Lecture Notes in Civil Engineering

T. Thyagaraj · P. T. Ravichandran ·
G. Janardhanan · S. Bhuvaneshwari ·
M. Muttharam · V. B. Maji *Editors*

Characterization and Behaviour of Natural and Engineered Geomaterials

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Preface

The Indian Young Geotechnical Engineers Conference is the biannual national flagship event of the Indian Geotechnical Society (IGS), New Delhi, to showcase the research work and case studies carried by the Young Engineers on wide range of topics in the realm of Geotechnical Engineering and Geoenvironmental Engineering. The Eighth Indian Young Geotechnical Engineers Conference 2021 (8IYGEC 2021) was held in Chennai through the virtual mode during October 21–23, 2021. The conference was organized under the flagship of the Indian Geotechnical Society (IGS) Chennai Chapter in association with Indian Institute of Technology Madras (IITM), Chennai, Anna University, Chennai, National Institute of Technical Teachers Training and Research, Chennai, and SRM Institute of Science and Technology, Kattankulathur.

The conference received an overwhelming response with six Keynote lectures and six Theme lectures delivered by renowned young and mid-level academicians and professionals across the globe. The invited keynote and theme lecture papers are being brought out as a special issue in the *Indian Geotechnical Journal*. Based on the two peer reviews, 178 full length papers were accepted for the oral presentations during the conference in the following conference themes:

1. Behaviour of Saturated and Unsaturated Geomaterials
2. Foundation Engineering
3. Rock Engineering
4. Ground Improvement
5. Geotechnical Investigation and Spatial Analysis
6. Geoenvironmental Engineering
7. Slope Stability and Landslides
8. Soil Dynamics and Earthquake Geotechnical Engineering
9. Computational Geomechanics
10. Transportation Geotechnics
11. Deep Excavations and Underground Structures
12. Reliability in Geotechnical Engineering
13. Offshore and Marine Geotechnology

It was felt necessary to publish the selected papers in the Springer Book Volumes for the benefit of the young contributing authors and the geotechnical engineering community in general. Depending on the discussion topics presented in the papers, the selected papers are placed in one of the following four volumes.

Volume 1: Characterization and Behaviour of Natural and Engineered Geomaterials
Volume 2: Analysis, Design and Construction Aspects of Geotechnical Structures
Volume 3: Ground Engineering and Applications
Volume 4: Soil Dynamics and Computational Geomechanics

This volume on **Characterization and Behaviour of Natural and Engineered Geomaterials** presents 23 peer-reviewed papers pertaining to the conference themes: Behaviour of Saturated and Unsaturated Geomaterials, Geoenvironmental Engineering, Geotechnical Investigation and Spatial Analysis and Offshore and Marine Geotechnology. The papers cover wide range of topics on characterization and behaviour of natural and engineered geomaterials which include soil suction characteristics, hydraulic and volume change behaviour of clay liners, collapse behaviour, contaminant transport, phytoremediation, microbial characterization and biochar amended soil in landfill covers, stabilization of soils, etc. This book is of interest to both academicians and practicing engineers.

The organizing team would like to thank all the authors for contributing their papers to the 8IYGEC 2021. We also would like to place on record of our appreciation to all the reviewers who helped us in providing the valuable review comments for improving the quality of the papers. We are grateful for support received from the former President of IGS, Prof. N. K. Samadhiya, and the former honorary secretary of the IGS, Prof. J. T. Shahu. Finally, we would like to thank Springer Publishing Team for bringing out these volumes for the benefit of the Geotechnical Engineering Community.

Chennai, India — T. Thyagaraj
Kattankulathur, India — P. T. Ravichandran
Chennai, India — G. Janardhanan
Chennai, India — S. Bhuvaneshwari
Chennai, India — M. Muttharam
Chennai, India — V. B. Maji

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Dr. V. B. Maji presently working as Professor in the Department of Civil Engineering, Indian Institute of Technology (IIT) Madras, joined the department in the year 2008. He received his Ph.D. degree from the Indian Institute of Science Bangalore, a Master of Technology degree, from the Institute of Technology (now IIT), Banaras Hindu University (BHU), India, and a Bachelor of Science Engineering degree from BIT Sindri, Dhanbad, India. Prior to joining IIT Madras, he has also worked as associate consultant in Advanced Technologies and Engineering Services (ATES), a consultancy division of AIMIL Ltd. New Delhi. His teaching and research interests include rock mechanics, tunneling, strength, and deformation behavior of rocks and rock masses.

