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Optimized dosage of copper slag based geopolymer for the stabilization of soft soil based on response surface method

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Abstract : The rapid pace of infrastructure development has led to the generation of significant amounts of waste materials. This paper focuses on the utilization of copper slag, a by-product of copper smelting, in road construction and soil stabilization. Copper slag contains various materials like iron, alumina, calcium oxide, and silica, making it a potentially valuable resource. With approximately 24.6 million tonnes of copper slag generated worldwide annually, finding sustainable ways to use this material is crucial to reduce environmental impacts associated with its disposal. Previous research has shown that incorporating copper slag into road construction materials improves both the physical and geotechnical properties of the material. In addition, the paper discusses the challenges posed by weak or soft soils in construction and the potential of copper slag as a stabilizing agent for such soils. The study investigates the optimal percentage of copper slag needed to enhance the strength of clayey soils through various tests like Atterberg's limits, Proctor, and California Bearing Ratio (CBR). The findings indicate that incorporating copper slag and blast furnace slag can effectively improve sub-grade strength, offering a sustainable solution for construction projects**.**

***Keywords* - RSM, copper slag, soft soil..**

I. INTRODUCTION

Copper slag, a byproduct of the pyrometallurgical extraction of copper, has long been viewed as waste in industrial processes. However, research has shown that this material holds significant potential for various construction applications. Studies by [1,2] have highlighted the potential of copper slag in road base construction, railroad ballast, and as an engineered fill, indicating its suitability for reuse. Chemical analysis by Das et al. (1993) revealed that copper slag contains high amounts of Fe2O3, SiO2, CaO, and other chemicals, making it ideal for chemical stabilization. Furthermore, research by [3] and [4]) has demonstrated that copper slag can be used as an aggregate in bituminous concrete and as a substitute for Portland cement, respectively, leading to increased compressive strength in concrete mixes.

The production of copper results in the generation of substantial amounts of slag, estimated at about 2.2 tons per ton of copper produced annually. This translates to approximately 24.6 million tons of slag generated worldwide each year. While slags containing less than 0.8% copper are often discarded or sold as products with properties similar to natural basalt or obsidian, recent research has explored various methods of utilizing and recovering metals from copper slag. Options for managing copper slag include recycling, recovering metal, producing value-added products, and disposal in slag dumps or stockpiles. Processed air-cooled and granulated copper slag exhibit favorable mechanical properties for aggregate use, including excellent soundness characteristics, abrasion resistance, and stability. Additionally, granulated copper slag has pozzolanic properties due to its low CaO content, and under certain conditions, it can exhibit cementitious properties, making it a potential partial or full replacement for Portland cement.

The utilization of copper slag in applications such as Portland cement replacement in concrete not only eliminates disposal costs but also reduces the overall cost of concrete production. Furthermore, research has indicated that copper slag possesses properties that make it suitable as an aggregate in asphalt paving applications, thereby offering a sustainable solution to the wastage of metal values and environmental concerns associated with its disposal. Researchers have explored various methods to maximize the utilization of copper slag, including recovery of metal values and preparation of value-added products like cement, cement replacement in concrete, fill, ballast, abrasive, aggregate, glass, and tiles. These studies underscore the importance of exploring innovative ways to harness the potential of copper slag in construction applications, leading to both economic and environmental benefits

II. METHODS AND MATERIALS

Soil

Soft soil refers to soils that exhibit low strength and high compressibility, often making them unsuitable for construction without prior treatment. These soils typically have high moisture content, a loose structure, and low bearing capacity, which can lead to settlement issues when loaded. The soil used in this study is collected from Raipur region.

Copper Slag

Copper slag in this study is collected from Gujarat is a by-product of copper smelting industries, primarily in areas like Dahej. It contains silica, iron oxides, and other trace metals, making it a valuable material for industrial use. Gujarat's copper slag is often utilized in construction for soil stabilization, concrete production, and as a substitute for sand in road construction. Due to its high strength and durability, it enhances the mechanical properties of the materials in which it is used, while also contributing to environmental sustainability by recycling industrial waste.

