Hybrid Applications of Fiber-Reinforced Polymers and Geopolymers in Soil Stabilization(enhancing Unconfined Compressive Strength and Shear Strength)

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Abstract

Soil stabilization is a fundamental technique in geotechnical engineering, aimed at enhancing the physical properties of soil to improve its load-bearing capacity, particularly for construction applications. This study investigates a novel hybrid approach combining Fiber Reinforced Polymers (FRPs) and geopolymers to enhance soil stabilization. FRPs, notably glass and carbon fibers, are known for their high tensile strength, moisture resistance, and durability, while geopolymers provide an environmentally friendly alternative with low carbon emissions and the potential for incorporating industrial by-products.
The research focuses on stabilizing silty clay soil sourced from a construction site in Kharar, Punjab, with varying percentages of FRPs (up to 5%) and a constant 5% geopolymer content. The mechanical properties of the treated soil, including unconfined compressive strength (UCS), cohesion, and shear strength, were evaluated over curing periods of 7, 14, and 28 days. Results demonstrate a significant improvement in soil strength, with UCS, cohesion, and shear strength all reaching their peak values with a 5% FRP and 5% geopolymer mix after 28 days of curing. Beyond this optimal fiber content, a decrease in mechanical properties was observed, likely due to reduced bonding efficiency and disruption of the soil matrix caused by excessive fiber content.
This hybrid stabilization method offers enhanced soil performance, providing a promising alternative to conventional stabilization techniques. The approach not only improves the mechanical properties of soil but also presents an eco-friendly and cost-effective solution. The findings hold practical implications for infrastructure projects in areas with unstable or unsuitable subgrades, and future research should focus on scaling up the application of this method and exploring additional materials for further enhancement.

Keywords: Fiber-Reinforced Polymers (FRPs), Geopolymers, Soil Stabilization, Hybrid Applications, Sustainable Engineering, Mechanical Properties, Geotechnical Engineering

1. Introduction

Stabilization of soil is fundamental in geotechnical practice because it forms the basis of the endeavor of improving the strength, both in regards to the stability and durability of the soil under a range of loading conditions and the various elements of nature. In the past, stabilization methods involved the use of cement, lime, or bitumen, even though the stabilization process is effective it raises environmental red flags due to high carbon footprint and high energy content (Bagheri et al., 2021)[4]. Such challenges therefore point to a need to look for sustainable and innovative ways of fulfilling modern engineering needs.
Fibre Reinforced Polymers commonly known as FRPs have been considered as a new frontier in soil stabilization. Recognized for considerably high tensile strength, low density, and high corrosion resistance, FRPs are the most suitable choice where loads are likely to be high or circumstances hostile (Wang et al., 2022)[15]. At the same time, geopolymers – cementitious binders derived from aluminosilicate containing industrial waste products – have attracted interest as green and sustainable alternatives to stabilizers. In addition to being more carbon-friendly, geopolymers increase the chemical and mechanical performances of the soil (Davidovits, 2015).[5]
Although both FRPs and geopolymers have their unique benefits, there is a lack of literature that explores the use of these two composite materials in combined form for enhancing the properties of soil. The use of multifunctional coatings prepared from these materials would be a good strategy to combine the mechanical and environmental advantages introduced by their hybridization while minimizing the weaknesses of single-material strategies. For example,

geopolymers have unparalleled chemical bonding and unprecedented durability, yet FRPs offer more flexibility and strength yielding a superb soil composite.
Thus, this research work seeks to fill the existing research gap by investigating the blend of FRPs and geopolymers for soil stabilization. It is focused on their mechanical characterization, performance durability, and life cycle assessment through experiments. The purpose is to offer a sustainable and effective method for the improvement and reinforcement of soil to advance infrastructural construction and core geotechnical concepts. This work opposes the engineering methodologies that took a long time to develop to address the impacts created by the engineering techniques and meets the present world's demands for sustainable engineering.

