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Relative effectiveness and sustainability assessment of low-carbon cement and geopolymer based soil stabilization methods

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ABSTRACT: Sustainability construction has been acknowledged as necessary in an effort to reduce the negative environmental impacts of the construction industry over the past two decades. Many different measures can be taken to improve the sustainability in construction of civil infrastructures and one of the most common practices is the use of construction materials with lower environmental impacts. In this study, the comparative effectiveness of such materials including low-carbon Portland limestone cement (PLC), calcined clay-based geopolymer, and recycled concrete aggregate fines (fRCA) to treat low-plasticity clay has been evaluated to examine their suitability for soil stabilization and their sustainability. Differences in the mechanical improvements to the performance of soil by the usage of these materials have been evaluated by comparing the unconfined compressive strength and resilient modulus data from literature. Also, a comprehensive life cycle sustainability analysis was carried out considering the resource consumption, environmental impact, and socio-economic impact for each material in comparison with traditional Ordinary Portland cement (OPC) treatment. PLC used in combination with fRCA as co-additive was found to be the most sustainable option when compared to the geopolymer treatment, due to its lower cost and usage of recycled materials despite having similar reduced environmental impacts. Findings from the study are highly relevant for geotechnical practitioners to aid in their decisions towards sustainable and resilient construction practices.
KEYWORDS: Ground improvement, Sustainable and resilient geotechnics, Geopolymers, Recycled and low-carbon materials.

1 INTRODUCTION

Problematic soils like soft and expansive clays cause persistent maintenance challenges, increase life-cycle costs, and compromise the safety and serviceability of infrastructure built on them (Gromko, 1974). These adversities are attributed to the highly active clay minerals that undergo significant volumetric changes with fluctuations in moisture content. Billions of dollars are annually spent to combat these problems through maintenance and rehabilitation works (Jones Jr & Holtz 1973).

Geotechnical engineers often employ diverse ground improvement techniques to deal with problematic soils. Calcium-based stabilization, most commonly implemented through the application of cement, has been the go-to option for treating soft subgrades and expansive soils (Puppala & Pedarla 2017). Through a combination of short-term physical modifications and long-term chemical and mineralogical transformations, these stabilizers significantly improve the response and increase the resiliency (Mahedi et al. 2020). Immediate effects include moisture reduction, flocculation and agglomeration attributed to the hydration reaction, cation exchange phenomena, and reduction in the thickness of diffuse double layer. These collectively have positive benefits in reducing the plasticity index, swelling potential, and in increasing the workability and compaction efficiency (Mahedi et al. 2018). Long-term benefits are mostly driven by pozzolanic reactions that lead to the formation of cementitious gels that bind soil particles and simultaneously modify the pore space. This not only improves strength but also reduces the moisture intrusion, both of which are essential traits for ensuring durability (Prusinski & Bhattacharja 1999).

Numerous documented success stories of the field applicability of calcium-based stabilization for improving the performance of subgrades for pavement infrastructure reveal its ease of implementation, proven efficacy, and long-term durability (Prusinski & Bhattacharja 1999; Pongsivasathit et al. 2019; Yan et al. 2023). While these benefits are significant and essential, they are accompanied by notable environmental trade-offs. In fact, cement production ranks as the second largest CO_2 emitting industry in the world, contributing about 7% of the global CO_2 counts (Andrew, 2018). These numbers stem from the energy intensiveness of the manufacturing process of ordinary Portland cement (OPC) itself. Thermal energy to maintain the kiln at 1450ºC and electrical energy demand for grinding raw materials and clinker significantly contributes to this (Ekinci et al. 2020). These increased CO_2 emissions greatly impact the climate and influence the life and health of society. All these environmental impacts that are inherent to the production and utilization of OPC have long been overlooked, largely overshadowed by the economic advantages and entrenched nature of the well-established cement industry. However, with raising global emphasis on promoting sustainable construction practices, the pursuit of green stabilizers is currently at its highest level (Mohamad et al. 2022). Researchers are actively looking for developing low-carbon and non-traditional stabilizers and attempt to incorporate local and recycled materials to bring down the environmental impacts without compromising on the strength requisites.