Behaviour of Saturated and Unsaturated Geomaterials

Effect of Suction and Rainfall Characteristics on Slope Stability: A Case Study of Idukki Slope Failure

Ammavajjala Sesha Sai Raghuram and B. Munwar Basha

Abstract The stability of slopes under rainfall conditions depends on the rainfall intensity, permeability, and soil water characteristics. The soil water characteristic curve (SWCC) connects soil suction to the soil water content. The SWCCs estimated using drying and wetting the soil samples are not identical because of the effect of hysteresis. The stability analysis of the slopes under drying and wetting cycles is not fully understood yet. Hence, in this study, the influence of drying and wetting SWCC on slope stability is examined and presented for a real case study. A massive slope failure was reported on the 9th of August 2018 due to severe rainfall at Idukki, Kerala. The influence of drying and wetting SWCC on the factor of safety of the Idukki slope is illustrated. An analytical study has been developed to examine the stability of the Idukki slope. Furthermore, the slope is analyzed for various rainfall intensities. Additionally, the critical failure surfaces at the time of failure for both drying and wetting SWCCs are presented. The findings demonstrated that wetting SWCC and rainfall intensity play a significant role in the stability analysis of slopes under rainfall conditions. Further, a significant shift in the position of the critical slip surface is observed for both drying and wetting SWCCs in unsaturated conditions. The wetting SWCC should be given consideration than drying SWCC in the stability analysis of rainfall-induced slope failures.

Keywords Unsaturated soils · Rainfall · Slope failure · Hysteretic SWCC · Factor of safety

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1 Introduction

Rainfall is one of the most common causes of slope failures. Rainwater can directly infiltrate the surface of the slope or it may indirectly increase the groundwater table from the bedrock [1]. The main reason for slope failures from a geotechnical standpoint is the reduction in effective stress associated with matric suction due to rainwater infiltration into the soil [2]. Several researchers investigated the rainfall-triggered slope failures based on numerical analysis and laboratory testing [1, 3–10]. The authors found that the stability of slopes under rainfall conditions is affected not only by the intensity of the rainfall but also by the permeability and water retention properties [7]. The soil water characteristic curve (SWCC) gives the relation between soil water retention and soil suction. The limit equilibrium (LE) methods for slope stability analysis assume that pore water pressure (PWP) is either positive or zero [2] in general. During rainfall conditions, the water content is variable along the failure surface. Hence, the PWP within the slope can be negative. Therefore, consideration of positive PWP for the slope that lies in the unsaturated zone may not be realistic and conservative. This assumption may lead to incorrect factors of safety.

The SWCC exhibits hysteresis due to entrapped air, contact angle, and ink bottle effects. Hence, the matric suction in drying SWCC is always more than the matric suction in wetting SWCC (Raghuram et al. [11]). The rainfall-induced slope failures consider drying path parameters (drying SWCC) for the estimation of the factor of safety ignoring the effects of hysteretic effects (i.e. wetting SWCC) [12–14]. Hence, due consideration should be given to the matric suction and wetting SWCC to include in the analysis of the slopes under rainfall conditions.

2 Objectives of the Study

It can be noted from the literature that very few studies investigated the significance of wetting SWCC in the design of slopes. The studies pertaining to wetting-induced slope failures are scarce. Therefore, the impact of drying and wetting cycles on the real case study of rainfall-induced slope failures is attempted in the present study. The following are the main aims of this study: (1) To highlight the influence of drying and wetting cycles on critical slip surfaces and the stability of the Idukki slope. (2) To study the influence of the rainfall intensity on the Idukki slope.

