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Sustainable Stabilization of Clayey Soil Utilizing Industrial Waste: Steel Slag and Silica Fume

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Abstract - The disposal of industrial waste materials and the poor engineering behavior of clayey soils are major concerns in geotechnical engineering. Weak clayey soils create significant challenges in construction due to their low strength, high plasticity, and poor load-bearing capacity. Stabilization of such soils is essential to improve their engineering performance and ensure safe and durable infrastructure development. At the same time, the increasing generation of industrial waste materials has raised serious environmental concerns regarding their disposal and management. This study aims to utilize steel slag and silica fume as sustainable stabilizing materials for improving the properties of clayey soil. In this investigation, steel slag was mixed with clayey soil in proportions of 10%, 15%, and 20%, while silica fume was added at 4%, 6%, and 8% by dry weight of soil. A series of laboratory tests were carried out on both natural and stabilized soil samples to examine the changes in geotechnical characteristics. The tests included Atterberg limits, Standard Proctor compaction test, Unconfined Compressive Strength (UCS) test and California Bearing Ratio (CBR) test. The experimental observations showed that the addition of steel slag and silica fume improved the overall behavior of the clayey soil. The treated soil exhibited higher strength and compaction characteristics along with reduced plasticity and permeability. The improvement is mainly due to enhanced particle bonding and the pozzolanic reaction occurring between soil particles and stabilizing materials. The results of this study indicate that steel slag and silica fume can be effectively used as alternative stabilizers for clayey soils. Their application not only improves soil performance but also supports sustainable waste utilization and environmentally friendly construction practices. This method can be adopted for pavement subgrades and other ground improvement applications in geotechnical engineering.

***Key Words*:** Compaction test, CBR, UCS, Silica Fume, Steel Slag

INTRODUCTION

All but the top layers of pavements, which are typically made of concrete and asphalt, are built using soil, a natural material. Industrial wastes like silica fume and steel slag have commercial value and enhance the soil's strength, workability, texture, and plasticity. The categorization and the intended level of soil quality improvement determine the type and quantity of additive to be used. A significant portion of India is covered in expansive soil, specifically black cotton soil, which presents significant challenges for construction projects. Given that these deposits' primary characteristics include low shear strength, high plasticity, compressibility, and substantial volumetric changes when saturated, it is vital to discuss some of their geotechnical features. As a result, they don't fit the specifications needed to be used in civil engineering projects. Geotechnical engineers design shallow or deep foundations when it is not available at a deeper depth. Even building a deep foundation can occasionally be challenging due to poor soil conditions. In these situations, several soil techniques are used to address the soil's vulnerability.

Its geotechnical qualities are enhanced and stabilized through the use of stabilization and reinforcement techniques. Soil stabilization is accomplished through a variety of methods. Admixtures like cement, lime, bitumen, chemicals, etc. can be used to stabilize the soil, or compaction can be used without adding any admixtures. It can also be achieved by adding fibers or strengthening materials to the soil. When adding materials that completely satisfy the specifications is a simpler way to make up for a shortfall in the readily available material, the soil is stabilized. To enhance the soft soil's engineering qualities, some industrial byproducts have recently been added. This aids in turning the industry's waste into useful products or the most desirable uses. Road construction, railroad ballast,

and hydraulic protection structures all use steel slag, a common industrial product and a major waste product of the steel industry. Because the free lime in the steel slag causes expansion, its use is restricted. Because steel slag contains free lime and other elements that are similar to Portland cement's chemical composition and mineralogy, it has more potential to be used in the building sector for soil stabilization. According to the Federal Highway Administration (FHWA), steel slag is a byproduct of producing steel that is produced in furnaces when impurities are removed from molten steel.

In order to produce steel, iron is oxidized by adding limestone and coke to remove surplus products like carbon and silicon. The steel slag shares physical characteristics with air-cooled iron slag and contains a significant amount of iron. Around 24 lacs tons of steel slag are produced annually by various steel factories in India, while between 96 and 145 million tons are produced annually worldwide. The experimental investigation of adding steel slag to clayey soil and its impact on compaction properties, unconfined compressive strength, shear strength parameters, and CBR value is the focus of this work. Additionally, the impact of various stabilizers on the ideal soil slag mixture has been investigated. Another waste heavily employed in soil stabilization is silica fume, which is an extremely reactive pozzolana, a by-product from the manufacturing of silicon and ferrosilicon alloys. It can be used moist or dry. Soils with silica fume can be particularly powerful. They may be quite resilient. Silica fume and Steel slag can be utilized as an efficient stabilizing agent on mixing with soil for the improvement of problematic soils for the usage in sub-grades and sub-bases.

2. Literature Review

Degou Cai et al. (2025) In order to create stabilized soil, three waste materials—rice husk ash (RHA), steel slag (SS), and iron tailing (IT) powder—were chosen and used in concert with cement. The microstructure, degree of hydration, and mechanical strength of the stabilized soil samples were assessed. According to the experimental findings, samples' mechanical qualities improved as the cement content increased. In particular, samples mixed with RHA exhibited the lowest strengths as compared to samples combined with SS and IT, suggesting that RHA has no effect on strength improvement. Additionally, compared to the reference batch, SS and IT demonstrated a significantly greater impact on enhancing the mechanical strength of the stabilized soil samples, with strength increasing rates as high as 60%. Additionally, the benefits of cement and waste materials on enhancing the performance of stabilized soil samples have been further demonstrated by the microstructure analysis results. Waste materials have been shown to improve the hydration reaction and pore structure. With a high usage of specific common wastes, the current work provides an insight into ecologically responsible road construction.