2. Literature Review

Overview of Stabilization of Soils

Ground improvement is an essential and widely applied geotechnical technique intended to enhance the mechanical properties of the subsoil or to increase the ultimate bearing capacity, bearing capacity multiplier, or uniformity coefficient of the soil mass. Traditional stabilization techniques are mainly related to the use of chemical agents such as lime, cement, and bitumen. However, these methods come with unprecedented disadvantages, including high carbon emissions during the manufacture of components (Bagheri et al., 2021)[4]. For instance, the stabilizer known as Portland cement is linked to about 8% of global emissions of CO_2 in a given year (Scrivener et al., 2018)[13]. Moreover, conventional methods have been known to fail in situations where there are high levels of organic or sulfate soils that are irregular.
Mechanical stability as another approach manipulates the physical characteristics of the soil in terms of density or by adding aggregates. Although the method allows increasing density and load-carrying ability, the statics achieve lower long-term stability for layouts under dynamic loads or adverse climatic conditions. As a result, FRPs and geopolymers have come out as superior materials that can give high performance and bring in novel and green architecture too.

Application of FRPs in Geotechnical Engineering

Fiber Reinforced Polymer composite is a material that is made of two or more constituent materials with fibers being the principal component in the composite. FRPs were initially designed for aerospace and structural engineering sectors and have been used in geotechnical engineering, possessing impressive mechanical characteristics including tensile strength, density, and endurance to environmental factors (Wang et al., 2022)[15]. FRPs are normally used as reinforcements in soil stabilization procedures to reinforce tensile and shear strength that will benefit infrastructure projects that are subjected to dynamic loads like roads, banks, and retaining walls.
It is noteworthy that due to specific properties of the FRPs, they are resistant to corrosion and chemical attacks that make use of the material in aggressive conditions possible, for instance, in sea coastal and industrial conditions. Additionally, improvements in the fabrication technologies have rendered these composites more inexpensive to use hence being incorporated into large structures. Research has shown that FRPs improve the ductility of the soil and the effect of settlement under cyclic loading and might be preferable to conventional reinforcement materials (Almeida et al., 2020)[2]. However, there are difficulties in the broad use of FRPs in geotechnical structures. It is therefore important that other considerations like UV resistance and durability over a long period, recyclability, as well as initial cost as compared with traditional construction materials should be discussed in subsequent research.

.Geopolymers in Sustainable Engineering

Geopolymers are inorganic polymer membranes prepared from aluminosilicate sources for example fly ash, slag, and kaolin through geo-polymerisation reaction. They are praised for having very low embodied energy, for using industrial waste and emissions, and for creating lesser greenhouse gasses especially compared to cement (Davidovits, 2015)[5]. Geopolymers also possess high chemical resistance, and thermal stability and are highly durable factors making them suitable for geotechnical applications in a given environment.
Geopolymer stabilization for soil utilization is a process whereby it is mechanically and chemically densified so that it can become more compacted and less permeable. In addition to encapsulating heavy metals, they provide extra value in the remediation of contaminated soil, thereby reducing the environmental hazard. Research has postulated that the application of geopolymer improves the quality of the soil by expanding the unconfined compressive strength, especially

under different cycles of wetting and drying (Kumar et al., 2021). Further, the flexibility of geopolymer formulations can be tailored to nullify some adverse soil fact[10]ors like an elevated level of organics and increased salinity.
Nevertheless, the application of geopolymers in soil stabilization studies is still at a rudimentary level. Substantial variability in raw materials, lack of consensus on the manufacturing process, and extreme sensitivity to curing conditions are also significant difficulties. To overcome these barriers, the intervention of researchers, industry, and policymakers is paramount in up-scaling and mainstreaming geopolymer applications.

Current Hybrid Frameworks and their Drawbacks

The concept of using FRPs to reinforce geopolymers applied in the stabilization of soil is relatively recent and offers the advantages of both FRPs and geopolymers. Geopolymers have a combined chemical system and their structures are very friendly to the environment while FRPs enhance the mechanical characteristics in dynamic load. Preliminary results suggest that some synergies allow for the mitigation of drawbacks of single-material solutions, e.g., the brittleness of geopolymers or the high cost of FRPs (Wang et al., 2022)[15].
For instance, it has demonstrated that hybrid systems offered improved mechanical interlocking of the soil particles to the stabilization matrix, to better shear and compressive strength. Furthermore, these systems suggest increased and improved durability in terms of performance in chemically aggressive areas particularly where sulfate and chloride are high. The field is relatively new and even though various aspects of the concept have been in use, large-scale applications are still scarce and mostly there has been no strictly defined procedure for how they can be applied.
These are constraints such as the failure of FRPs to interface with the geopolymer matrices, the possibility of raising the cost, and the use of specific equipment to implement the geopolymer composites. Further research must be conducted on how these materials can be made to complement each other better and how manufacturing costs can be reduced to widen the utilization of the products.