Recently, the market for Portland Limestone cement (PLC), a sustainable alternative for OPC, that is manufactured by replacing portion of clinker (which is the main energy and emission intensive ingredient) with finely ground limestone (that does not require high temperature calcination) is gaining thrust due to its comparable strength and durability aspects (Cost et al. 2013). Approximately, about 8 to 10% lower CO_2 emissions are expected through incorporation of 5 to 15% limestone. Limited studies have attempted using PLC for soil stabilization works. Also, recent research works on utilizing recycled materials shows promising trends for incorporating Recycled concrete aggregate fines (fRCA) into soil stabilization works (Singh et al. 2023). fRCA, which is essentially a byproduct from concrete waste recycling process, demonstrated significant contributions to modifying the workability and mechanical properties of soils. Utilizing the combination of PLC with fRCA for soil stabilization was recently explored by Biswas et al. (2025). In their study, the associated durability and mechanical strength gains were established through comprehensive laboratory evaluations.

In parallel, geopolymers that are synthesized through the alkaline activation of aluminosilicate-rich industrial by-products such as fly ash or slag, forming a three-dimensional inorganic polymer network, could be potential nontraditional alternatives for soil stabilization (Zhang et al. 2013; Sahoo & Singh 2022; Chou et al. 2024). Different types of geopolymers are already developed by the efforts of researchers using a diverse range of alkali activators and aluminosilicate precursors, and their effectiveness for soil stabilization is being researched extensively. Recent research works by Chou et al. (2024), and Chou et al. (2025), demonstrated the efficacy of using locally available calcined clay as aluminosilicate source for synthesizing geopolymer for soil stabilization. The calcined clay based geopolymer (CCGP) was found to significantly improve the strength, stiffness, and swelling-shrinkage characteristics of expansive soils. These changes were attributed to the morphological changes and reduction of macro pores within the soil matrix.

While both these low-carbon cement-based and nontraditional geopolymer-based stabilizers have been proven to improve the properties of soil, their relative effectiveness and efficacy remain elusive both from mechanical and sustainability perspectives. Hence, this paper attempts to bring out these aspects by comparing the mechanical improvements by PLC combined with fRCA (PLC + fRCA) reported by Biswas et al. (2025) with the performance of calcined clay based geopolymer (CCGP) reported by Chou et al. (2025) for stabilizing expansive soils. In addition, a detailed sustainability assessment was performed for both the methods (using PLC + fRCA and CCGP) to evaluate the overall benefits. Sustainability assessment includes environmental impact and economic considerations. In the field of civil engineering, LCA has been applied to assess the environmental performance of various infrastructure systems, including buildings, bridges, and pavement structures, over their entire life cycle (Das et al. 2018; da Rocha et al. 2016; Das et al. 2022). The sustainability assessment provides a comparative analysis of the environmental and economic impacts of both the solutions. The comparisons made and results presented in this paper are expected to provide enhanced clarity on the usage of both these methods and help practitioners make more informed and sustainable decisions.

2 MATERIALS AND METHODS

2.1 *Soils*

Key geotechnical properties of the soils used by Biswas et al. (2025) and Chou et al. (2025) are summarized here in Table 1 for quick reference.

Table 1. Soil properties

Parameter	Soil S1 (Biswas et al., 2025)	Soil S2 (Chou et al., 2025)
Specific gravity	2.74	2.72
Sand content (%)	39.4	16.8
Silt content (%)	35.7	21.2
Clay content (%)	19.6	60.0
Liquid limit (%)	41	36.8
Plasticity index (%)	25	19.4
Optimum moisture content (OMC, %)	15.6	13
Maximum dry unit weight (MDUW, kN/m^3)	17.4	14.7

Essentially, both the soils are low-plasticity clays (CL) as per the Unified Soil Classification System. More detailed descriptions about these soils are available in Biswas et al. (2025) and Chou et al. (2025). In particular, both the soils have swell-shrink potential, indicating their susceptibility to moisture variation and making them highly suitable candidates for stabilization research.

2.2 *Stabilizers*

While Biswas et al. (2025) used commercial Portland Limestone cement (PLC) as binder and recycled Concrete aggregate fines (fRCA) as co-additive, Chou et al. (2025) employed a novel calcined clay based geopolymer (CCGP) made with locally available clay that is calcined at 800ºC and activated using a solution made of KOH and silica fume. The sources of these materials, their properties, and synthesis procedures are all available in Biswas et al. (2025) and Chou et al. (2025).