Sher Shah et al. (2025) Using glass powder and steel slags as industrial wastes, the current study aims to explore various soil properties, including California bearing ratio, unconfined compressive strength, plasticity index, and maximum dry density. Steel slags and glass powder both significantly alter the various soil properties of the two soil samples. When glass powder and steel slag were added, the PI values of soil samples dropped from 13.7% to 10.1% and from 13.1% to 8.3%, respectively. Combining both with the specified percentage content significantly reduced the PI, with the largest decrease of 1.4% at 10% GP and 20% SS. In a similar vein, the MDD rose as the SS and GP contents increased; the highest increases were noted for 10% SS (1.92 g/cc) and 10% GP (1.96 g/cc), respectively. However, combining 10% GP and 20% SS with glass powder and steel slag produced the highest growth of 2.21 g/cc. Glass powder and steel slag both raised the CBR value. 10% SS (8.7%) and 10% GP (9.6%) showed the biggest increases. The blend of 10% G.P. and 20% SS with steel slag and glass powder showed the greatest increase of 17.6%. The number increased by over 183.8% from its initial value. Consequently, one popular and economical way to enhance soil qualities for stabilization is to utilize glass powder and steel slag.

Yaniam et al. (2025) There is a scarcity of land with suitable soil conditions due to the quick growth of towns and the growing demand for construction. Because builders frequently have to work with poor soils that are easily available in the area, soil stabilization is an extremely significant technique. By altering the soil's characteristics, these methods increase its durability and strength. There are limited research on the combined impact of areca fiber and silica fume on the durability and improvement of peat soil in Ziro Valley, Arunachal Pradesh, despite the fact that numerous soil stabilization strategies have been investigated. Soil specimens were subjected to a variety

of tests, including UCS, CBR, SEM, EDX, compaction, physical and index properties, etc. Up to 0.5% of its dosage with soil, areca coir (20–30 mm) increased soil quality; however, at greater doses, dispersion issues arise. Depending on the type of soil, different weight ratios of areca fiber (0.3%, 0.5%, and 0.7%) and silica fume (6%, 8%, and 10%) are used to obtain the ideal conditions. The cementatious ingredient, silica fume, greatly boosts the strength of peat. MDD rises and OMC falls as a result. When areca-reinforced soil is added, OMC rises and MDD falls. After 28 days of curing, the S+8%SF+0.5%AF mix in this study had the highest UCS value of 369.256 kPa, demonstrating its efficacy in enhancing the strength of peat soil. Additionally, the S+10%SF+0.5%AF mixture's CBR values increased the most, from 2.27% to 11.1% (soaked) and 3.45% to 13.71% (unsoaked).

Xianzeng Shi et al. (2024) This article aims to tackle the low comprehensive utilization rate of industrial solid waste by focusing on three specific issues related to slag: steel slag, the recycling of silica fume, and the mechanisms for improving the strength of slag-steel slag-silica fume composites. The analysis of the mixture's macro strength at different curing ages is conducted by the two metrics of unconfined compressive strength and splitting tensile strength, supplemented by microscopic tests such as X-ray diffraction, scanning electron microscopy, and Fourier transform infrared. The discussion focused on the internal dynamics of hydration product production and the modification of strength in slag and steel wollastonite cementitious material when stimulated by a sodium hydroxide and sodium silicate mixed solution as an alkali activator. The findings on strength reveal that the optimal proportion of slag, steel slag, and silica fume is 6:3:1, accompanied by a lye modulus of 1.2 and a lye content of 6% when cured under standard conditions for 28 days, resulting in a compressive strength of 2.44 MPa for the polymer base composed of slag, steel slag, and silica fume. The outcomes demonstrate that the hydration products of the geopolymer are primarily calcium-silicate-hydrate (C-S-H) gel, with a lesser presence of ettringite (AFt) crystals. The introduction of slag diminishes the calcium/silicon ratio and enhances the aluminum/silicon ratio, thereby increasing the degree of gel polymerization. The hydration process of steel slag yields silicon dioxide and calcium hydroxide that interact to form C-S-H gel. Silica fume delivers a potent source of active silicon to the system, while its seeding and pozzolanic properties enhance the hydration process.

Haojie Li et al. (2023) A high-performance geopolymer cementing substance, mostly composed of green steel slag and fly ash, was formulated and activated using sodium silicate alkalinity to address the geological risk posed by unstable loess slopes susceptible to collapse and landslides. The investigation examined the mechanical characteristics and microstructural alterations of loess subjected to varying amounts of steel slag-fly ash geopolymers and different curing durations through a range of experiments, including unconfined compressive strength, direct shear, disintegration, scanning electron microscopy, and X-ray diffraction. The findings indicate that the utilization of geopolymers significantly enhances the internal friction angle, cohesiveness, and unconfined compressive strength of loess, while simultaneously reducing the quantity and speed of disintegration of stabilized soil. The consolidated soil blended with 20% geopolymer and cured for 28 days exhibited an internal friction angle of 31.12°, a cohesiveness of 81.09 kPa, and an unconfined compressive strength of 570.86 kPa. These figures are 1.62, 1.76, and 3.36 times more than the corresponding values of loess, respectively. Moreover, the degradation of consolidated soil within 1800 seconds is minimal, merely 1.97%. The efficacy of curing is significantly influenced by the age of the hardened soil. The duration of curing may be extended to substantially enhance the mechanical characteristics of the solidified soil. When the geopolymer content is 20% and the curing duration is prolonged to 28 days, the internal friction angle, cohesiveness, and unconfined compressive strength enhance by approximately 0.23, 0.48, and 1.61 times, respectively, in comparison to a curing period of 7 days. The SEM and XRD examinations indicated that the cementitious substances of C-S-H and C-A-S-H generated from the hydration of steel slag-fly ash geopolymer may proficiently occupy the voids among soil particles and enhance the mechanical characteristics of solidified soil. The findings of this research may offer a conceptual foundation for the enhancement of loess subgrade with steel slag-fly ash geopolymer.