3. Materials and Methods

3.1 Materials

The soil used is a silty clay soil collected from a local region of Kharar, Punjab. The basic properties of soil are shown in table 1. The Fiber Reinforced Polymers (FRPs) used are Glass fibers; known for high tensile strength and resistance to moisture also small amounts of carbon fibers are used which offers excellent durability and chemical resistance. Short fibers having 15mm length are used. The Young's modulus of these fibers is 70 GPa and tensile strength is 1400 MPa and the elongation at break is 3%. Alkaline activator (solution of $Na2SiO3$ and NaOH) is used as a geopolymer.

Table1. Properties of Silty clay soil

Properties of Silty Clay	**Values**
Liquid Limit (%)	35.12
Plastic Limit (%)	15.16
Plasticity Index (%)	19.96
Specific Gravity	2.63
Water content (%)	18.62
Density (g/cm3)	1.6

3.2 Sample Preparation

Soil was oven-dried, sieved, and mixed with predetermined proportions of FRPs (Fiber Reinforced Polymers) and Geopolymer binders. Fiber Reinforced Polymers were added at 1%, 3%, 5%, 7%, 9% by weight of the dry soil. Geoployer solution was prepared by mixing NaOH (8M) and Na2SiO3 in a 1:2 ratio. The fixed percentage of geopolymer solution of 5% was added to the mixture by weight of dry soil.The hybrid mixture was thoroughly blended to ensure uniform distribution.

3.3 Laboratory Tests

Cylindrical soil specimens were prepared by mixing silty clay soil with varying percentages of Fiber Reinforced Polymers (FRPs) and a fixed 5% geopolymer. The specimens underwent curing for 7, 14, and 28 days to assess the strength development over time. During the curing periods, the soil specimens were subjected to a series of mechanical tests to evaluate their improved properties.

The Unconfined Compressive Strength (UCS) test was conducted on the cured specimens at a strain rate of 1% per minute, in accordance with standard testing procedures. This test was performed to determine the soil's resistance to axial load and to assess the impact of FRP and geopolymer additives on the soil's load-bearing capacity. The UCS test results were recorded at three curing intervals (7, 14, and 28 days), allowing for the examination of strength development over time. These results provided critical insights into the optimal combination of FRP and geopolymer content that maximized the strength of the stabilized soil.

Additionally, Direct Shear Tests were conducted to determine the shear strength parameters, including cohesion and internal friction angle, of the stabilized soil. The shear tests were performed at the same curing intervals to evaluate how the hybrid stabilization approach affected the soil's resistance to shearing forces. The shear strength parameters were determined by applying a constant shear rate until failure occurred, allowing for a comprehensive analysis of how the hybrid stabilization impacted the soil's structural integrity under lateral forces.

These tests provided valuable data on the mechanical properties of the stabilized soil, with particular emphasis on the synergistic effects of FRP and geopolymer on both compressive and shear strength. The combination of UCS and shear strength testing offered a comprehensive assessment of the soil's improved stability and load-bearing capacity, essential for applications in construction and geotechnical engineering.

4. Results and Discussion

Table 2. Illustrates the Unconfined Compressive Strength of soil stabilized with varying FRP (Fiber Reinforced Polymers) percentages and 5% geopolymer over 7,14 and 28 days. The UCS increases with FRP content, peaking at 5%, where maximum strength (405.2 KPa) is achieved at 28 days. This highlights the synergistic effect of FRP and Geopolymer, enhancing soil strength and durability. However , beyond 5% FRP, UCS declines, likely due to reduced bonding and compaction efficiency.

