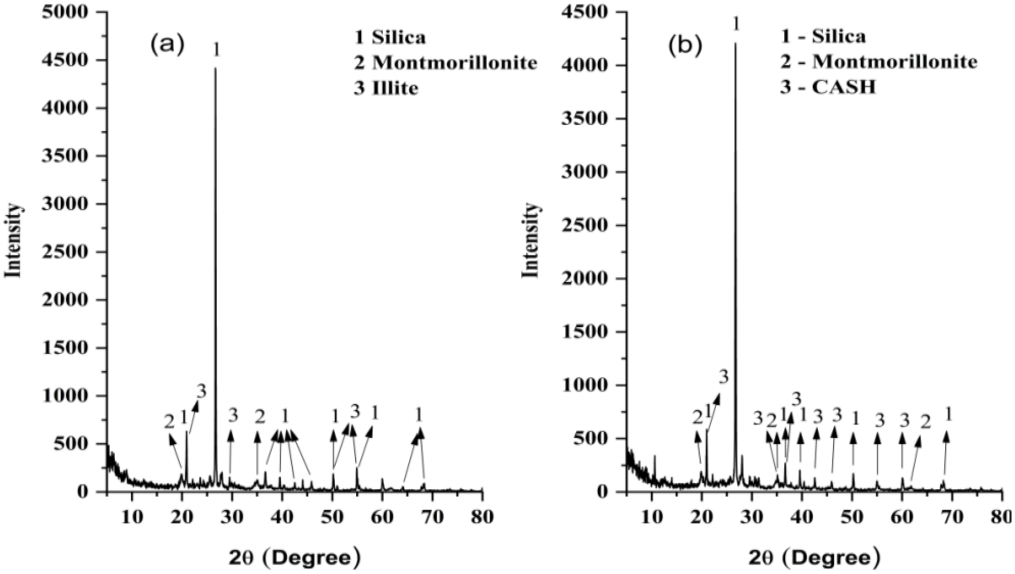

Figure 15. XRD patterns of (a) Untreated clay, (b) Clay treated with 25% ceramic waste.

5.6.4. FTIR analysis

Figures 16 (a) and (b) represent the FT-IR spectrum for the untreated and optimal ceramic-treated clayey soil, respectively, in the absorption range of 400-4000 cm-1. The band of about 800 cm-1 depicts the availability of amorphous silica [58, 59]. Significant vibration around 1024 cm-1 validates the presence of alumino silicate mesh, emerging due to the availability of clay minerals [60]. The presence of clay minerals is also indicated by the strong vibrations in OH stretching around 3600 cm-1 in FT-IR spectra of both untreated and ceramic-treated clayey soil [61].

5.7. Application of ceramic waste as a soil stabilizer for Indian rural roads

Rural roads account for 85% of the overall road network in India [62]. These rural roads are built under the Indian government's Pradhan Mantri Gram Sadak Yojana initiative. Due to the government's limited financial resources, there is an increased interest in lowering pavement construction costs. Improved CBR value of subgrade soil reduces the thickness of top pavement layers and the construction cost. To simulate the worst conditions, a soaked CBR test is performed while building these rural roads (IRC-37-2001) [63]. As per IRC: SP-20- 2002 [64], the minimum required CBR value of the construction material for designing subgrade and sub-base courses must be 10% and 15%, respectively. In this experimental study, the soaked CBR value of untreated clay and clay treated with 5%, 10%, and 15% ceramic waste (by dry weight) is less than 10%. The soaked CBR value of clay treated with 20% CW is 12%. Hence, this composition satisfies the minimum soaked CBR criteria of subgrade only. However, on further treating the clayey soil with 25% and 30% CW, the soaked CBR value obtained was 15% and 17%. Thus it can be concluded that clay composite containing 25% and 30% CW satisfies the minimum CBR requirement criteria of both sub-grade and sub-base materials for the construction of rural roads.