Sheikh et al. (2023) The subgrade soil is a crucial component of the road pavement system, offering foundational support to the pavement layers including the subbase, base, and wearing courses. The characteristics of the subgrade soil are crucial for the

pavement structure design. Any deficiency in the subgrade soil will influence all the pavement layers situated above it, particularly flexible pavement. The subgrade must possess sufficient stability in unfavorable weather conditions to sustain the pavement. Inadequate subgrade conditions result in undulations, ripples, depressions, and displacement of asphalt surfaces. Stabilization is a broad word that refers to the several methods employed to modify soil qualities to improve its engineering performance and applicability in diverse engineering projects. The soil analysis was conducted by combining the soil sample with varying proportions of Fly ash, Silica fume, and GGBS.

Ahmad S. et al., (2023) Expansive soil is characterized by its ability to alter its volume by expanding and contracting. These soil varieties predominantly consist of montmorillonite, a mineral capable of water absorption, resulting in soil expansion due to volume increase. These expansive soils, capable of contracting or expanding with seasonal variations in moisture levels, may pose a considerable threat to engineered infrastructures. Numerous research endeavors have examined expansive soils and analyzed their characteristics, along with methods for their enhancement. This research employs three proportions of lime, cement, and silica fume (5, 7, 9%) to stabilize expansive soil, divided into two segments: the initial segment involves a consolidation test to measure the free swell and swell pressure of both untreated and treated soils; the subsequent segment applies the grouting technique as a field process to enhance bearing capacity. The findings indicate that soil treated with varying proportions of lime, cement, and silica fume shows a reduction in free swell and swelling pressure by about 65% and 76%, respectively, when contrasted with untreated soil. The soil infused with silica fume enhances the load-bearing capability of footings situated on the treated soil by roughly 64% to 82% for the soil modified with 5% and 9% silica fume, respectively, in contrast to untreated soil.

Mansour Ebailila et al. (2022) Silica fume and ground granulated blast-furnace slag (GGBS) have demonstrated efficacy in stabilizing sulfate soils as a precursor to lime. Nonetheless, it remains uncertain which precursor exhibits superior strength and swelling. Consequently, the binary combinations of lime–silica fume and lime–GGBS were individually blended with unadulterated kaolin soil and sulfate-treated kaolin soil at a constant dosage of 3L7S and 3L7GGBS, respectively. Subsequently, a comprehensive multi-scale investigation was undertaken, incorporating unconfined compression strength (UCS), linear expansion, derivative thermogravimetric (DTG) analysis, X-ray diffraction, and scanning electron microscopy (SEM) to assess their efficacy. The engineering test outcomes indicated that the binary mixtures of lime–silica fume and lime–GGBS are appropriate for stabilizing non-sulfate and sulfate-treated soil, respectively, with the former exhibiting superior expansion properties and the latter demonstrating enhanced UCS. This disparity in performance can be attributed in part to the elevated calcium oxide concentration in 3L7GGBS, which leads to an increased quantity of ettringite, and in part to the superior pozzolanic activity of silica fume that hastens lime consumption and limits ettringite formation, adversely affecting fabric modification.

Pawar et al. (2022) Employing steel slag for the stabilization of soil represents a contemporary utilization of this material. This research primarily aims to examine the influence of steel slag on the strength properties of clay soil. Steel slag is mixed with clayey soil in proportions of 10%, 15%, 20%, 25%, and 30% of its dry weight. In our research, the ideal proportion of steel slag was established by evaluating the peak unconfined compressive strength. A sequence of additional laboratory examinations has been conducted on this ideal mixture to assess its appropriateness as a stabilizing agent. The examination was similarly performed with traditional stabilizing agents, including 10% fly ash and 5% cement with clayey soil, and the optimal mixture was identified. Subsequently, the outcomes are evaluated in accordance. The aforementioned investigation indicates that including steel slag markedly enhances strength parameters relative to fly ash, although exhibits inferior strength when compared to cement.

Megha S. Mahaladkar et al., (2022) The primary aim of this research is to examine the influence of index characteristics of clayey soils when combined with silica fume and basalt fiber. A sequence of laboratory tests has been performed on samples containing 0%, 5%, 10%, 15%, and 20% Silica fume, together with 0.05%, 0.1%, 0.15%, and 0.2% Basalt fiber based on the weight of dry soil. The test outcomes indicated a notable alteration in the consistency limits of samples using Silica fume and basalt fiber. The study revealed that Silica fume is an advantageous substance for

altering the index properties of black cotton soil, rendering it appropriate for various construction endeavors. The incorporation of basalt fiber significantly enhances the compressive strength of BC soil in contrast to silica fume.

Mohamed A. Sakr et al., (2020) This research examined the impact of employing micro silica fume for soil stabilization via a laboratory analysis. Test outcomes indicated that the incorporation of micro silica fume can significantly reduce the free swell index value by 69% when utilized at a concentration of 25%. The swelling pressure diminishes from 410 kN/m2 to approximately 330 kN/m2 and 302 kN/m2 with micro silica fume contents of 5% and 25%, respectively. This illustrates the efficacy of the suggested enhancement in the amelioration of expansive soils. This enhancement method is used in many civil engineering construction endeavors, such as slope stabilization and road embankments.