2.3 *Optimal dosages and specimen preparation*

Both studies (Biswas et al., 2025; Chou et al., 2025) have recommended their respective optimal dosages following similar protocols. While Biswas et al. (2025) recommended 8% PLC along with 15% fRCA (by weight) as the optimal dosage for PLC + fRCA treatment, Chou et al. (2025) suggested 20% CCGP (by weight), comprising calcined clay, KOH, and silica fume, as optimal dosage for the geopolymer based treatment.

Both the studies employed the following specimen preparation strategies for mechanical performance evaluations and are outlined here again in this paper to provide a quick overview. Initially, the natural soils were oven-dried, crushed, and pulverized. The untreated specimens were prepared by evenly mixing the dry natural soils with the OMC shown in Table 1. Treated specimens were prepared by uniformly mixing the target dosage of PLC + fRCA or CCGP with dry natural soils, followed by adding the required water to reach the OMC and mixing thoroughly to achieve a homogeneous blend. The prepared mixes were equilibrated at room temperature for 10 minutes prior to molding into various specimens. All specimens were compacted into cylindrical molds with a height-to-diameter ratio of 2:1 to achieve the MDUW. For reference, the MDUW and OMC values were 17.8 kN/m^3 and 15.6% for PLC + fRCA, and 14.8 kN/m^3 and 21.0% for CCGP, respectively. After demolding, both treated specimens were cured for 7 days at room temperature (23.5± 0.5ºC) in a hermetically sealed chamber with approximately 100% relative humidity to ensure sufficient moisture during the curing stages.

2.4 *Testing procedures employed*

Both the studies have employed similar testing protocols and devices for evaluating the strength improvements of the stabilized soils, making direct comparisons possible and meaningful.

To evaluate the improvement in the strength properties of the treated specimens, unconfined compressive strength (UCS) tests were performed on untreated and treated samples in both the studies (Biswas et al., 2025; Chou et al., 2025). The UCS tests on PLC + fRCA specimens were conducted in accordance with ASTM D1633, which requires soaking the specimens in water for 4 hours prior to testing, with a compression rate of 1.3 mm/min. For CCGP specimens, ASTM D2166 was followed, in which testing is conducted directly after the curing period, with a compression rate of 1%/min. Triplicate samples were tested in both the studies, and the average value was used to represent the UCS.

Similarly, to evaluate stiffness, both the studies conducted Repeated Load Triaxial (RLT) tests on untreated and treated specimens in accordance with AASHTO T-307 to evaluate the efficacy of low-carbon cement based, and geopolymer based stabilization techniques. In both studies, a preconditioning phase of 500 load cycles was performed prior to testing, to eliminate initial plastic strains. Subsequently, 15 loading sequences, each comprising 100 cycles, were applied under varying confining pressures and deviatoric stresses. The resilient modulus for each stress state was calculated by averaging the values from the last five cycles of each sequence.

2.5 *Sustainability assessment*

The comprehensive sustainability assessment consists of Life Cycle Analysis (LCA) for environmental assessment, and Life Cycle Cost Analysis (LCCA) for economic assessment. The LCA comprises of two segments for assessing the environmental assessment, which comprises of two segments, Life Cycle Inventory (LCI) and Environmental Impact Assessment (EIA) (Das et al. 2018). The sustainability assessment was carried out in this study to facilitate the comparative evaluation of the stabilization strategies employed by Biswas et al. (2025) and Chou et al. (2025). The comparative analysis of both the stabilizers was benchmarked against traditional OPC treatment to establish relative performance.

The assessment framework was adapted from the methodology proposed by Das et al. (2018) with necessary refinements to suit the present study. This framework computes a sustainability index (I_{SUS}), which is a function of three constituent indices, namely, resource consumption index (I_R), environmental impact index (I_{ENV}), and socio-economic impact index (I_{SE}) as expressed in Equation 1,

$$I_{SUS} = (W_1 \times I_R) + (W_2 \times I_{ENV}) + (W_3 \times I_{SE}) \quad (1)$$

where W_1, W_2, and W_3 denote the weighting factors assigned to each index, reflecting their relative importance within the specific project context, with the constraint that their sum equals unity. For the present study, equal weights of 1/3 were allocated to W_1, W_2, and W_3, respectively. However, these weights can be modified for different projects depending on the corresponding importance of each category.