Table.2 UCS (Unconfined compressive strength) values at 7, 14 and 28 days

FRPs (Fiber Reinforced Polymer) %+ 5% Geopolymer	7 Days unconfined compressive strength (KPa)	14 Days unconfined compressive strength (KPa)	28 Days unconfined compressive strength (KPa)
0%	151.3	170.1	215.6
1%+5%	170.8	211.2	243.7
3%+5%	222.3	269	320.4
5%+5%	278	342.7	405.2

7%+5%	219.4	291.3	357
9%+5%	201.5	230.6	306.3

The consistent strength gain over time emphasizes the curing process's role in stabilization . These findings establish 5% FRP with 5% geopolymer as an optimal blend for effective soil stabilization.Similarly table 3 shows the cohesion values of soil stabilized with varying FRP percentages and 5% geopolymer at 7, 14 and 28 days. Cohesion improves with increasing FRP content, peaking at 5%, where maximum cohesion (42.7 KPa) is achieved at 28 days due to enhanced fiber soil interlocking and geopolymer curing.

Table 3. Cohesion Values (KPa) at 7, 14 and 28 days

FRPs (Fiber Reinforced Polymer) %+ 5% Geopolymer	7 Days Cohesion (KPa)	14 Days Cohesion (KPa)	28 Days Cohesion (KPa)
0%	12	17.4	20.1
1%+5%	17.5	20.3	25.6
3%+5%	21.7	27.1	33
5%+5%	26.8	34.4	42.7
7%+5%	23	30.2	36.2
9%+5%	19.5	24.8	31

Beyond 5% FRP, cohesion decreases, likely due to excessive fiber content disrupting the soil matrix. Table 4 shows shear strength variations with FRP percentages and 5% geopolymer. Shear strength peaks at 5% FRP(137 KPa at 28 days), indicating optimal stabilization. Beyond 5% excess fiber reduced soil strength.

Table 4. Shear Strength Values (KPa) at 7, 14 and 28 days

FRPs (Fiber Reinforced Polymer) %+ 5% Geopolymer	7 Days Shear Strength (KPa)	14 Days Shear Strength (KPa)	28 Days Shear strength (KPa)
0%	48.1	62	72.3
1%+5%	56.2	63.9	77.7
3%+5%	74	87.4	104.8
5%+5%	98.7	118.3	137
7%+5%	83.3	105	121.4
9%+5%	71.2	89.4	104.6

