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Rheological study of soil-cement-GGBFS mixture

Etude rhéologique du mélange sol-ciment-GGBFS

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ABSTRACT: The rheological parameters of the soils and soil-cement mixtures, such as storage modulus, loss modulus, viscosity, flow points, shear stress, yield stress, and many more, are being studied to examine and understand the response of the soil microstructure subjected to external stress. In this study, a stress-controlled rotational rheometer is used on several test specimens of clay soil mixed with Ordinary Portland Cement (OPC) and Ground Granulated Blast Furnace Slag (GGBFS). The soil specimens underwent shear deformations at the rate of 0.01% to 100% using a 50 mm diameter measuring shaft at various time intervals during the Amplitude Sweep Test (AST). AST was performed to investigate the viscoelastic properties of the soil paste having OPC (15% by weight of dry soil) and different proportions of GGBFS (0%, 20%, 30%, and 40% by dry weight of OPC). The obtained test results showed that, when the strain rate was low, storage modulus (G') exceeded loss modulus (G") for all the samples (15%C-0%G, 15%C-20%G, 15%C-30%G, 15%C-40%G). Notably, the sample with 20% GGBFS replacement (15%C-20%G) exhibited the highest G' value among all compositions, which indicates that the 20% GGBFS replacement sample deforms and returns to its original state more quickly than the other samples.

RÉSUMÉ: Les paramètres rhéologiques des sols et des mélanges sol-ciment tels que le module de stockage, le module de perte, la viscosité, les points d'écoulement, la contrainte de cisaillement, la limite d'élasticité et bien d'autres sont étudiés pour examiner et comprendre la réponse de la microstructure du sol soumise à des contraintes externes. Dans cette étude, un rhéomètre rotatif à contrainte contrôlée est utilisé sur plusieurs éprouvettes de sol argileux mélangées à du ciment Portland ordinaire (OPC) et à du laitier de haut fourneau granulé broyé (GGBFS). Les échantillons de sol ont subi des déformations par cisaillement à un taux de 0,01% à 100% à l'aide d'un arbre de mesure de 50 mm de diamètre à différents intervalles de temps au cours du test de balayage d'amplitude (AST). L'AST a été réalisée pour étudier les propriétés viscoélastiques de la pâte de sol contenant de l'OPC (15% en poids de sol sec) et différentes proportions de GGBFS (0%, 20%, 30% et 40% en poids sec d'OPC). Les résultats des tests obtenus ont montré que, lorsque la vitesse de déformation était faible, le module de conservation (G') dépassait le module de perte (G") pour tous les échantillons (15%C-0%G, 15%C-20%G, 15%C-30%G, 15%C-40%G). Notamment, l'échantillon avec 20% de remplacement de GGBFS (15% C-20% G) présentait la valeur G' la plus élevée parmi toutes les compositions, ce qui indique que l'échantillon de remplacement de 20% de GGBFS se déforme et revient à son état d'origine plus rapidement que les autres échantillons.

Keywords: Amplitude sweep test (AST); ground granulated blast furnace slag (GGBFS); loss modulus (G"); rheometer; storage modulus (G').

1 INTRODUCTION

At present, the extensive production of industrial wastes such as fly ash, ground granulated blast furnace slag (GGBFS), silica fumes, and more presents a major global concern due to its significant environmental, social, and economic implications. As industries continue to expand and manufacturing processes intensify, the need to dispose of the generated wastes also intensifies significantly (Buddhdev and Timani, 2021). Ground Granulated Blast Furnace Slag (GGBFS) is one of such industrial by-products of steel industries that are produced in millions of tonnes globally, including India. GGBFS is a well-known Supplementary Cementitious Material (SCM) that possesses pozzolanic and latent hydraulic properties, and it is used to partially replace Ordinary Portland Cement (OPC) to a certain extent depending on applicability. Over the past few decades, OPC has been widely employed in the stabilization of soft clay soils. The soil-cement mixtures, comprising soil, cement, and water, exhibit qualities like better strength gain, reduced permeability, compressibility, improved durability, etc., that make them suitable for a variety of applications, ranging from road construction to foundation stabilization (Choudhary et al., 2023). However, the use of OPC raises notable environmental concerns due to the carbon dioxide (CO_2) emissions generated in its manufacturing process. OPC is directly accountable for approximately 5% of artificial CO_2 emissions, with 1 tonne of cement production yielding 800 kg of CO_2 (Damtoft et al., 2008; Gartner, 2004). In recent years, researchers and engineers have explored the incorporation of SCMs like ground granulated blast furnace slag (GGBFS) to enhance the performance of soil-cement blends further. GGBFS undergoes a strong reaction with calcium hydroxide, a by-product of cement hydration, resulting in the production of additional cementitious compounds like calcium silicate hydrate (CSH) and calcium aluminate hydrate (CAH) (Yi et al., 2015).

