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# Utilization of GGBS as a sustainable cement replacement in soil-cement columns: enhancing ground stabilization through industrial waste

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**ABSTRACT**

**Introduction.** A soil-cement composite, comprising a thoroughly blended mix of soil, cement, and water, has played a crucial role in the construction of various civil infrastructures like bridge foundations, tunnels, highway embankments, foundations for port and harbour structures, and many more. Though efficient, traditional high-cement formulations pose severe environmental concerns, leading to the exploration of alternative materials that can bring sustainability to construction practices.
**Materials and methods.** This study focuses on utilizing "Ground-Granulated Blast-Furnace Slag" (GGBS) to explore its impact on the engineering characteristics of soil-cement mixtures. In this investigation, clay soil is blended with 20 % of OPC and varying proportions of GGBS (20, 25 and 30 % by weight of cement) as a replacement for OPC.
**Results.** The composite mixture is subjected to several Unconfined Compressive Strength (UCS) tests to assess the undrained shear strength of soil-cement-GGBS mixtures at distinct curing intervals (7, 14, and 28 days). Field emission scanning electron microscopy (FE-SEM) is also employed to examine the microstructure of the soil-cement composite, revealing the arrangement of particles, pore structures, and the distribution of cementitious materials.
**Conclusions.** The results show that the composition having clay soil and 20 % cement, replaced with 20 % GGBS, yields maximum strength among all tested compositions with a significant increase of 24 % compared to the conventional soil-cement mixture of clay soil and 20 % cement only.

**KEYWORDS:** soil – cement, ground-granulated blast-furnace slag (GGBS), ordinary portland cement (OPC), unconfined compressive strength (UCS), soil – cement – GGBS mixture, scanning electron microscopy (SEM)

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# Молотый гранулированный доменный шлак — устойчивый заменитель цемента в грунтоцементных колоннах: повышение качества укрепления грунта промышленными отходами

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**АННОТАЦИЯ**

**Введение.** Грунтоцементный композит — тщательно перемешанная смесь грунта, цемента и воды — играет важнейшую роль в строительстве различных объектов гражданской инфраструктуры, таких как фундаменты мостов, тоннелей, насыпи автомобильных дорог, фундаменты сооружений портов и гаваней и др. Несмотря на эффективность, традиционные цементные составы с высоким содержанием цемента вызывают серьезные экологические проблемы, что заставляет искать альтернативные материалы, способные обеспечить экологическую устойчивость строительства.
**Материалы и методы.** Изучено влияние молотого гранулированного доменного шлака на технические характеристики грунтово-цементных смесей. Использовалась сканирующая электронная микроскопия для изучения микроструктуры грунтово-цементного композита, выявления расположения частиц, структуры пор и распределения цементирующих материалов.

**Результаты.** Глинистый грунт смешивается с 20 % портландцемента и молотым гранулированным доменным шлаком в разных пропорциях (20, 25 и 30 % по весу цемента) в качестве замены портландцемента. Композитная смесь несколько раз подвергается испытаниям прочности на одноосное сжатие недренированной смеси грунта, цемента и молотого гранулированного доменного шлака на разных этапах твердения (7, 14 и 28 дней).
**Выводы.** Результаты показывают, что состав, содержащий глинистый грунт и 20 % цемента, замененного на 20 % молотого гранулированного доменного шлака, обладает максимальной прочностью по сравнению со всеми другими испытанными составами со значительным увеличением на 24 % по сравнению с обычной грунтоцементной смесью на основе глинистого грунта.

**КЛЮЧЕВЫЕ СЛОВА:** грунт – цемент, молотый гранулированный доменный шлак, обычный портландцемент, прочность на одноосное сжатие, смесь грунт – цемент – молотый гранулированный доменный шлак, сканирующая электронная микроскопия