Fig 1: The UCS variations for different FRP percentages at 7, 14 and 28 days

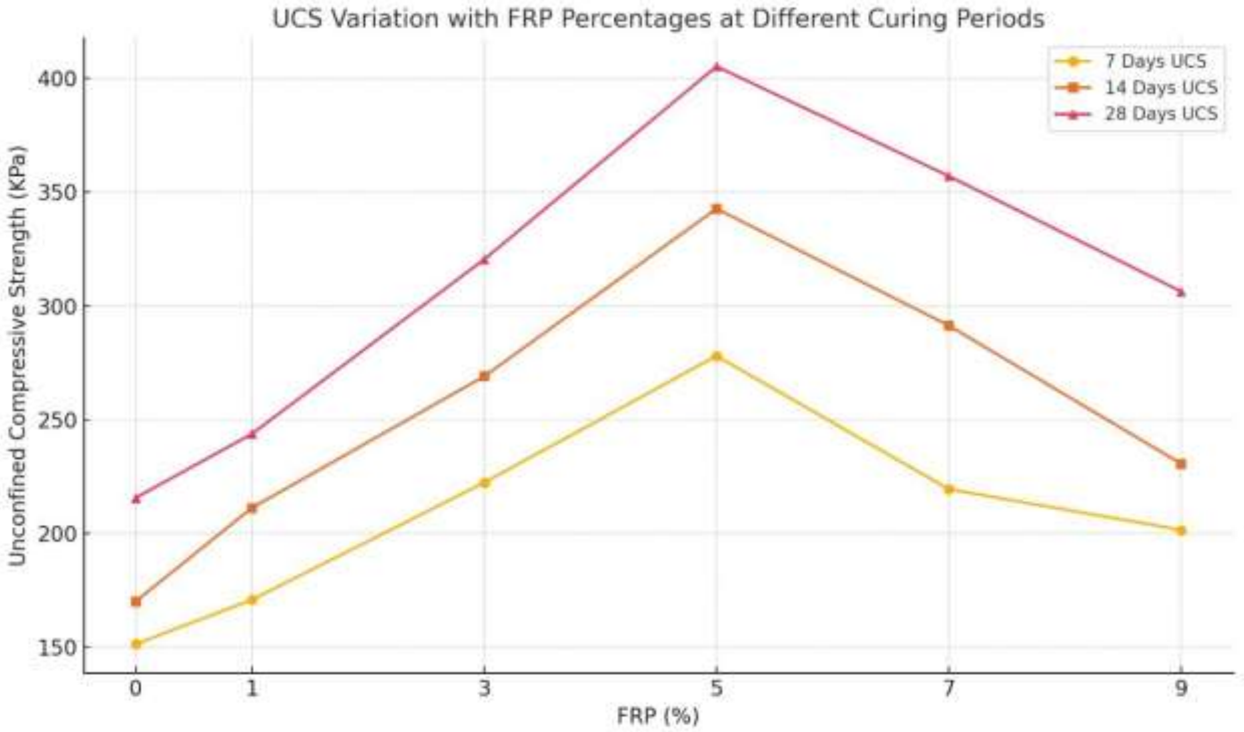
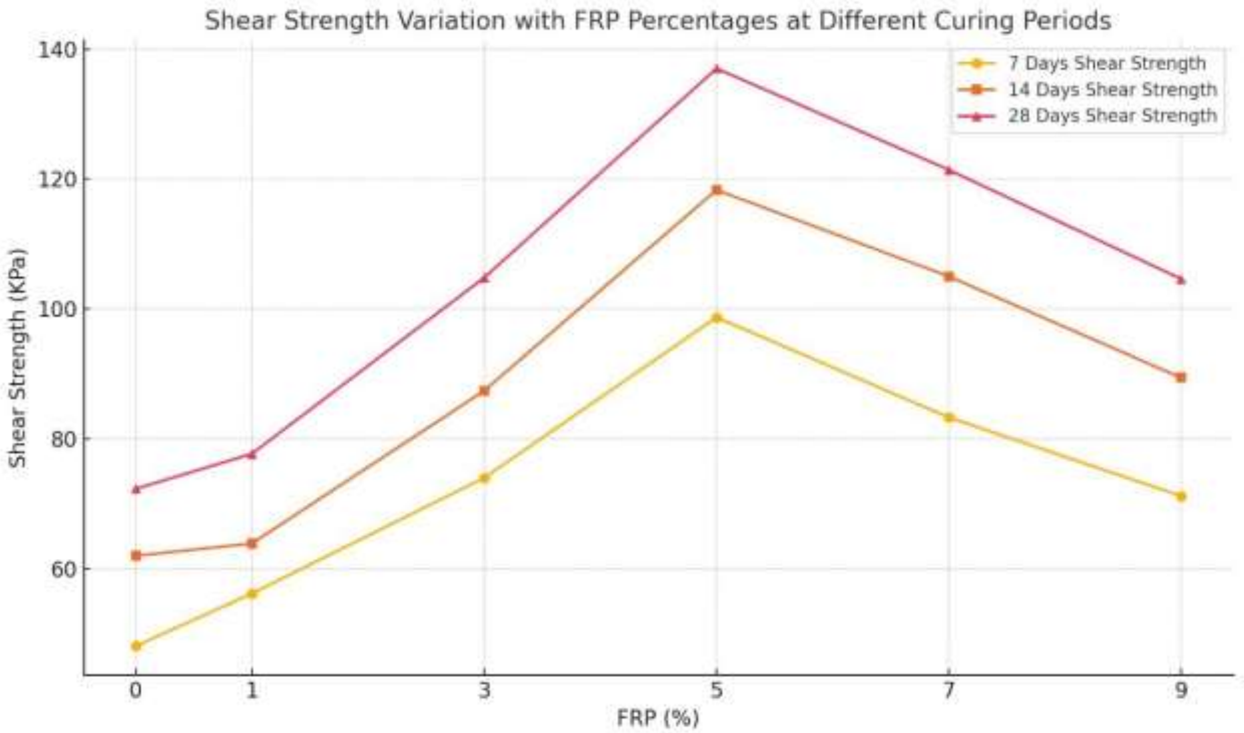