In the current scenario, most of the SCMs have been under-utilized except for Fly Ash (FA). FA has been widely employed to enhance the mechanical properties of fine-grained soils, such as maximum dry density, swelling, optimum moisture content, consistency limits (Barman and Dash, 2022), shear strength, compressibility (Singh et al., 2021a, 2021b) and many more. However, there is very limited information available in the research studies regarding the utilization of GGBFS in geotechnical engineering. D.D. Higgins et al. (1998) studied the possible utilization of GGBFS to improve the strength of lime-stabilised clay soils. The authors conducted experimental tests on different lime/slag ratios on two different clay soils, Kaolinite and Kimmeridge Clay. From this study, it was found that with an increase in the curing period, the strength of the clay-lime-GGBFS mixture also increased significantly for both the above-mentioned soils. It was also found that GGBFS alone has no effect on the strength enhancement of the soils and it requires an activator like lime, cement, etc. to provide significant strength. Yi et al. (2015) used Carbide-slag (CS) activated GGBFS for the stabilization of soft clay soils. The investigation focused on exploring the strength gained behaviour of soft clay soils when added with CS-GGBFS at varying proportions by performing a series of UCS tests. The results revealed that maximum unconfined compressive strength gain was observed for an optimum CS content of 4-6% in the soil-CS-GGBFS mixture. The UCS values were almost twice for CS-GGBFS stabilized soft soils in comparison to cement-treated soft soils.

Some researchers have conducted comprehensive investigations, including rheological evaluations, to investigate as well as understand the possible advantages and limitations related to the usage of GGBFS in soil-cement mixtures. Rheology, the study of the flow and deformation of materials, provides insights into the material's behaviour under external stress conditions. Amplitude sweep test (AST) in rheology is often employed to investigate the viscoelastic properties of materials, including soil-cement mix. AST involves applying oscillatory shear stress or strain to a material and observing its response over a range of amplitudes while maintaining a constant frequency. By varying the level of oscillatory amplitudes, the material's viscoelastic properties can be assessed by measuring its storage modulus, loss modulus, and yield stress as a function of the applied stress. The storage modulus (G') reflects the material's elastic or 'solid-like' behavior, while the loss modulus (G") represents its viscous or 'liquid-like' behavior. Yield stress, on the other hand, marks the transition from a solid-like to a fluid-like state, crucial for understanding flow initiation under stress. A few researchers used rheology to investigate different characteristics of virgin clay soils and clay combined with various additives. Celik and Akcuru (2020) investigated the use of Bottom Ash (BA) as a mineral component in permeation grouts made of cement. This study tested 28 various mix proportions with six different BA contents and four different water contents using a number of analytical and experimental procedures. According to the findings, there was no noticeable change in yield stress values for any water-to-binder (w/b) ratio when BA was substituted. The substitution of BA had some minor effects on yield stress; nonetheless, for all combinations, there was a noticeable downward trend in yield stress values as the w/b ratio increased. Wang et al. (2021) examined how temperature and hydration time affect the rheological characteristics of Ordinary Portland Cement (OPC) slurries, particularly emphasizing the simulation of high-temperature conditions in a laboratory setting. Portland cement PO42.5 samples with water-to-cement ratios (W/Cs) spanning from 0.5 to 2.0 were prepared for the rotational viscometer. The research also explored the rheological models and the laws governing the observed changes in rheological parameters for cement slurries exhibiting different degrees of hydration across varying temperatures ranging from 30°C to 80°C. Newton, Bingham, and power law models were applied to fit the rheological test data, and a mathematical analytical expression was introduced for the fitted curve. It is worth noting that GGBFS can augment the engineering properties of clay soil when used as a partial replacement for OPC in soil-cement mixtures. However, there is limited information available regarding the rheology of GGBFS-mixed soil-cement combinations.

In this study, rheological parameters like viscosity, yield stress, and flow behaviour index are investigated to understand the rheological characteristics of GGBFS-mixed soil-cement mixtures. Rheology is conducted at different time intervals with various GGBFS proportions as replacements for OPC.

2 MATERIALS AND METHODOLOGY

2.1 Materials

Clay soil used in this study was collected from a test site in IIT Indore, Madhya Pradesh, India. OPC and GGBFS were obtained through collaboration with industrial partners. Figure 1 illustrates the particle size distribution (PSD) curve of the soil. In accordance with the Unified Soil Classification System (USCS), adopted from ASTM D-2487-98, the soil is categorized as highly compressible clayey soil. The index properties of the clay soil are listed in Table 1.

Table 1. Index properties of clay soil.