Soundara B et al., (2019)

This experimental investigation examines the strength characteristics and ideal moisture content necessary for attaining the highest dry density of clay soil, incorporating sisal fibers and silica fumes in different ratios.An unconfined compression strength (UCS) test was performed to assess the strength of natural clay and clay enhanced with silica fume (5%, 10%, 15%) and sisal fibers (0.25%, 0.5%, 0.75%) individually, as well as in various combinations by altering the ratio of sisal fiber for each silica fume proportion. The ideal moisture content and peak dry density were obtained from a typical Proctor test conducted using a small compaction device.The test findings revealed that an increase in silica fume concentration reduces the maximum dry density from 1.81g/cc to 1.613g/cc; likewise, a rise in sisal fiber content also leads to a decrease in maximum dry density from 1.81g/cc to 1.61g/cc. The ideal moisture content exhibits minor fluctuations with the incorporation of sisal fibers and silica fume, measured at approximately 16.67%.

Faisal Farooq dar et al. (2019) The establishment of foundations, road embankments, and pavements on very soft soil is a formidable challenge for civil engineers. Contemporary civil engineers are compelled to erect buildings on accessible locations without taking into account the soil composition. The expenses of construction can be significantly reduced by opting for indigenous resources, including local soils, for the foundational layers of the pavement, such as the sub-base course and subgrade soil. If the local soil's stability is insufficient to bear the wheel loads, its characteristics are enhanced by soil stabilization methods. The foremost obstacle confronting the processing and manufacturing sectors is the disposal of residual waste materials. Byproducts that are typically hazardous, flammable, caustic, or reactive provide significant health and ecological risks. Consequently, the management of industrial waste is a significant concern for the current generation. This step necessitates an effective, economical, and environmentally friendly approach to address the disposal of residual industrial waste materials. A prevalent and practical method for employing these waste materials is through the construction of roads, highways, and embankments. If these materials can be effectively employed in the construction of roads, highways, and embankments, the pollution issue resulting from industrial waste can be significantly mitigated. This study concentrated on the application of industrial byproducts such as Ground Granulated Blast Furnace Slag (GGBS) and silica fume as a stabilizing agent.

Joshi et al. (2018) The incorporation of steel slag enhances the load-bearing ability and fortitude of black cotton soil, hence indirectly reducing construction expenses. Various proportions of 5%, 10%, 15%, and 20% steel slag have been employed to enhance the stability of black cotton soil and to assess its viability as a construction material for roadways. The steel slag obtained from Kalika Steel in Jalna and the black cotton soil sourced from Himayatbaugh in Aurangabad. The entire software was executed in two stages. In the initial step, essential tests including Atterberg limit, C.B.R, and standard proctor compaction test on unadulterated soil were conducted to evaluate the maximum dry density and optimum moisture content. The black cotton soil was combined with 5%, 10%, 15%, and 20% of steel slag in two stages.

Shubham more et al., (2018) The issue of industrial waste disposal is escalating in contemporary times. Hazardous waste is impacting both the environment and the land. In order to safeguard the land and ecosystem from industrial refuse, we repurposed that refuse for construction activities. At present, the global yearly output of steel slag is approximated to be between 90 and 135 million metric tons. Consequently, steel slag is utilized for the stabilization of black cotton soil and for reducing waste. The incorporation of steel slag enhances

the load-bearing ability and fortitude of black cotton soil, hence indirectly reducing construction expenses. Various proportions of 5%, 10%, 15%, and 20% steel slag have been employed to enhance the stability of black cotton soil and to assess its viability as a construction material for roadways. The steel slag obtained from Kalika Steel in Jalna and the black cotton soil sourced from Himayatbaugh in Aurangabad. The entire software was executed in two stages. During the initial phase, essential tests including Atterberg limit, C.B.R, and standard proctor compaction test on unadulterated soil were conducted to evaluate the maximum dry density and optimum moisture content. In the second phase, the black cotton soil was combined with 5%, 10%, 15%, and 20% of steel slag.

Kawther et al., (2018) Investigated the Rehabilitation of Clayey Soil by the Application of Silica Fume. Various proportions of silica fume incorporated with the soil sample are 0%, 3%, 5%, and 7%. Assessments such as specific gravity, compaction properties, swell and swell pressure, California Bearing Ratio (CBR), and compressive strength evaluations were performed on the prepared and altered soils. The findings indicated that augmenting silica fume content results in a reduction of the plasticity index and liquid limit, while simultaneously increasing the plastic limit and optimal water content. The maximum dry unit weight values also diminish. The utilization of silica fume enhances compressive shear strength, California Bearing Ratio (CBR), swelling, and swell pressure.

Chand et al. (2017) Soil is a naturally occurring substance utilized in the building of all layers of pavements except for the surface layers (i.e., concrete and asphalt) and is subjected to classification tests to ascertain its engineering properties. A significant area of Central India and a section of South India is enveloped in black cotton soils. These soils exhibit significant swelling and shrinkage properties, along with an exceedingly low California Bearing Ratio and shear strength. Consequently, enhancement of these attributes is necessary. The current research seeks to ascertain the characteristics of black cotton soil augmented by Steel slag and Copper slag in a stochastic fashion. The soil utilized is a variety of black cotton soil sourced from Vempalle, Kadapa District, at a depth of 1.5 meters from the natural ground surface. The soil specimens were formed with four varying proportions of Steel slag (5%, 10%, 15%, and 20% by weight of soil), while maintaining a constant 20% of Copper slag. The unconfined compression test is performed following 0, 7, and 14 days of cure. CBR assessment conducted over a soaking duration of four days for both treated and untreated soil specimens.