Fig 2: Shear Strength variations for different FRP percentages at 7, 14 and 28 days



5. Challenges and Future Directions

5.1 Challenges

Nevertheless, challenges confronting the application of the hybrid approach to soil stabilization include the following to be adopted fully. Among the major sources of error, an essential one is a variation in the characteristics of raw materials used for geopolymer preparation. The reactants used in the preparation of fly ash, slag, and other precursors can thus differ in several ways leading to immense variability in the structure and characteristics of the resultant geopolymer (Kumar et al., 2021)[10]. The constant quality and reliability in production are possible only with the use of production standardization.

The first limitation of FRPs is the relatively high cost of installation as compared to conventional construction methods, mainly because of the initial cost of materials. While the recurrent billing is offsetable through the life-cycle cost saving hence driving the investment in the long run, the costs of purchasing such a System may act as a barrier to adoption especially in resource constrained projects. This matter might be somewhat eased by finding affordable techniques for manufacturing and researching other types of fiber materials.
Some of the technical issues pose a problem and include the compatibility of the FRPs with geopolymers. Though efforts have been made through processes such as surface treatment using silane coupling agents, studies have revealed that more work is still needed to enhance this bond when the above mentioned materials experience environmental conditions (Wang et al., 2022)[15]. Further, the integrated systems in the field necessitate high-tech tools and a qualified workforce in the implementation, which may prevent the effectiveness of the hybrid system in the area of unwanted geography or nascent technology.
Finally, the disposal and recycling of FRPs create environmental problems in different environments. While these improvements contribute to the sustainability of the hybrid system during its useful life cycle, their end-of-life management involves decision-making to avoid the generation of unwanted waste (Almeida et al., 2020)[2]. Such a development might be managed by innovations in fiber raw materials, which could be biodegradable or recyclable

5.2 Future Research

As with any research on new composite materials, more work is required to enhance the bonding between FRPs and geopolymers especially in different operational conditions in the field. Further studies should be conducted on how to achieve more consistent geopolymers production, by standardizing the production processes which use locally available industrial wastes as raw material. However, there is a need to assess the environmental life cycle of FRPs in particular, including recycling and disposal or end-of-life solutions to ensure that the overall prospects of a hybrid approach are optimally sustainable as regards Wang et al. (2022)[15]. There is a need for more cooperation between industry players and academics to build on this technology. The observations from the pilot projects that incorporate hybrid stabilization in several soil types should support the laboratory results and convince the stakeholders. PPPs may help develop hybrid stabilization strategies for infrastructure projects around the worldThe concept of a hybrid stabilization technique takes the best of both materials hence overcoming existing limitations in the stabilization of soils and at the same time contributing to global sustainable development.

6. Conclusion

The use of Fiber Reinforced Polymers (FRPs) in combination with geopolymers presents a promising and innovative solution for soil stabilization, enhancing both mechanical properties and sustainability. Geopolymers provide superior chemical bonding, durability, and ecological compatibility, while FRPs contribute high tensile strength and elasticity. This hybrid approach significantly improves the unconfined compressive strength (UCS), cohesion, and shear strength of silty clay soil, making it an effective alternative to conventional stabilization methods.
Experimental results show that the optimal mix of 5% FRP and 5% geopolymer yields the best performance in terms of UCS, cohesion, and shear strength, with peak values observed at 28 days of curing. Beyond this optimal blend, further increases in FRP content resulted in decreased mechanical performance, likely due to reduced bonding and compaction efficiency.
This hybrid stabilization method offers a cost-effective, environmentally friendly, and durable solution, particularly for large-scale infrastructure projects in regions with geological instability. The long-term performance and reduced maintenance needs of treated soils make it a viable alternative to traditional methods. Future research should focus on scaling this approach and exploring other materials to optimize its effectiveness for broader applications in geotechnical engineering.

7. References

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Figures and Tables