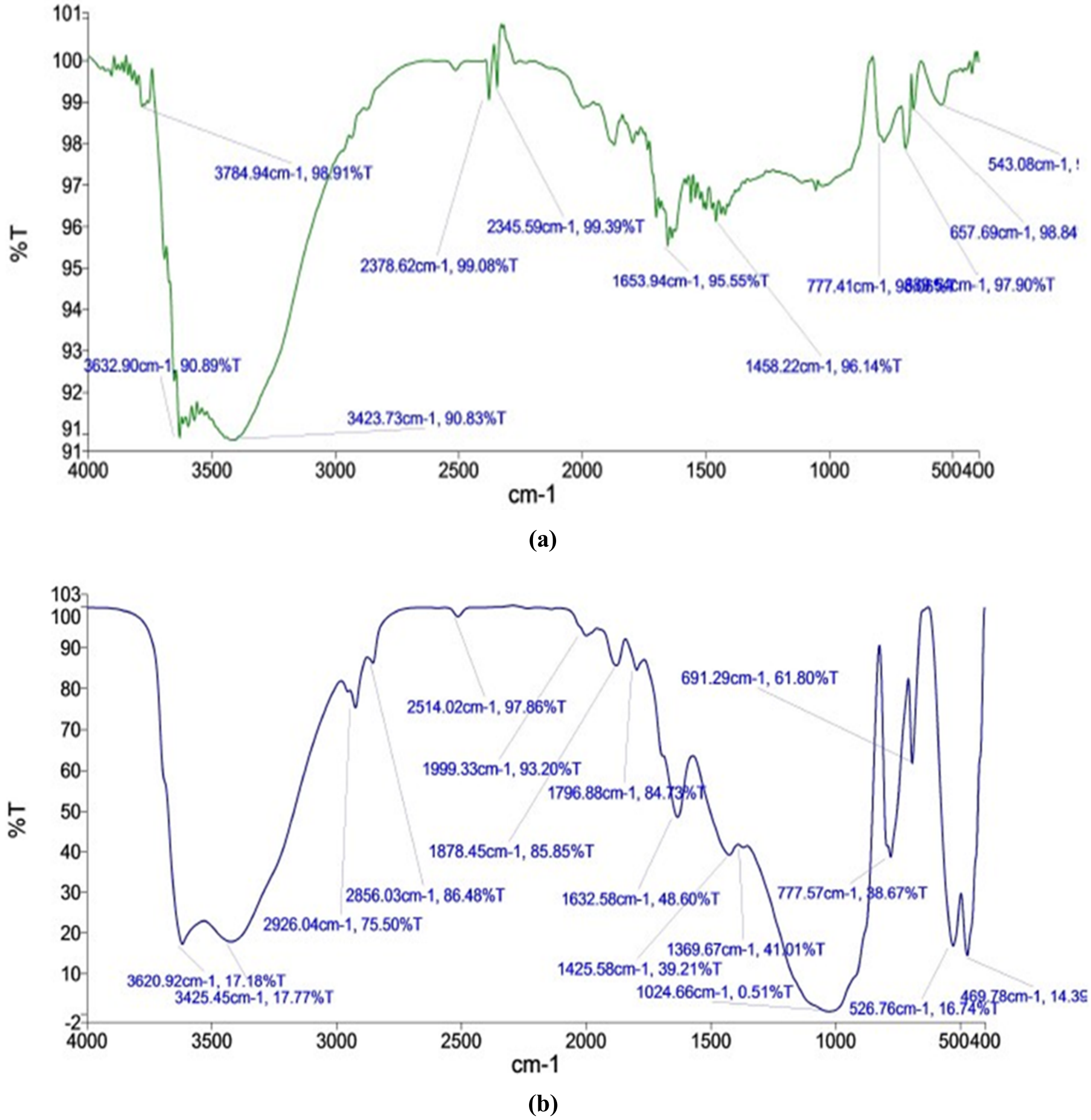

Figure 16. a) FT-IR spectra of clayey soil. b) FT-IR spectra of optimal ceramic-treated clayey soil (CL + 25% CW).

6. Conclusions

Based on the experimental study of utilizing CW to stabilize clayey soils, the following conclusions could be drawn based on the results.

- The increase in the proportion of CW reduced the LL and PL of clay-CW composites. The reduction in LL and PL was attributed to the non-expansive nature of ceramic particles.
- The compaction parameters of clayey soil were notably improved by incorporating CW in clay. The γmax of the clay-CW composite increased with the percentage of CW, while the ωopt reduced with the increasing percentage of CW.
- In comparison to untreated clay, the unconfined compressive strength of CW-treated clayey soil after 28 days of curing period was enhanced by almost four times. Maximum UCS was obtained at 25% ceramic content (28 days curing period). Further increase in CW content resulted in decreasing the UCS. The increase in UCS was also dependent on the curing period.
- The incorporation of CW in clayey soil notably increased the CBR performance in both soaked and un-soaked conditions, thereby, may cause a substantial reduction in the thickness of the pavement. Thus by reducing the overall pavement thickness, the overall cost of highway construction can be significantly reduced. CBR values of clay treated with 25% and 30% CW

satisfied the minimum CBR requirement of subgrade and sub-base materials as per IRC: SP-20-2002.