Shalabi et al. (2017) Elevated water content in these soils will result in significant expansion and a decrease in shear strength and foundation carrying capacity. The engineering characteristics of various soil types can be enhanced through the application of additives and chemical stabilizers. This study utilized by-product steel slag to enhance the engineering characteristics of clay soils. Laboratory and field experimental initiatives were established to examine the influence of incorporating varying proportions of steel slag on the plasticity, swelling, compressibility, shear strength, compaction, and California bearing ratio (CBR) of the modified materials. The findings from the clay soil tests indicated that with an increase in steel slag content, the dry density, plasticity, swelling potential, and cohesion intercept of the soil diminished, but the angle of internal friction augmented. The test outcomes indicated that the CBR value escalated with a rise in slag content.

Hattamleh et al. (2017) This research aimed to investigate the efficacy of fine steel slag aggregate (FSSA) in enhancing the geotechnical characteristics of high plasticity subgrade soil. The mechanical and engineering characteristics of initial soil and fine steel slag were assessed. Subsequently, fine steel slag (FSSA) was incorporated into the prepared soil samples at dry weight percentages of 0%, 5%, 10%, 15%, 20%, and 25%. The efficacy of the FSSA was evaluated based on enhancements in consistency limits, compaction, free swell, unconfined compressive strength, and California bearing ratio (CBR). The test findings indicate that 20% FSSA additions will decrease the plasticity index and free swell by 26.3% and 58.3%, respectively. Additionally, the incorporation of 20% FSSA additives will enhance the unconfined compressive strength, maximum dry density, and CBR value by 100%, 6.9%, and 154%, respectively. In summary, FSSA positively influenced the geotechnical attributes of the soil and can serve as an additive to enhance the geotechnical properties of subgrade soil, while also addressing waste disposal issues.

K. Saranya et al., (2017) The incorporation of industrial byproducts in diverse engineering initiatives has gained popularity in India. This is required because to the disposal issues linked to it. Copper slag and silica fume are currently the most often utilized byproducts in

the construction sector. Substantial amounts of this refuse are amassed and discarded on expensive terrain, resulting in the depletion of valuable arable land. Incorporating these wastes into the current soil composition without entirely excavating and replacing it with a different soil type may serve as a cost-effective enhancement method compared to cement mixing and soil stabilization, which are costly. This paper presents a comprehensive assessment of prior research conducted by various scholars on the efficient application of copper slag and silica fume.

Abdelzaher et al., (2016) Investigated the stabilization of subgrade pavement layers utilizing lime, silica fume, and nano silica. The tested concentrations of lime were 2, 4, 6, and 8%, and for SF, they were 5, 10, and 15%, while NS utilized 1, 2, and 3%. A range of assessments performed included the modified Proctor test, Atterberg limits test, free swelling (FS%) test, unconfined compressive strength (UCS) test, and California bearing ratio (CBR) test. Finally, a direct shear (DS) test was conducted on the optimal mixtures derived from the preceding test. The findings revealed that the (OMC) rose, whilst the (MDD) significantly diminished for all additives employed, and the plasticity index (P.I) also declined. The FS% diminished, with the most significant decline in FS% observed for the two combinations (8% L + 15% SF) and (8% L + 3% NS). The UCS was enhanced by incorporating both SF and NS activated with lime into the experimental soil, with the optimal ratios for the two mixtures being 6%L+10%SF and 6%L+3%NS for conventional and nanomaterial additions, respectively.The peak CBR value was observed at 8% L + 10% SF, whereas the DS findings demonstrated that the incorporation of 6L+10SF and 6L+3NS enhanced the soil characteristics (cohesion and internal friction angle).

2.3 RESEARCH GAP

Studies on the combined application of silica fume and steel slag for stabilization of clayey soil are very few. Previous research has mainly examined their use alone or with other stabilizing blends.

The best proportions of steel slag and silica fume for the maximum improvement of the soil should be determined. The overall effect on MDD, OMC, UCS, CBR is not well established.

Further investigation is also required on the interaction of silica fume and steel slag with the clay particles and the resulting pozzolanic and cementitious reactions. Therefore, the present study is intended to develop a sustainable stabilization method using these two industrial by-products and to evaluate their effectiveness to enhance properties of clayey soil.

2.4 OBJECTIVES OF THE STUDY

The objectives of the research work are:

- To determine Atterberg's limits and specific gravity of the virgin soil.
- To determine the compaction characteristics, Maximum Dry Density (MDD) and Optimum Moisture Content (OMC) of soil mixed with Silica Fume and Steel slag.
- To evaluate the combined effect of Silica Fume and Steel slag on Unconfined Compressive Strength (UCS).
- To find out California bearing ratio (CBR) values at different proportions of Silica Fume and Steel slag mix with clayey soil.
- To identify the optimum mix proportion of Silica Fume and Steel slag for maximum strength.