Compaction test

Copper slag at varying percentages (0,10,20,30, and 40%) was thoroughly mixed with the soft soil and then compaction tests were carried out to evaluate the maximum dry density (MDD) and optimum moisture content of the mix..

III. RESULTS AND DISCUSSION

3.1Atterberg limits

The Atterberg limits are essential for the characterization of soils that indicates the plastic nature of the soil. Atterberg limits test carried out on soft soil with different percentages of copper slag is shown in Figure 4.1. The liquid limit of the soil was determined using Casagrande’s apparatus, following IS 2720 part 5 (1985) guidelines. This test aimed to gather at least five data points to plot the flow curve. The plastic limit, on the other hand, was determined by rolling out a thread of the soil's fine portion on a nonporous glass plate until it crumbled at a diameter of approximately 3 mm.

3.2 RESPONSE SURFACE METHODOLOGY

Response Surface Methodology (RSM) is a statistical technique used to design and optimize systems or products, introduced by K. B. Wilson and George E. P. Box in 1951. It is particularly valuable for scientists and engineers, allowing them to control systems with minimal experiments. RSM is widely applied in industry, especially when multiple input factors affect a process or product's quality or performance. By optimizing input parameters, RSM can save both time and money [5–7]. RSM develops regression models and optimizes responses using experimental data, even when dealing with complex output functions requiring lengthy computations. Its advantage lies in designing experiments that ensure the right data is gathered while minimizing the number of experimental trials needed to evaluate various responses and interactions [8]. However, RSM's second-order polynomial model may not fit all systems with curvature, a limitation that can be addressed through model transformations or by restricting the independent variables [9]. Additionally, multivariate regression is another statistical approach used to estimate unknown parameters, showing how a response variable relates to one or more predictors using raw data.

3.3 Development of RSM model

In this study, the experimental design was carried out using Face Centered Central Composite Design (FCCCD), which is essential for developing a response surface model. The FCCCD for a four-factor design includes sixteen factorial points, six central points, and eight axial points. The central points effectively represent the curvature of the system. By including the axial points, the pure quadratic components can be accurately estimated when curvature is present [10].

3.4 Optimization study

To identify the optimal ratios of independent variables (CS, SSR, M, and CD) in the soil, CS, and alkali activator mixture for achieving maximum UCS performance, this research applied a desirability function approach for each dependent (response) variable (i.e., UCS). This method transforms each dependent variable (yi) into a specific desirability function (di), ranging from 0 to 1. The desirability function (di) equals zero when the dependent variable, in this case, UCS, falls outside a permissible range. Conversely, the desirability function equals one when the dependent variable reaches its target or goal. From a statistical perspective, the optimal values of independent variables can therefore be considered valid. Ultimately, the design factors for the combinations were chosen based on the highest overall desirability (D) value.

The optimization process employed the statistical software "Design-Expert," developed by Stat-Ease Inc., which assisted in determining the optimal values of the independent variables (CS, SSR, M, and CD). The software offers preferences such as "maximum," "minimum," "target," and "in range" for both independent and dependent variables. Additionally, for independent variables, a preference called "equal to" is available. In this study, the "in range" preference was applied to the input variables, while the response variable (UCS) was optimized for maximum performance.

Based on the experimental design, the optimization process considered the following ranges for the variables: Copper Slag (10-40%), Sodium Silicate to Sodium Hydroxide Ratio (0.5-1.5), Sodium Hydroxide concentration (8-12 molal), and Curing Days (0-28 days). The objective of the optimization study was to predict the ideal values for these parameters to maximize UCS performance within the specified ranges. As a result of the optimization, a list of candidate solutions with optimal values was generated.

The creation of a three-dimensional (3D) response surface graph (Fig. 1) illustrating the maximum UCS value allowed for the exploration of the impact of independent variables (CS & CD) on UCS, aiding in the optimal use of Copper Slag. The plot displays the response (UCS) as a function of the independent variables, represented as a smooth curved surface in 3D space. In

Figure 2, a contour plot is shown, which helps identify the optimal values of the independent variables that influence UCS, highlighting the regions with maximum and minimum points within the experimental area.