3 Site Geology

Kerala experienced the worst-ever slope failures between the 1st of June and the 18th of August 2018 in its history since 1924. It is reported that during the same period Kerala received 2428.9 mm of rainfall, which is more than 42% of the normal

Fig. 1 Idukki slope failure (Nazlin and Hari [15])

average. Idukki, the worst-affected district, was devastated by 143 slope failures. Due to these slope failures, 10,500 hectares of agricultural land are affected, 49 fatalities are reported, 11 people are missing, 51 people are injured, 45 crores of agricultural loss, and 1050 houses are destroyed. One such major slope failure was reported on 9th August 2018 in the Idukki district which is presented in Fig. 1. The properties of Kerala slope geometry reported by Nazlin and Hari [15] are considered in the study. The MATLAB program developed by Basha et al. [16] is extended for rainfall-induced slope stability analysis. Figure 2 demonstrates the geometry of the Idukki slope. The height of the Idukki slope (H) = 10 m which is inclined at an angle of $\omega = 60°$ (refer to Fig. 2). The shear strength parameter values used in the analysis are considered from Nazlin and Hari [15]. The soil is clayey sand (SC) as per USCS classification. The height of the water table (H_w) is considered as 3.3 m below the toe of the slope.

3.1 Soil Properties

The present study uses the SWCC model proposed by van Genuchten [16] for the analysis which is given as.

$$\theta_w = \theta_r + \frac{\theta_s - \theta_r}{\left[1 + (\psi\alpha)^n\right]^{\left(1-\frac{1}{n}\right)}} \tag{1}$$

where ψ is the matric suction, α is the inverse of air entry value (AEV), and n represents the slope of SWCC, θ_r is the residual water content, θ_w represents the volumetric water content, and θ_s represents the saturated water content.

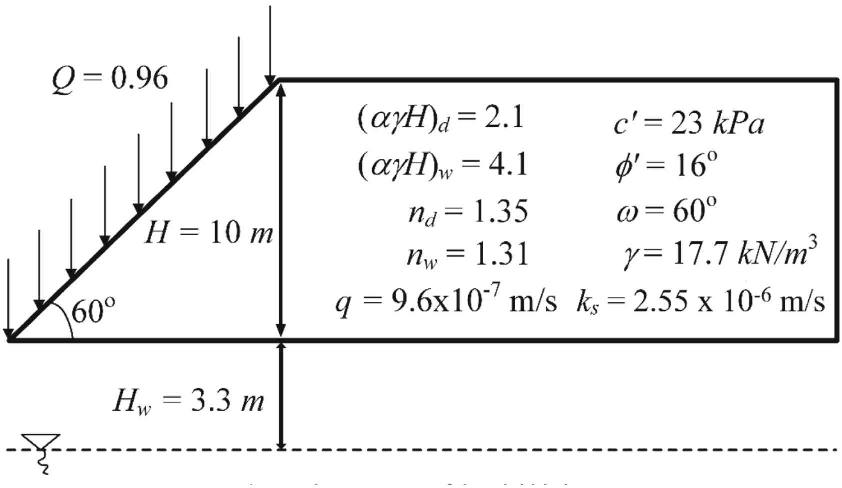

Fig. 2 The geometry of the Idukki slope

Table 1 Shear strength and hydraulic properties of the soils

Properties	Silty sand
dry unit weight (γ)	17.7 kN/m^3
internal angle of friction (ϕ')	16°
saturated hydraulic conductivity (k_s)	2.55 × 10^{-6} m/sec
Cohesion (c')	23.0 kPa

Table 1 presents the shear strength properties of the Idukki slope (Nazlin and Hari [15]). The values of α_d and n_d are not available. Therefore, α_d and n_d are considered as 0.012 kPa^{-1} and 1.35 respectively for clayey sand (SC). Raghuram et al. [14] proposed equations to estimate the fitting parameters of wetting SWCC from the fitting parameters of drying SWCC. These equations are used in the present analysis to obtain the fitting parameters of wetting SWCC. The parameters of wetting SWCC, α_w and n_w are 0.023 kPa^{-1} and 1.31 respectively. In the first stage, the Idukki slope has been analyzed for unsaturated conditions. In the later stage, various rainfall intensities are considered.

4 Factor of Safety of Slopes Under Rainfall Conditions

Force and moment equilibrium equations for the Morgenstern-Price method of slices proposed by Basha et al. [16] and Fredlund et al. [17] to estimate the factors of safety (FS_{MP}) of the finite slopes under saturated and unsaturated soils are employed in the present study. Lu and Griffiths [18] proposed an equation for estimating the suction stress under rainfall conditions which is given in Eq. (2).

$$\chi(u_a - u_w) = \frac{-\ln\left[\left(1 + \frac{q}{k_s}\right)e^{-\alpha\gamma_w z} - \frac{q}{k_s}\right]}{\alpha\left[1 + \left(-\ln\left[\left(1 + \frac{q}{k_s}\right)e^{-\alpha\gamma_w z} - \frac{q}{k_s}\right]\right)^n\right]^{\left(\frac{n-1}{n}\right)}} \quad (2)$$

where z = distance between the water table and the base of the slice under consideration, q = rainfall intensity, k_s = saturated hydraulic conductivity of the soil, and γ_w = unit weight of water.