3. Materials

3.1 soil The lumps of the collected soil of the site were broken up with a wooden hammer, and then left to dry in the open air beneath cover. It was thoroughly mixed and sieved through 2.35mm IS sieve. The amount of dirt required for each test was drained from polythene bags and dried in oven for 24 hours at 105°C/5°C. The dirt was cooled to room temperature. The virgin soil used has the following different properties:

Table no. 1 Properties of soil used in the study

S. No.	Properties	Result
1.	Liquid limit (%)	31
2.	Plastic limit (%)	18
3.	Plasticity Index (%)	13
4.	Specific Gravity	2.62
5.	Maximum Dry Density (KN/m^3)	17.4
6.	Optimum Moisture Content (%)	12.60
7.	Soil Classification	CL (Low Compressibility

		Clay)
8.	CBR (%) (soaked)	1.8
9.	CBR (%) (Unsoaked)	2.5
9.	UCS (7days) (kN/m$^{2)}$	220
10.	UCS (10days) (kN/m$^{2)}$	247

3.2 SILICA FUME

In this study, the silica fume used for stabilization of clayey soil was obtained from Mahalaxmi Chemicals Enterprises, Delhi. The true density of silica fume is 2.0–2.5 Mg/m^3 and the bulk density is 0.3–0.5 Mg/m^3. Silica fume is mainly composed of amorphous (non-crystalline) silicon dioxide, and is produced in electric arc furnace. The raw materials are quartz, coal and wood chips. The ash from this process is collected and sold as silica fume.

Table 2: The properties of silica fume are given below;

S.No	Parameters	Mass (%)
01.	Silica as SiO_2,	85-95%
03.	Lime as CaO	0.8-2%
04.	Magnesia as MgO	1-2%
05.	Alumina as Al_2O_3	1-3%
06.	Iron Oxide as Fe_2O_3	0.5-1%
07.	Density , kg/m^3	600kg/m^3

3.3 STEEL SLAG

Steel slag was obtained from Ludhiana for this research. The steel slag underwent crushing to achieve finer granules and was sorted to the required size. The dry soil sample received the steel slag in assorted weight proportions. The smaller fraction of steel slag was identified as a non-plastic substance. The chemical makeup of steel slag is illustrated in Table 3.3 below.

Table 3 Chemical composition of Steel Slag

S.No	Compound	Composition (%)
1	Sio_2	10-19
2	Al_2O_3	1-3
3	FeO	10-40
4	CaO	40-52
5	MgO	5-10
6	MnO	5-8
7	P_2O_5	0.5-1

3.4 RESEARCH METHODOLOGY:

PREPARATION OF SAMPLE

The sample is obtained from clay soil that has passed through a 425-micron filter. The optimal moisture level and highest dry density of the sample are established by a laboratory micro compaction test. This experimental research involves the preparation and assessment of many material combinations for their unconfined compressive strength and California bearing ratio. The combinations of materials include: (i) clay and silica fumes, where the silica fume level varies at 04, 06%, and 08%. (ii) Clay and steel slag with various concentrations of 10%, 15%, and 20%. The inclusion rate of the specified elements is determined as a fraction of the overall sample weight, where the weights of silica fume and steel slag are used in place of the clay soil weight. The cumulative sample weight across all permutations of the composite soil sample should be uniform.

METHODOLOGY

Present study is to know geotechnical properties of soil and improve its properties by adding admixtures like silica fume and steel slag in different proportions. The soil sample was collected from 1.5m deep in ground from local area. The soil is investigated for different index properties and engineering properties in the laboratory.

- Specific gravity test

- Atterberg's limit test
- Compaction test
- Unconfined Compression test

1. Specific Gravity Test (IS 2720-3 (1980)):

Specific gravity G is defined as the ratio of total weight of sample to the weight of equal volume of water.

2. Atterberg's limit test:

- Liquid limit test (LL) (IS 2720-5 (1985))
- Plastic limit test (PL) (IS 2720-5 (1985)) The plastic limit is defined as the water content

Corresponding to the arbitrary limit at which the soil passes from plastic state to semisolid state of consistency. It is minimum water content at which the change in the shape of the soil is accomplished by visible cracks when work beyond this limit, soil crumbles.

- Plasticity index (PI) - The difference between liquid limit and plastic limit is known as plasticity index.

3. Compaction Test (IS 2720-7 (1980))

4. Unconfined Compression Test (IS 2720-10 (1991))

5. California Bearing ratio Test (IS 2720-16 (1987))

4. EXPERIMENTAL RESULTS AND DISCUSSIONS

For experimental study different nomenclatures have been prepared with different proportions of ingredients, which have been shown below:

4.1 Mix Proportion Used

Table no. 4.0: Various Mix proportions of Soil, Silica fume and Steel Slag

S.N.	Nomenclature	Description of the additives added with the soil		
		Soil (%)	Silica fume by (%) of weight of soil	Steel Slag by (%) of weight of soil
1.	S	100	0	0
2.	S1	90	0	10
3.	S2	85	0	15
4.	S3	80	0	20
5.	S4	96.0	4	0
6.	S5	94.0	6	0
7.	S6	92.0	8	0
8.	S7	82.0	3	15
9.	S8	79.0	6	15
10.	S9	76.0	9	15

4.1 STANDARD PROCTOR TEST

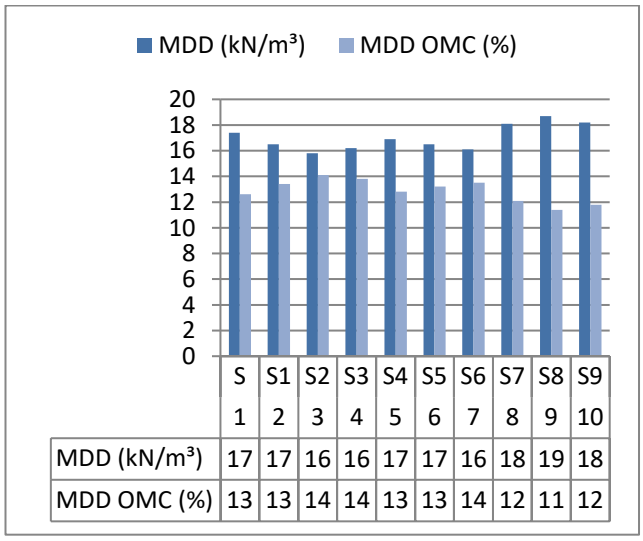
The laboratory test analysis employs various combinations of 15% Steel Slag as a constant alongside 4%, 6%, and 8% of Silica Fume. The numbers listed below demonstrate the fluctuation of optimum moisture content and dry density in relation to the proportion of silica fume and steel slag. The primary factors influencing the strength and longevity of pavements built on subgrades are the compaction properties of the soil. Any subgrade soil can be engineered at optimal moisture content (OMC) to achieve and sustain adequate stability under the influence of different load types for the necessary duration. Figure 1 and Table 4.1 illustrate that the compaction criteria are crucial for achieving the necessary sustainability of the pavement.