The value of I_{SUS} serves as a direct indicator of overall impact, with lower values denoting more favorable and environmentally sustainable stabilizers. Among its constituent indices, I_R quantifies the overall weighted embodied energy (EE), expressed in megajoules (MJ) consumed by all the resources involved throughout the assumed boundary condition of cradle-to-site. This calculation encompasses the energy involved in extracting the raw materials, manufacturing, and transportation to the project site. The energy involved in extraction and manufacturing was combinedly considered as one index (EE-Production), while the transportation (EE-Transportation) was considered as another index. The resource transportation to the project site was assumed to have a haulage distance of 50 miles. Both these units were assumed to have equal weightage of 0.5 in the calculation of I_R.

I_{ENV} index captures environmental burdens across three impact categories: Global Warming Potential (GWP), Acidification Potential (AP), and Eutrophication Potential (EP). For the purpose of deriving a composite I_{ENV} score, each category was assigned an equal weighting factor (w_i of 1/3, for $i = 1, 2$, and 3) as shown in Equation 2.

$$I_{ENV} = (w_1 \times GWP) + (w_2 \times AP) + (w_3 \times EP) \quad (2)$$

It is important to emphasize that, in sustainability evaluation, the environmental contribution of the geopolymer (CCGP) treatment was attributed solely to calcined clay, as it is the primary constituent. The impacts associated with the alkaline activator and silica fume were considered negligible due to their comparatively minor influence across impact categories (Samuel et al., 2020). The contribution of each stabilizer component to the respective impact categories (e.g., GWP, AP, EE) was adopted from values reported in established literature sources (Hammond & Jones, 2011; Heath et al., 2014; Samuel et al., 2020).

The I_{SE} index, representing the socio-economic dimension, was determined from the total treatment costs associated with each stabilization method. Unit price data for OPC, PLC + fRCA were obtained from the local market survey. The price of CCGP was assumed to be 50% more than the cost of OPC (Samuel, 2020).

3 RESULTS AND DISCUSSION

This section presents the comparative effectiveness of low-carbon PLC + fRCA-based soil stabilization and non-traditional geopolymer-based treatment with their optimal dosages, quantified in terms of both engineering performance (from Biswas et al., 2025, and Chou et al., 2025) and sustainability assessments (from the current study).

3.1 *Engineering performance*

The comparison of unconfined compressive strength (UCS) values of untreated specimens and specimens stabilized with PLC + fRCA and CCGP is provided in Figure 1. For Soil S1 (Biswas et al., 2025), the untreated specimen had a UCS of 371 kPa, which increased nearly sevenfold to around 3 MPa following treatment with PLC + fRCA (Figure 1a). This pronounced improvement was attributed to cement hydration and formation of calcium silicate hydrate (C-S-H) gels that bind soil particles, along with the long-term contribution of pozzolanic reactions forming secondary cementitious products.

In the case of Soil S2 (Chou et al., 2025), the untreated specimen displayed a UCS of 250 kPa, indicating insufficient strength for subgrade applications in transportation infrastructure. Treatment with CCGP increased the UCS by approximately 2.5 times (Figure 1a). The strength enhancement in CCGP-treated soils is primarily due to geopolymerization reactions, which effectively bind soil particles within the geopolymer matrix.

A comparative assessment of the two stabilization techniques indicates that PLC + fRCA provides superior performance, with UCS gains approximately three times greater than those achieved with CCGP. This is likely attributable to the reactive cementitious nature of PLC, which facilitates more rapid strength development, whereas the strength gain in CCGP-treated soils is governed by the geopolymerization process, resulting in comparatively lower improvements.

The resilient modulus (M_R), an essential parameter in pavement design, is strongly affected by chemical stabilization. The M_R values obtained from the 13th sequence of the repeated load triaxial test, conducted in accordance with AASHTO T307, are commonly used in pavement design as they reflect typical in-service stress conditions. Hence, the corresponding M_R results from both studies are compared and presented in Figure 1b. Treatment with both stabilizers led to a substantial increase in specimen stiffness; however, unlike the UCS results, both stabilizers produced comparable improvements in the M_R. For example, untreated Soil S1 exhibited an M_R of 78.5 MPa, which increased by approximately 150% to 201 MPa following treatment with PLC + fRCA (Biswas et al., 2025). For Soil S2, the untreated M_R of 87.2 MPa improved by about 99% to 173 MPa after treatment with CCGP (Chou et al., 2025). These enhancements are attributed to the development of compounds that bind soil particles, thereby reducing deformability and increasing the stiffness of the treated soils.