Property	Value
Natural water content (%)	14.50
Optimum moisture content (%)	28.5
Liquid limit (%)	79.20
Plastic limit (%)	35.62
Specific gravity	2.70
Shrinkage limit (%)	11.35
Maximum dry unit weight (kN/m^3)	1.44
USCS soil classification	CH

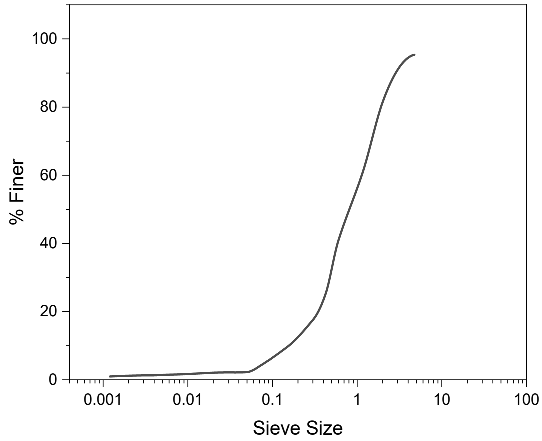

Figure 1. Particle size distribution (PSD) curve of clay soil.

For preparing the test samples, fine clay soil (passing through 600 microns) was mixed with 15% OPC (by dry weight of soil), and three different percentages of 20%, 30%, and 40% of GGBFS were used to replace OPC in the same soil-cement mixture. The soil-OPC-GGBFS mixture was thoroughly mixed for 15 minutes using a mechanical mixer. To maintain consistency and provide sufficient hydration opportunities, the water was added as 1.5 times the liquid limit of clay soil (Choudhary et al., 2023). After the mixing, the slurry sample prepared was kept for 60 minutes in a bowl to provide appropriate time for the hydration process (Buddhdev and Timani, 2021). The bowl was covered with a moisture-retaining film for this entire time to prevent any moisture loss. The different proportions of clay soil, OPC, and GGBFS taken for the testing sample preparation are shown in Table 2.

Table 2. Different proportions of the mix used for this experimental study.

Soil (g)	OPC (By weight of soil) (%)	GGBFS Replacement (By weight of OPC) (%)	Final amount (Soil+ OPC+ GGBFS) (g)
300	15%	0%	300+45
		20%	300+36+9
		30%	300+31.5+13.5
		40%	300+27+18

2.2 Testing procedure

The Amplitude Sweep Test (AST) was performed to study the response of the soil-OPC and soil-OPC-GGBFS mixture under the application of external stresses. To ascertain the rheological characteristics of the sample, Anton Paar-Modular Compact Rheometer (MCR) 102 with a 50mm diameter parallel plate measuring shaft is employed. Table 3 illustrates the configurational setup for AST with controlled shear deformation (CSD) referred from previous studies (Khaidapova et al., 2018).

Table 3. Configuration setup of conducted Amplitude Sweep Test (AST).

Parameters	Corresponding values
Plate distance	D= 2mm
Shear deformation	γ= 0.01% to 100%
Number of Measuring points	25 points
Angular frequency	0.5 Hz ($\omega = \pi$ s-1)
Duration of experiments	15 min

A small quantity of 15-20 grams of the prepared sample is carefully placed on the rheometer's fixed measuring plate. A normal force of FN = 12N was applied during the test to maintain an undisturbed quasi-elastic soil structure after lowering the top measuring plate up to the required measuring gap of 2 mm. For the given soil-OPC-GGBFS mixture, the test samples underwent six tests performed at 20-minute intervals, starting from 60 minutes post mixing process, to observe the variations of different rheological properties like G', G" with respect to shear strain.

3 RESULTS AND DISCUSSION

3.1 G'/G" vs. shear strain

The amplitude sweep test demonstrates the relationship between various rheological properties, including the loss modulus (G"), storage modulus (G'), flow point, and yield point, as shown in Figure 2. It exhibits three distinct phases. Phase 1: In this phase, both the loss modulus (G") and storage modulus (G') are parallel, indicating the elastic behavior of the sample. This means that the material primarily stores and releases energy when subjected to deformation, and it quickly returns to its original shape once the deformation is removed. Phase 2: The point where G' and G" become equal signifies the transition from elastic to Newtonian behavior of the sample. Phase 3: The final phase indicates that the bonding between sample particles is breaking down, and the viscous characteristics start to dominate. In this phase, G" (loss modulus) has a higher value than G' (storage modulus). It represents the material's tendency to flow and deform readily, with less ability to return to its original shape after deformation.