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## INTRODUCTION

Soil-cement mixtures have long been utilized in geotechnical engineering for a variety of applications, including soil stabilization, pavement subgrades, slope protection, and the construction of embankments and foundations. These mixtures improve the engineering properties of soils by enhancing compressive strength, reducing plasticity, controlling swelling and shrinkage, and minimizing permeability. The soil-cement mixture is considered a cost-effective remedy for soil stabilization in construction projects due to the economic benefit of utilizing locally accessible materials and minimizing dependency on costly imported materials mix (Solihu, 2020; Choudhary et al., 2023) [1–13]. Cement is the key component in soil-cement mixtures that serves as a fundamental binder, and it is readily used as a chemical additive in soil stabilization due to its several advantages like easy availability, low cost, durable end products, resistance towards acid and chemical attacks and many more. However, the extensive use of cement leads to negative environmental consequences, primarily due to the high energy consumption during production and significant carbon dioxide emissions (Gupta and Chaudhary, 2020; Cruz Juarez and Finnegan, 2021). To mitigate this negative environmental impact, very few studies have been conducted to find appropriate substitutes and cement alternatives that can provide appreciable strength. Among the various conventional supplementary cementitious materials (SCMs), Ground-Granulated Blast-Furnace Slag (GGBS) is regarded as one of the most effective substitutes for cement. When incorporated in appropriate proportions, GGBS improves the strength and durability of cement hydration products. As a by-product of the iron and steel manufacturing process, obtained from blast furnaces, GGBS possesses inherent pozzolanic properties. Its addition enhances the physical and mechanical properties of soil-cement mixtures by reacting with calcium hydroxide (lime) produced during the early stages of cement hydration, forming additional cementitious compounds such as Calcium Silicate Hydrate (C-S-H) gel, Calcium Alumino-Ferrite (CAF), and Calcium Hydroxide (CH), among others. These compounds reduce void spaces in the soil-cement matrix. Additionally, GGBS helps lower the heat generated during the cement hydration reaction. Recent studies have highlighted the potential of using industrial waste-based SCMs to enhance the engineering properties of clay soils (Åhnberg, 2006; Horpibulsuk et al., 2012; Johnson Singh et al., 2022; Singh et al., 2020; Singh et al., 2021). However, very few researchers have studied the utilization of SCMs to replace a part of lime and cement in soil stabilization. Kinuthia and Wild conducted several laboratory tests like UCS, CBR, swelling index, and many more on GGBS mixed lime-clay mixtures to analyze the changes in the engineering characteristics of clay soil. The results obtained revealed that the clay soil's compressive strength was considerably increased by the addition of GGBS. Arulrajah et al. explored the potential use of industrial waste by-products like fly ash (F) and slags (S) in deep soil mixing methods for soft soil treatment. A set of laboratory experiments, including UCS, flexure beam, and SEM tests, were carried out on test specimens prepared at three different water contents of 0.75, 1.0, and 1.25. In terms of strength and stiffness, the results illustrated significant improvement in the soft clay soils for an optimum binder content of 20 % and optimum F and S content as 5 and 15 %, respectively. Du et al. conducted a comparative study on lightweight cement-treated soil with lightweight geopolymer-treated soils by performing several tests like UCS, mercury intrusion porosimetry (MIP), hydraulic conductivity, SEM images, and thermogravimetric analysis (TGA). They found out that lightweight geopolymer-treated soils improved the permeability and the strength properties and provided better engineering performances than lightweight cement-treated soils. While other SCMs like fly ash and silica fume also offer beneficial properties, GGBS is particularly advantageous due to its higher cementitious value and slower rate of hydration, which contributes to lower heat generation and greater long-term strength development. GGBS also provides superior resistance to sulfate attack and alkali-silica reactions, making it a more durable choice for geotechnical applications where soils are exposed to aggressive environmental conditions. Utilizing GGBS in soil stabilization aligns well with several United Nations Sustainable Development Goals (UN SDGs), particularly SDG 9 (Industry, Innovation, and Infrastructure), SDG 11 (Sustainable Cities and Communities), and SDG 13 (Climate Action).

This study explores the strength gain characteristics of soil-cement-GGBS mixture by blending clay soil with 20 % cement (by weight of dry soil) and varying proportions of GGBS (20, 30 and 40 % by weight of cement) by conducting UCS tests. SEM was employed to observe the microstructure of the soil-cement composite, revealing the arrangement of particles, pore structures, and the distribution of cementitious materials.