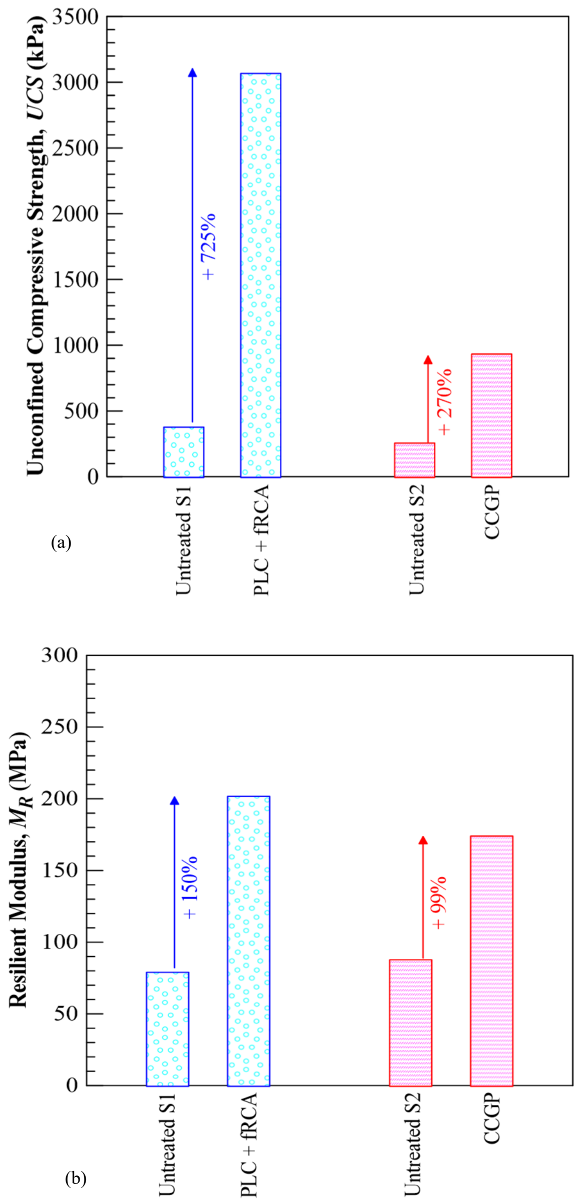

Figure 1. Comparison of engineering performance of PLC + fRCA and CCGP treatments: (a) unconfined compressive strength and (b) resilient modulus.

3.2 *Sustainability assessment*

This section discusses comparative sustainability assessments of PLC + fRCA and CCGP treatments for soil stabilization in comparison to conventional OPC treatment. Figure 2 shows a radar map indicating the normalized sustainability performance for all the individual subcategories considered within the environmental impact, embodied energy, and cost analysis for the three different treatment methods.

It can be observed from the radar plot that the PLC + fRCA method has relatively lower values in most of the categories, except for EE-Transportation, indicating it as an ideal solution from a sustainability perspective. Stabilization with CCGP was observed to have the highest weighted value for cost analysis due to the high price of geopolymer and its high dosage requirements. However, it has relatively low and comparable values for the rest of the indices. OPC has the highest values in three of the six selected categories, GWP, EP and EE-Production. For OPC case, the cost and EE-Transportation were observed to be low, because of the low dosage and relatively cheaper price per unit weight, indicating less cost and lower energy consumption for transport.

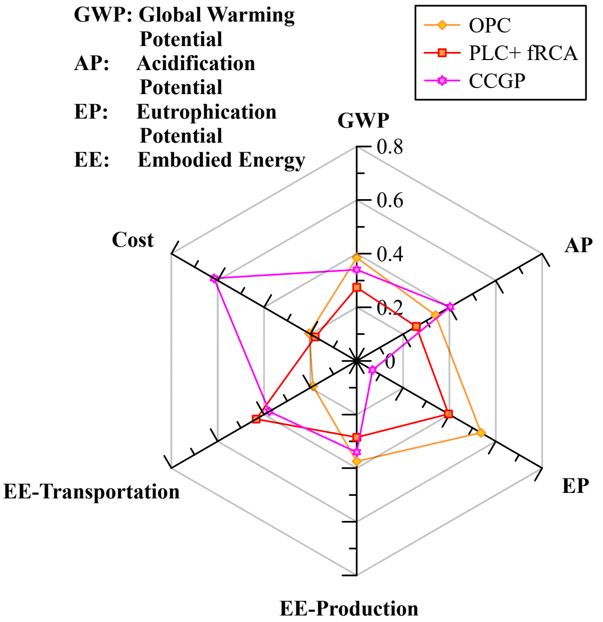

Figure 2. Radar chart indicating index values for various individual impact categories