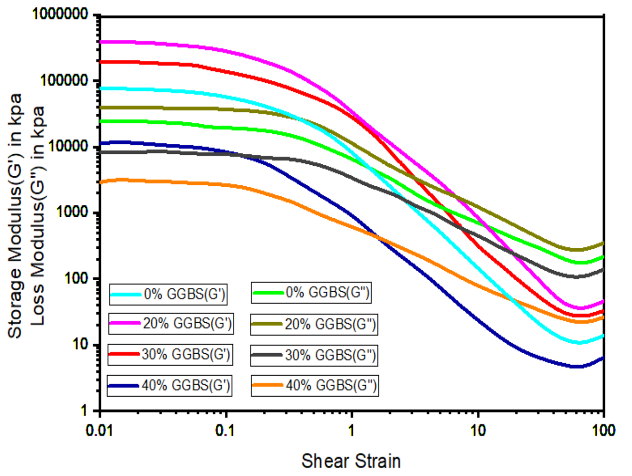

Figure 2. Amplitude sweep test data for clay soil with 15% OPC and 0%, 20%, 30%, and 40% GGBFS replacement.

As shown in Figure 2, the major focus of AST was to examine the viscoelastic behaviour of samples with 15% OPC sample with different percentages of GGBFS replacement (0%, 20%, 30%, 40%). From the results, it can be observed that when the shear strain was low, G' exceeded G" for all the samples (15C, 15%C-20%G, 15%C-30%G, and 15%C-40%G). Notably, the sample with 20% GGBFS replacement (15%C-20%G) exhibited the highest G' value among all compositions. This indicates that the 20% GGBFS replacement sample primarily stores and releases energy when subjected to deformation and returns to its original shape more quickly than the other samples. As the applied shear strain increased, G" surpassed G', and the samples began to exhibit fluid-like behavior. The point at which this transition from elastic to viscous behavior occurs, represented by the intersection of G" and G', is indicated as the flow point. In Figure 2, the order in which the flow point was reached for the compositions is as follows: 15%C < 15%C-40%G < 15%C-30%G < 15%C-20%G. It implies that the sample with 20% GGBFS replacement has the least tendency to behave like a fluid compared to the other samples, as it reached the flow point later.

3.2 Flow points

Figure 3 illustrates the relationship between flow point values with respect to varying GGBFS replacement in soil when mixed with OPC. Li et al. (2018) presented a distinct relationship between the packing density and the rheological properties. It states that, as the packing density decreases leads to the requirement of higher water content and lower workability. The angular particles in the GGBFS form a framework in the packing system and reduce the packing density of the soil sample. From Figure 3, it is evident that when 20% of GGBFS is used to replace OPC in the mixture, the material becomes fluid enough to flow (the flow point tends to increase). However, further increment in the GGBFS content increases the viscosity and reduces the flow point of the composite mixture.

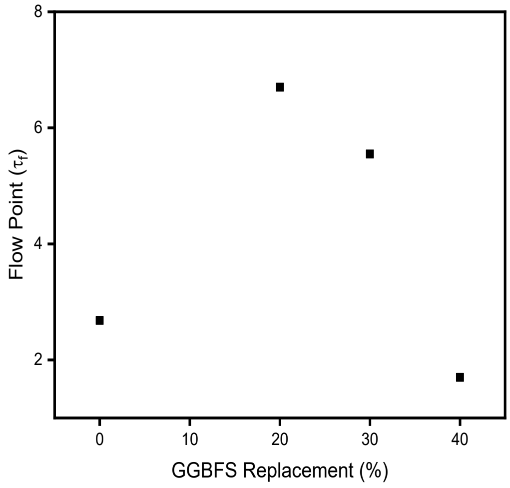

Figure 3. Variation of flow point with the addition of OPC with different GGBFS replacement ratios.

4 CONCLUSIONS

This study investigates the influence of various GGBFS ratios on the rheological parameters of clay soil blended with OPC. A set of experimental tests conducted through the Amplitude Sweep Test explores the deformation behavior. The conclusions drawn from the experimental findings are as follows:

i. It has been observed that adding GGBFS with OPC has a considerable impact on the stiffness, structural stability, and shear behaviour of reconstituted soil because the reaction happening between OPC and GGBFS makes very good bonding with soil particles.
ii. The increase in GGBFS replacement raises the flow point, loss modulus, and storage modulus, which indicates that the soil stability and strength have increased due to good soil particle interlocking.
iii. With an increase in GGBFS content, the viscosity of the Soil-OPC-GGBFS mixture also increases, which increases the flow point values. This increased viscosity has the consequence of decreasing the mixture's inclination to flow and disperse.

It is to be noted that the current study mainly focussed on the deformation behaviour of the soil-OPC-GGBFS mixture for a certain proportion. However, there are many aspects of this study, such as dynamic mechanical analysis, time-dependent deformation behaviour, optimization of GGBFS content at different moisture content, in-depth microstructural analyses, and long-term durability of GGBFS-blended soil-cement mixtures under diverse environmental conditions to better understand the impact of GGBFS on the soil-cement mixtures.

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