## MATERIALS AND METHODS

The clay soil used in this study was obtained from a test pit located on the IIT Indore campus, Madhya Pradesh, India. The soil was sieved using a 2 mm IS sieve, dried in a hot air oven for 24 hours, and stored in an airtight container. Ordinary Portland Cement (OPC) and Ground-Granulated Blast-Furnace Slag (GGBS) were provided through collaboration with industrial partners. Based on the Unified Soil Classification System (USCS), following ASTM D-2487–98 and IS: 1498–1970 standards, the soil is classified as highly expansive clay, as shown in Fig.1. The fundamental properties of the clay soil are summarized in Table.

In this study, prepared raw clay soil was added with 20 % of OPC (specific gravity $G_s$ = 3.10) and appropriate water content to obtain slurry-type consistency. The major constituents, including clay soil, cement, GGBS, and water, were thoroughly mixed with the help of a mechanical mixer.

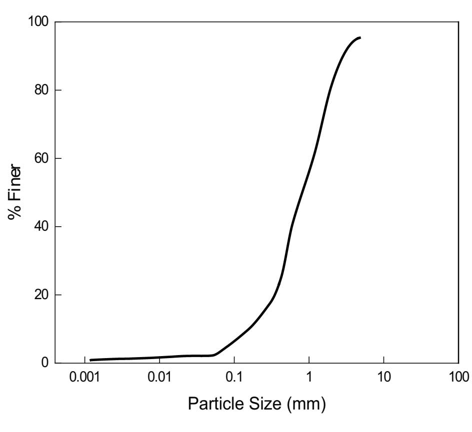



**Fig. 1.** Grain size distribution (GSD) curve of clay soil

**Рис. 1.** Кривая гранулометрического состава глинистой почвы

Basic properties of clay soil

Основные свойства глинистой почвы

| S.No. | Property | Value |
|---|---|---|
| 1. | Natural water content, % | 15.38 |
| 2. | Specific gravity | 2.71 |
| 3. | Liquid limit, % | 81.05 |
| 4. | Plastic limit, % | 36.44 |
| 5. | Optimum moisture content, % | 29 |
| 6. | Maximum dry unit weight, kN/m$^3$ | 1.425 |
| 7. | Shrinkage limit, % | 11.20 |
| 8. | USCS soil classification | CH |

Sixteen specimens of soil-cement-GGBS compositions were prepared with a 20 % cement content by weight of dry soil, using high polymer density molds (HPDM) with an internal diameter of 44 mm and a height of 98 mm. The cement content was subsequently substituted with 0, 20, 30 and 40 % by the weight of dry cement. To preserve the consistency in the mixtures and provide adequate hydration, the amount of water added was 1.5 times the liquid limit of the soil. Each mixture was then carefully poured into the molds and made specimen air-free with the help of a mechanical stirrer. The freshly molded mixtures were left for 24 hours at room temperature to achieve appreciable strength. After 24 hours of specimen preparation, the specimens were removed from the molds and placed in a curing tank, where they underwent a continuous curing procedure in submerged condition. Before conducting UCS tests, the specimens were taken from curing tank and allowed to rest at room temperature for five minutes to facilitate evaporation of surface water. Afterward, a series of UCS tests were conducted to evaluate the mixture's undrained shear strength and unconfined compressive strength at 7-, 14- and 28-days of curing. Following the completion of UCS testing, SEM imaging was also utilized on the tested specimens to provide insights into microstructural details.

## RESULTS OF THE RESEARCH

### Unconfined Compressive Strength

The Unconfined Compressive Strength (UCS) test, conducted in accordance with ASTM D7012–23, was used to determine the undrained shear strength and unconfined compressive strength of the soil-cement-GGBS mixtures. During the test, a compressive load was applied at a strain rate of 1.25 mm per minute. The UCS test was performed on specimens with different mixture combinations and curing durations. The results indicated that the compressive strength of all mixtures increased with extended curing times. Previous studies have often identified an optimum content of 20 % Ordinary Portland Cement (OPC), demonstrating considerable strength and stability in soil-cement mixtures (Pham, Koseki, Dias,