5 Results and Discussion

The hysteresis of SWCC as shown in Fig. 3 shows that the drying curve is a portion of SWCC from initial saturation to residual saturation. On the other hand, a wetting curve starts from a residual condition and advances to a saturated state during wetting. Additionally, Fig. 4 shows that the difference in factor of safety (FS_{MP}) computed using drying and wetting cycles is significant.

It is reported that suction in wetting is always lesser than drying due to the contact angle effect (Raghuram et al. [11]). This is because the matric suction is

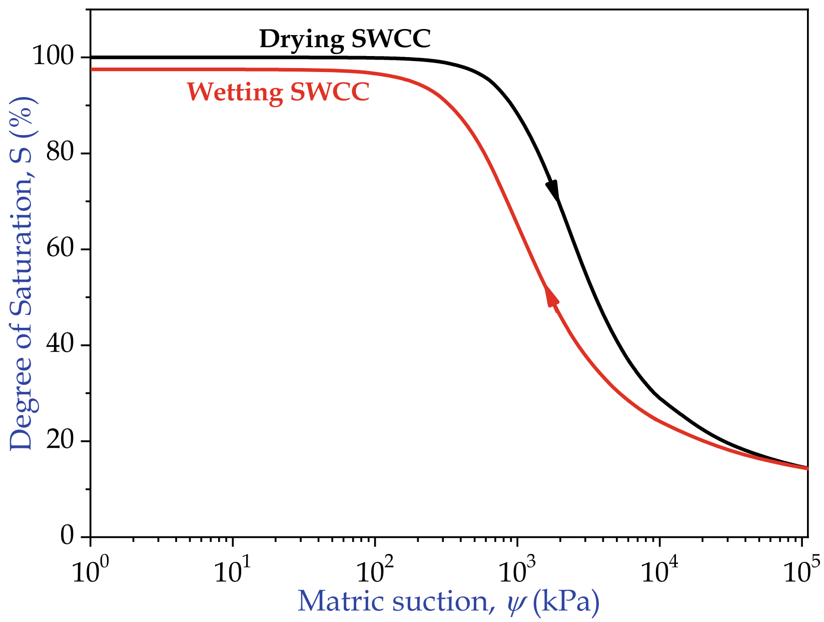

Fig. 3 Hysteretic soil water characteristic curve (SWCC)

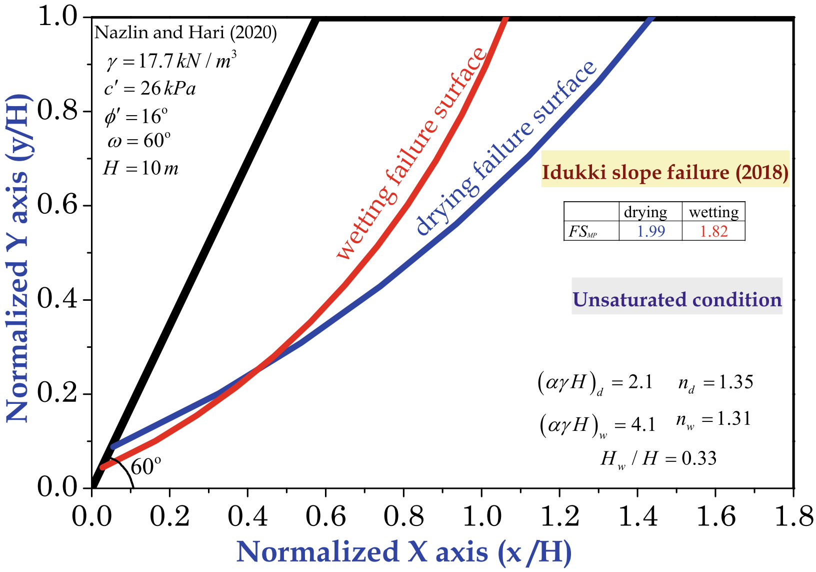

Fig. 4 The critical failure surfaces of the Idukki slope computed using drying and wetting SWCCs in unsaturated conditions

high in the case of drying SWCC when compared with wetting SWCC for a constant water content. Hence, the increase in shear strength contributed by matric suction is significant and has a considerable effect on the hysteretic SWCC.