Table 4.1: Results of OMC and MDD for mix proportions of Soil, Silica Fume and Steel Slag

S No.	Soil Sample	MDD (kN/m^3)	OMC (%)
1.	S	17.4	12.60
2.	S1	16.50	13.40

3.	S2	15.80	14.10
4.	S3	16.20	13.80
5.	S4	16.90	12.80
6.	S5	16.50	13.20
7.	S6	16.10	13.50
8.	S7	18.10	12.10
9.	S8	18.70	11.40
10.	S9	18.20	11.80

Fig: 1 Variations b/w MDD and OMC of Silica fume, Steel Slag & soil with different Ratios



	S 1	S1 2	S2 3	S3 4	S4 5	S5 6	S6 7	S7 8	S8 9	S9 10
MDD (kN/m³)	17	17	16	16	17	17	16	18	19	18
MDD OMC (%)	13	13	14	14	13	13	14	12	11	12

- The incorporation of steel slag and silica fume affected the compaction properties of the modified clayey soil. The maximum dry density rose from 17.40 kN/m³ to 18.70 kN/m³ with the augmentation of silica fume content to 6%. This improvement may result from the superior compaction of soil and steel slag particles, but the tiny silica fume particles occupied some of the existing voids. This led to a somewhat compact soil composition. The maximum dry density was subsequently diminished to 18.20 kN/m³ with the incorporation of 9% silica fume. This reduction can be ascribed to the existence of surplus fine particles that could disrupt the organization of the particles and diminish the overall packing efficiency.
- The OMC exhibited a contrasting trend compared to the MDD. It diminished from 12.60% to 11.40% with the addition of 6% silica fume, signifying that a reduced quantity of water was necessary to attain the optimal dry density. The reduction could be linked to enhanced compaction of the soil–steel slag–silica fume blend. At 9% silica fume, the optimum moisture content rose to 11.80%, which may be ascribed to the increased surface area of the supplementary fine silica fume particles and their elevated water demand. Consequently, the mixture including 15% steel slag and 6% silica fume exhibited the most advantageous compaction characteristics among the evaluated combinations.

4.2 CALIFORNIA BEARING RATIO TEST

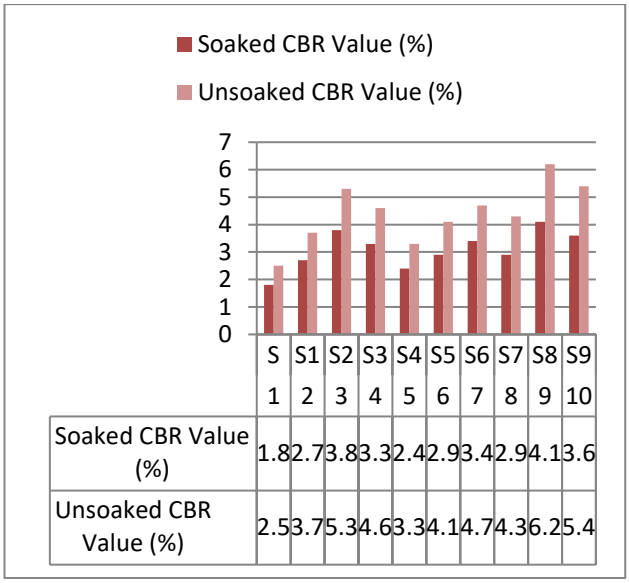
For the laboratory test analysis, the various combinations of 15% Steel Slag as a constant and 04, 06% and 08% of Silica Fume are utilized. The subgrade's California bearing ratio (CBR) is an important strength characteristic for predicting the thickness of the pavement's subgrade. According to IS: 2720 (Part 16) – 1987 the CBR values for clay subgrades are low. Different admixtures must be used to enhance the CBR of the clay subgrade. The California bearing ratio test was engaged for both soaked and unsoaked states for standard compaction results with the proportions of constant15% Steel Slag as a constant and 04, 06% and 08% of Silica Fume content as shown in figure 2 and tabulated in table 4.2.