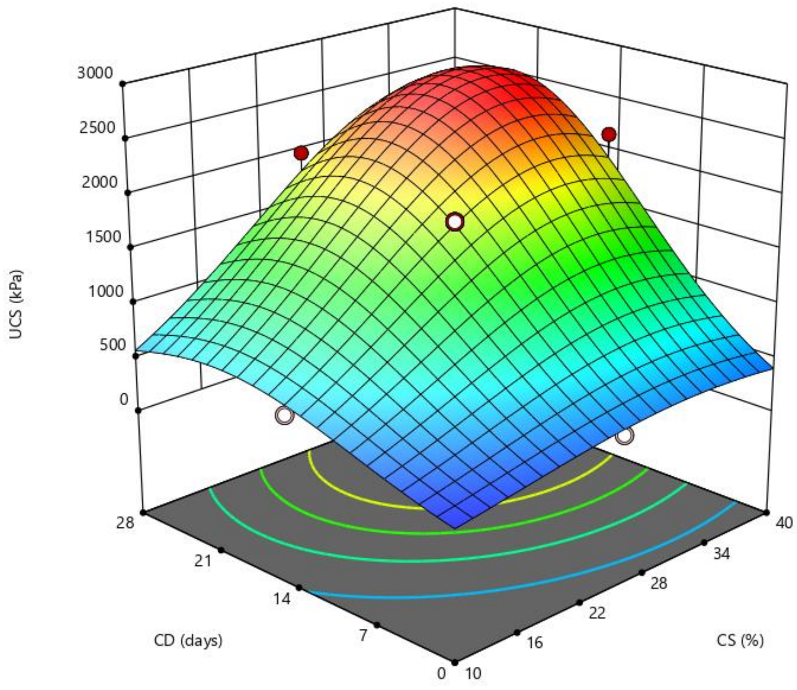

Figure 1 Three-Dimensional (3D) Response Surface Plot

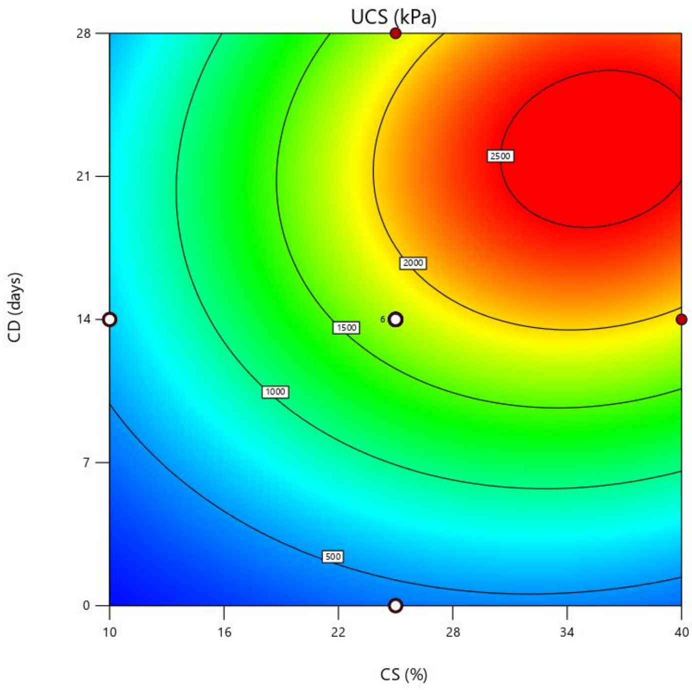

Figure 2 Contour Plot for UCS Result at An Optimized Dosage

IV. CONCLUSIONS

In the study, optimization of input parameters was accomplished using a response surface model, which integrates a quadratic equation enhanced by a natural log transformation. This approach allows for the precise estimation of the maximum unconfined compressive strength (UCS) of the material being tested. By incorporating statistically significant terms into the model, this research improved the accuracy of their predictions. The response surface model helps to analyze the relationship between various input parameters and their impact on UCS, enabling the identification of optimal conditions for achieving the highest compressive strength. This method provides a robust framework for predicting and fine-tuning material properties in geotechnical engineering, ensuring that the outcomes are both reliable and effective.

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