For example, the factor of safety (FS_{MP}) computed using drying and wetting cases are 1.99 and 1.82 respectively. Further, it can be observed that there is a significant shift in the position of the slip surfaces for both drying and wetting cycles. The reason could be attributed to the drying curve offering more suction and thereby more resistance along the failure surface. Hence, the length of the failure surface is marginally more in the case of drying when compared to the wetting cycle.

5.1 Influence of Rainfall Intensity, Drying and Wetting Cycles on Factor of Safety

The normalized rainfall intensity (Q) (i.e. $= q/k_s$) is varied from 0 to 1.0 in the present study. Figure 5 demonstrates the influence of wetting and drying cycles on the factor of safety (FS_{MP}) of the Idukki slope under rainfall conditions. Figure 5 also shows that there is a significant difference in the factors of safety (FS_{MP}) estimated using drying and wetting SWCCs under rainfall conditions. Figure 5 depicts that the factors of safety (FS_{MP}) reduced significantly from 1.99 to 1.11 and 1.82 to 1.11 in drying and wetting cases respectively.

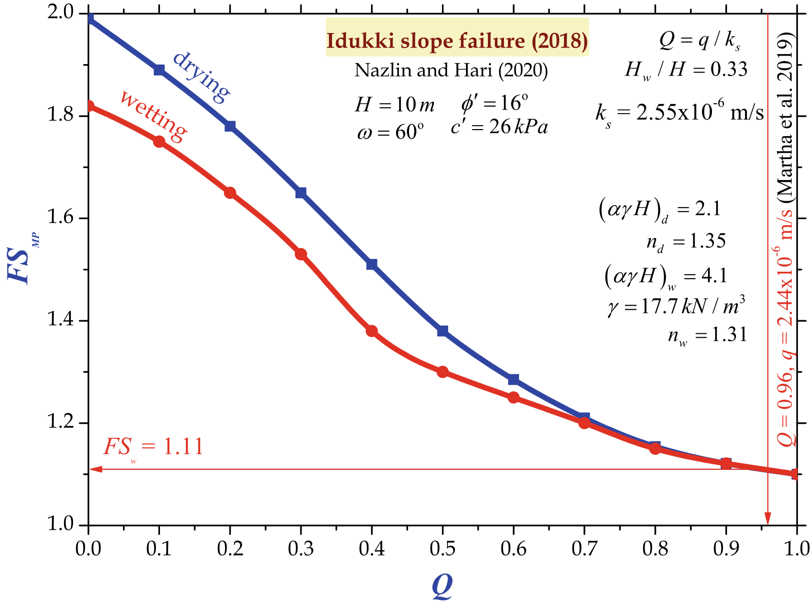

Fig. 5 Influence of rainfall intensity on FS_{MP} of Idukki slope for drying and wetting cycles

Furthermore, it is noted that the factor of safety (FS_{MP}) computed using drying and wetting cycles is negligible when $Q > 0.7$. This can be attributed to most of the soil pores being occupied with water during the high-intensity rainfall and therefore reducing the matric suction in the soil. Hence, at high intensity rainfall, both drying and wetting factors of safety (FS_{MP}) are the same. Figure 5 shows that at the time of failure, the normalized rainfall intensity (Q) is 0.96 and the factors of safety (FS_{MP}) are 1.11 and 1.11 in drying and wetting cycles which is less than the allowable factor of safety of 1.5 as per the IS 14342 code [19]. It indicates that the Idukki slope was not stable. An important observation that can be made from Fig. 5 is that the Idukki slope could have been stable as the factor of safety (FS_{MP}) $\geq$ 1.5 for the rainfall intensity (Q) $\leq$ 0.3 as per the IS 14342 code.