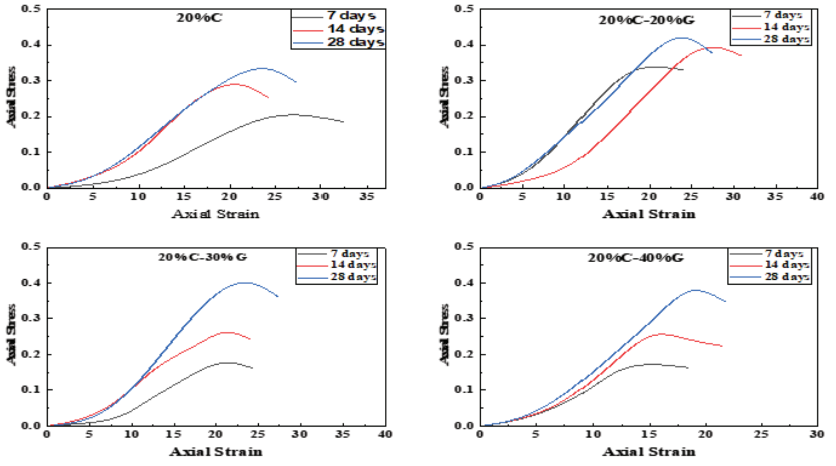



**Fig. 2.** UCS Tests results of Soil + 20 % Cement content with different GGBS concentration at different curing durations

**Рис. 2.** Результаты испытаний на одноосное сжатие смеси грунта + 20 % цемента с различной концентрацией молотого гранулированного доменного шлака на разных этапах твердения

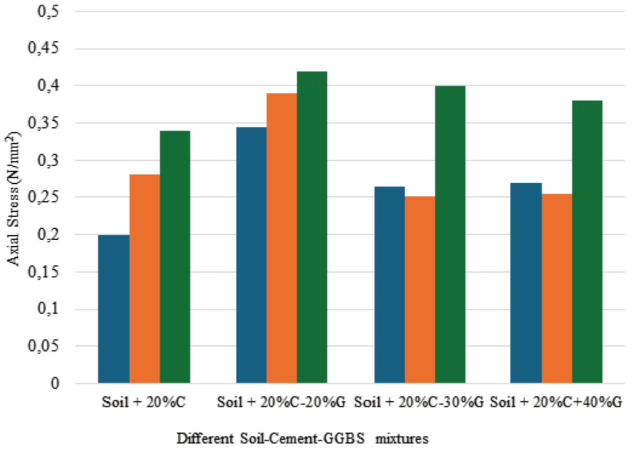



**Fig. 3.** Variation of Axial Stress for different soil – cement – GGBS mixtures for different curing durations

**Рис. 3.** Изменение продольного напряжения для разных смесей грунт – цемент – молотый гранулированный доменный шлак на разных этапах твердения

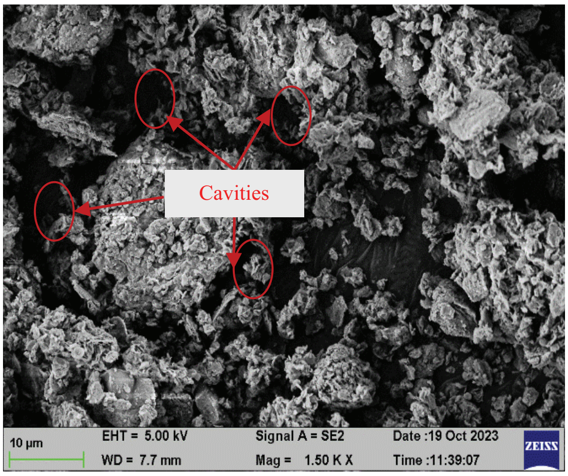
2021; Solihu, 2020). Shows that the strength gain variation of specimens with varying constituents increases for varying curing times of 7-, 14- and 28-days respectively (Fig. 2). Moreover, it has been experimentally determined that specimens subjected to a 28-day curing period exhibit maximum compressive strength gain among all the compositions.

A soil mixture with 20 % cement and 20 % GGBS blend shows maximum values of 0.41925 N/mm$^2$ and 0.2096 N/mm$^2$ for undrained shear strength and unconfined compressive strength, respectively. The strength of the specified composition is 24 % higher in comparison to that of the traditional soil-cement mixture with 20 % cement content. The obtained results greatly emphasize the importance of GGBS in improving the strength qualities of combinations while encouraging the use of sustainable materials.