Table 4.2: Results of CBR of Silica Fume and Steel Slag Mix with Clayey Soil

S No.	Soil Sample	Soaked CBR Value (%)	Unsoaked CBR Value (%)
1.	S	1.8	2.5
2.	S1	2.7	3.7
3.	S2	3.8	5.3
4.	S3	3.3	4.6

5.	S4	2.4	3.3
6.	S5	2.9	4.1
7.	S6	3.4	4.7
8.	S7	2.9	4.3
9.	S8	4.1	6.2
10.	S9	3.6	5.4

Fig: 2 Variations CBR values of Silica fume, Steel Slag & soil with different Ratios



	S 1	S1 2	S2 3	S3 4	S4 5	S5 6	S6 7	S7 8	S8 9	S9 10
Soaked CBR Value (%)	1.8	2.7	3.8	3.3	2.4	2.9	3.4	2.9	4.1	3.6
Unsoaked CBR Value (%)	2.5	3.7	5.3	4.6	3.3	4.1	4.7	4.3	6.2	5.4

- The findings of the CBR test demonstrated that the bearing capacity of clayey soil was enhanced by the incorporation of silica fume up to 6%. In the saturated state, the CBR value rose from 1.8% to 4.1% as the silica fume content increased. This enhancement can be ascribed to the enhanced interconnection of soil and steel slag particles, together with the incorporation of fine silica fume particles into the gaps. These modifications enhanced the barrier against infiltration. As the silica fume level rose to 9%, the wet CBR diminished to 3.6%.
- A comparable pattern was noted for the unsoaked CBR. The CBR rose from 2.5% to 6.2% till reaching 6% silica fume, then fell to 5.4% at 9%. The enhanced interaction of particles and a denser soil composition may have resulted in the elevated value at 6% silica fume. The 9% decrease could be attributed to the surplus fine silica fume content, which may disrupt particle arrangement and diminish the efficacy of the stabilizing mixture.
- From the obtained results, 15% steel slag with 6% silica fume gave the highest soaked and unsoaked CBR values among the mixes tested.

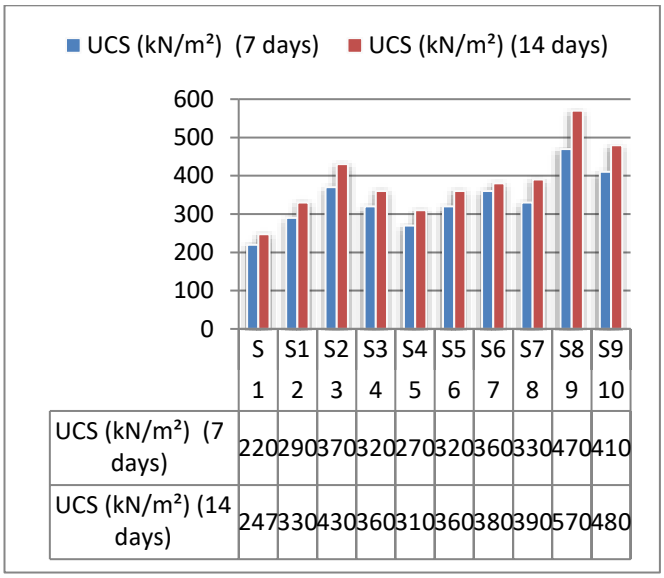
4.3UNCONFINED COMPRESSION STRENGTH TEST

For the laboratory test analysis, the various combinations of 15% Steel Slag as a constant and 04, 06% and 08% of Silica Fume are utilized. As per IS: 2720 (part-10), the UCS test was performed on both 7 days curing period & 10 days curing period specimen samples at a constant strain of 0.125mm/minute. The results of the unconfined compressive strength parameters of various combinations are being tested under a compressive force and final values are shown in Figure 3 and tabulated in table 4.3.

Table 4.3: Results of UCS of 7 and 14 days Silica Fume and Steel Slag Mix with Clayey Soil

S No.	Soil Sample	UCS (kN/m²) (7 days)	UCS (kN/m²) (14 days)
1.	S	220	247
2.	S1	290	330
3.	S2	370	430
4.	S3	320	360
5.	S4	270	310
6.	S5	320	360
7.	S6	360	380
8.	S7	330	390
9.	S8	470	570
10.	S9	410	480

Fig: 3 Variations UCS values of 7 and 14 days curing period of Silica fume, Steel Slag & soil with different Ratios



	S 1	S1 2	S2 3	S3 4	S4 5	S5 6	S6 7	S7 8	S8 9	S9 10
UCS (kN/m²) (7 days)	220	290	370	320	270	320	360	330	470	410
UCS (kN/m²) (14 days)	247	330	430	360	310	360	380	390	570	480

- The UCS increased from 220 kPa to 470 kPa after 7 days of curing, with the maximum value obtained at 15% steel slag + 6% silica fume. At 9% silica fume, the UCS decreased to 410 kPa.
- After 14 days, the UCS further increased to 570 kPa at 6% silica fume, while it decreased to 480 kPa at 9%. The higher strength at 14 days indicates continued strength development with curing.
- Overall, 15% steel slag + 6% silica fume gave the best UCS performance, indicating this as the optimum combination among the tested mixes.

5. CONCLUSIONS

The experimental study on stabilization of clay soil using steel slag and silica fume has resulted in the following conclusions:

1. The compaction characteristics of clayey soil improved with addition of steel slag and silica fume up to an optimum proportion. The maximum MDD of 18.70 kN/m3 and minimum OMC of 11.40% were obtained at 15% steel slag and 6% silica fume.
2. CBR soaked increased from 1.8% to 4.1% and CBR unsoaked increased from 2.5% to 6.2% at optimum combination. Further addition of silica fume up to 9% resulted in decrease of both CBR values.
3. The UCS increased from 220 kPa to 470 kPa after curing for 7 days with 15% steel slag and 6% silica fume. With the increase of the silica fume content to 9% UCS reduced to 410 kPa.
4. The UCS after 14 days of curing was 570 kPa for 15% steel slag and 6% silica fume compared to 480 kPa for 9% silica fume. This means further strength development with increasing curing time.
5. Above 6% silica fume, the reduction in CBR and UCS indicates that excessive fine material can reduce the efficiency of the stabilization process.
6. 15% steel slag and 6% silica fume was found to be the most preferable mixture in terms of MDD, OMC, soaked and unsoaked CBR and UCS.

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