Table 2 lists the calculated weighted values of the resource consumption index (I_R), environmental impact index (I_{ENV}), and socio-economic impact index (I_{SE}). The values indicate a direct correlation to the weighted values shown in Figure 2. With the I_{SE} of the CCGP being the highest, 20.5% of the overall index value, due to the higher cost and dosage of the geopolymer. The I_R values of PLC + fRCA and CCGP are similar, but OPC has the lowest value, translating from the lower cost and required dosage, indicating less production and transportation impacts. However, the OPC is found to have the highest environmental impact value (I_{ENV}), despite the lower dosage of OPC required compared to the dosages of the other two treatments, displaying its significant environmental impacts.

Table 2. Sustainability indices for treatments employed by Biswas et al. (2025) and Chou et al. (2025) in comparison with traditional OPC treatment

Stabilizer	I_R	I_{ENV}	I_{SE}	$\boldsymbol{I_{SUS}}$
OPC	9.39	14.02	6.84	**30.25**
PLC + fRCA	11.98	10.30	5.97	**28.25**
CCGP	11.96	9.02	20.53	**41.50**

The overall sustainability index, I_{SUS}, calculated by assigning equal weights to each of the assessment categories, shows that the CCGP has the highest value, suggesting it is the least favorable choice. This can be attributed to its high cost, translating to a high I_{SE} value, despite having the lowest I_{ENV} value and a comparable I_R value. Contrarily, the other alternative solution for the use of OPC, the use of PLC + fRCA, showed a promising result with the lowest sustainability index of 28.25. Despite having the highest mixing percentage of 23% by weight (8% PLC + 15% fRCA), the use of recycled materials implied cheaper cost and lesser environmental impacts.

If only I_R and I_{ENV} are considered, OPC shows the highest index value, CCGP shows the lowest value, and PLC + fRCA lies in between. This suggests that both the alternative solutions are environmentally sustainable than the use of OPC for stabilization. However, when the socio-economic aspect is included, the order of impact is observed to change significantly.

It is important to note that the categories under consideration for the sustainability assessment have their respective impact on each of the available solutions. The weightage values considered in this study are assumed to be equal; however, it is important to select appropriate weights for each individual category depending on the type of project and the importance associated with each category.

4 CONCLUSIONS

Current geotechnical engineering practice has several techniques for ground improvement and soil stabilization. It is important to constitute a framework to assess which of the applicable solutions would be a better-suited option for overall sustainability benefits. This study explores the relative efficiency and efficacy of two recent soil stabilization techniques with low-carbon cement based (PLC + fRCA proposed by Biswas et al., 2025), and a geopolymer based (CCGP developed by Chou et al., 2025), in comparison with traditional OPC treatment. In addition to the comparison of mechanical improvements achieved by these solutions, a sustainability assessment was performed. The sustainability assessment consists of Life Cycle Analysis (LCA) and Life Cycle Cost Analysis (LCCA). The sustainability analysis was performed under the cradle-to-site boundary condition. Key findings from the study are as follows:

- The formation of cementitious materials following stabilization led to improvements in both UCS and resilient modulus for all treated specimens. PLC + fRCA exhibited greater enhancement in UCS compared to CCGP; however, the improvements in resilient modulus were comparable between the two stabilization techniques.
- While environmental considerations alone indicate CCGP treatment as the most favorable choice, due to the higher cost of the geopolymer, CCGP has the highest overall sustainability index (I_{SUS}) value, making it a cost-prohibitive alternative.
- Overall, the I_{SUS} values indicate that the PLC + fRCA has the lowest value of the sustainability index, making it the most favorable choice among the considered options, due to the utilization of recycled materials along with a relatively smaller dosage of low-carbon cement in comparison to the geopolymer treatment that requires higher dosages of CCGP.
- It is extremely important to arrive at a balance between the cost and the environmental impacts to come up with a practicable and sustainable solution for soil stabilization works. Further research on developing low-cost geopolymers could significantly enhance their usage for developing resilient infrastructure.

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