- The decreasing pattern in swelling pressure was obtained in clay-ceramic composites with increased CW content. The reduction of swelling pressure was attributed to replacing swelling clay particles with non-expansive CW particles.
- SEM analysis of untreated and CW-treated clay exhibited the aggregation of clay particles, which is accountable for the improved cohesion. SEM images of untreated clay show porous structure and voids in the soil. In contrast, white patches of cementitious products (CASH) were noticed in the treated soil. Furthermore, the pores in the untreated soil were packed with these cementitious products, resulting in a denser and more compact soil matrix.
- As per the EDS analysis, the Wt% of major elements (Al and Si) decreased due to pozzolanic reactions in treated soil. Moreover, Ca detected in the EDS spectrum of treated soil validated the development of cementitious products.
- XRD analysis confirmed that soil mineralogy was significantly affected after ceramic treatment. Generation of new peaks, reduction in the peak of silica, and disappearance of Illite peak assured the formation of cementitious product (CASH).
- FT-IR investigation revealed several particular absorption bands linked with clay minerals. On comparing the FT-IR spectrum of untreated and treated clay, changes in intensity were noticed, indicating the development of new cementitious compounds.

The results of the experimental study found that using CW as a soil stabilizer is a good alternative to traditional stabilizers like lime and cement. However, further analysis is needed to investigate the durability of CW-stabilized clayey soil.

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Declaration

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2. There is no funding source for carrying out this experimental study.

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تثبیت خاک با استفاده از ضایعات سرامیکی: یک مطالعه تجربی

پانکاج راثور* و سورِش کومار تیواری

گروه مهندسی عمران، موسسه ملی فناوری مالاویا، جیپور، هند

ارسال ۲۰۲۲/۱۱/۲۲، پذیرش۲۰۲۳/۰۲/۰۹

* نویسنده مسئول مکاتبات: rce9060@mnit.ac.in2019

چکیده:

هدف اصلی این تحلیل تجربی، درک اثربخشی ضایعات سرامیکی (CW) در تثبیت خاک رسی است. اثر افزودن درصدهای مختلف CW (۵، ۱۰، ۱۵، ۲۰، ۲۵ و ۳۰ درصد) بر خواص ژئوتکنیکی خاک رسی با انجام یک سری آزمایشات آزمایشگاهی مانند آزمایش حدی آتربرگ و تراکم ارزیابی می‌شود. آزمایش، تست مقاومت فشاری نامحدود (UCS)، تست نسبت باربری کالیفرنیا (CBR) و تست فشار تورم. تجزیه و تحلیل ریز ساختاری شامل میکروسکوپ الکترونی روبشی (SEM)، طیف‌سنجی پراکنده انرژی (EDS)، پراش اشعه ایکس (XRD) و طیف‌سنجی تبدیل فوریه فروسرخ (FT-IR) بر روی کامپوزیت‌های خاک رس و سرامیک بهبود یافته و بهبود نیافته انجام شد. نتایج به‌دست‌آمده نشان می‌دهد که اختلاط ۳۰ درصد ضایعات سرامیکی در خاک رسی، حداکثر وزن واحد خشک (γmax) را از ۱۷/۲۰ کیلو نیوتن بر متر مکعب (CL + 0 در صد CW) به ۱۸/۲۵ کیلو نیوتن بر متر مکعب (CL + 30 در صد CW) افزایش می‌دهد. مقاومت فشاری نامحدود خاک رسی با افزودن ضایعات سرامیکی افزایش می‌یابد. حداکثر UCS 217 کیلو پاسکال با محتوای ۲۵ درصد سرامیک به دست آمد که پس از آن شروع به کاهش می‌کند. به طور مشابه، روند افزایشی در نتایج CBR با افزایش محتوای ضایعات سرامیکی مشاهده شد. افزایش CBR تقریباً ۱۵۲٪ (شرایط خیس نشده) و ۱۴۲٪ (شرایط خیس شده) است. در عین حال، افزودن ضایعات سرامیکی در خاک رسی محدودیت‌های آتربرگ، آب محتوای بهینه (ωopt) و فشار تورم را کاهش می‌دهد. "از مطالعه تجربی می‌توان نتیجه گرفت که CW می‌تواند به عنوان یک تثبیت کننده خاک جایگزین پایدار استفاده شود".

کلمات کلیدی: ضایعات سرامیکی، تثبیت، حداکثر وزن واحد خشک، آزمایش مقاومت فشاری نامحدود، خاک رسی.