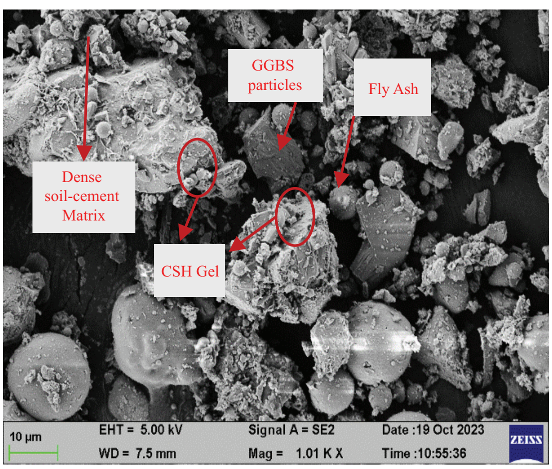
Fig. 3 elucidates the impact of different Ground-Granulated Blast-Furnace Slag (GGBS) contents on the axial stress of soil-cement-GGBS mixtures over various curing durations (7, 14 and 28 days). The result indicates that the addition of GGBS significantly enhances the strength of the mixtures, with a consistent increase in axial stress observed for all compositions as the curing time extends. Notably, the mixture with 20 % Ordinary Portland Cement (OPC) and 20 % GGBS exhibits a considerable increase in axial stress compared to the mixture containing only 20 % OPC, suggesting that incorporating GGBS improves the mixture's mechanical performance. As the GGBS content rises to 30 and 40 %, the axial stress continues to increase, albeit at a slower rate, indicating diminishing returns beyond a certain replacement level.

### Scanning Electron Microscopy

In this work, FE-SEM was conducted using FE-SEM Supra 55 (Carl Zeiss, Germany) with a magnification of 500X on specimens of virgin clay soil and GGBS blended soil-cement mixture having 20 % cement and




*a*




*b*

**Fig. 4.** SEM images of (*a*); raw clay soil and clay soil + 20 % cement + 20 % GGBS at 28-days of curing (*b*)

**Рис. 4.** Изображения, полученные с помощью сканирующего электронного микроскопа (*a*); сырого глинистого грунта и глинистого грунта + 20 % цемента + 20 % молотого гранулированного доменного шлака на 28-й день твердения (*b*)

20 % GGBS replacement cured for 28 days as illustrated in Fig. 4, respectively. The SEM images of clay soil show the texture of the clay particles and the pores available in the matrix. Fig. 4, *b* confirms bond formation and development of hydration products such as calcium aluminate hydrates (CAH), calcium silicate hydrates gel (C-S-H gel), and Ettringite. Hydration production is confirmed by the creation and dispersion of these products, which helped in the development of strength of composites. The angular shape of the GGBS particles also helps in better interlocking and strength development. The SEM images provide crucial insights on the interfacial connection of GGBS and soil-cement particles.

## CONCLUSION AND DISCUSSION

This study utilized GGBS as a SCM in the soil-cement mixture to improve its strength and durability. Several laboratory tests were conducted on different soil and soil-cement-GGBS mixture specimens to determine the basic properties as well as engineering properties. The current study illustrated the strength properties of soil-cement-GGBS mixture with varying compositions for different curing time. The conclusions drawn from the results of the current study are as follows:

- it exhibits a strong reaction with calcium hydroxide ($Ca(OH)_2$), a by-product of cement hydration, leading to the formation of additional cementitious compounds., reducing the cavities and improving the overall strength and durability of the soil-cement mixture;
- the mixture of clay soil with 20 % cement and 20 % GGBS blend cured for 28 days shows a significant increase in the values of undrained shear strength and unconfined compressive strength of 0.41925 N/mm$^2$ and 0.2096 N/mm$^2$ respectively, as compared to other compositions. This composition exhibits a 24 % increase in strength compared to the conventional soil-cement mixture with 20 % cement content;
- this experimental study focuses on the strength development of clay soil mixed with 20 % OPC, and the cement proportion is replaced with GGBS at varying ratios. However, there are further areas in which more research needs to be done to improve the current understanding and investigation of various parameters, such as optimization of mix ratios, effect of curing conditions, long-term performance, time-dependent stress-strain behaviour, shear strength behaviour, field scale validation and many more.

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