5.2 Drying and Wetting Cycles Influence on Critical Failure Surface at the Time of Failure

Figure 6 shows the effect of wetting and drying cycles on the critical failure surface at the failure for the Idukki slope under rainfall conditions. The results presented in Fig. 6 show that the critical failure surfaces are almost the same for drying and wetting cycles at the time of Idukki slope failure due to high-intensity rainfall. Matric

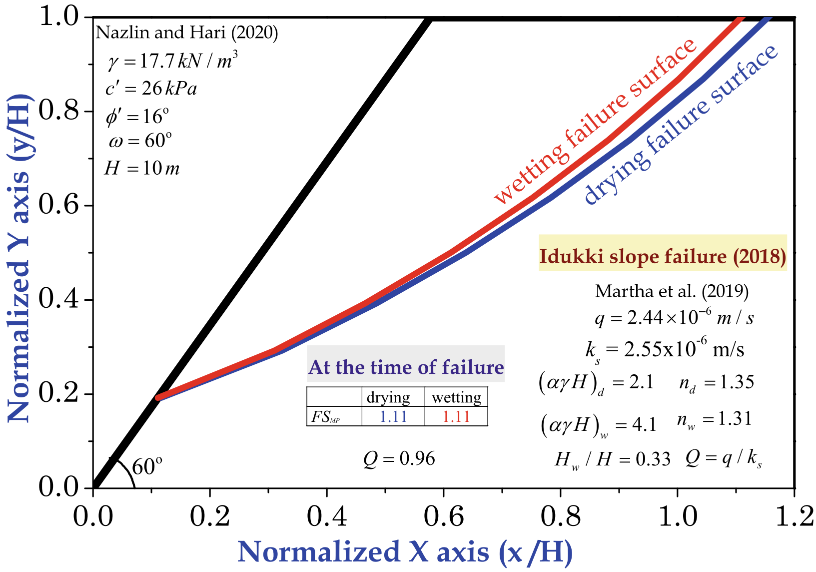

Fig. 6 The critical failure surfaces of the Idukki slope were computed using drying and wetting SWCCs at the time of failure

suction in the soil disappears during high-intensity rainfall and therefore, similar failure surfaces can be expected during wetting and drying cycles.

6 Conclusions

The current study emphasized the importance of considering wetting SWCC for slope stability analysis under rainfall conditions. The major conclusions are summarized below:

- The Idukki slope is stable in unsaturated conditions as the factor of safety (FS_{MP}) is very high in both wetting and drying cycles.
- A considerable difference in the factor of safety (FS_{MP}) is observed when it is estimated using drying and wetting SWCCs under various rainfall intensities.
- It is observed that the factors of safety (FS_{MP}) obtained from both drying and wetting SWCCs give the same factor of safety when the rainfall intensity is $Q >$ 0.7. This could be attributed to all the soil pores being occupied with water under heavy rainfall conditions.
- The factor of safety during the time of failure in drying and wetting cases are 1.11 and 1.11 respectively for $Q = 0.96$.
- It is noted that the Idukki slope could have been stable for the rainfall intensity (Q) ≤ 0.3 as the factor of safety (FS_{MP}) ≥ 1.5 as per IS 14342 code

The analysis results revealed that due consideration must be given to wetting SWCC and the rainfall intensity while designing the slopes under rainfall conditions.

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Effectiveness of Methylene Blue Value Test to Assess the Modification in Calcium Carbide Residue Treated Clayey Subgrade Soil

A. G. Sharanya, M. Heeralal, and T. Thyagaraj

Abstract The methylene blue value (MBV) test was used to determine the effectiveness of calcium carbide residue (CCR) in imparting short-term clay soil modification and to determine the percentage of CCR required to achieve optimum flocculation. The MBV of both untreated and treated clay mixed with different percentages of CCR (6, 9, and 12%) are compared. The results show the MBV gradual reduction with an increase in CCR content and reached a flex point at 9% CCR inclusion. The MBV reduced from 2.33 g/100g for untreated clay to 0.75 g/100g for 9% CCR-treated clay and remained constant with a further increase of CCR to 12%. This MBV can be used to determine the susceptibility of clay to effective modification, track the surface area transition of soil particles, and quantify the amount of CCR required for short-term modification. The chemical evolution of the soil was confirmed using the results of X-ray powder diffraction (XRD), and infrared spectroscopy (IR). The micro-level analysis affirms the cation-exchange reaction and flocculation of clay due to the reactivity of CCR. The MBV analysis along with pH value is recommended as an efficacious preliminary test to confirm the flex value of CCR required for immediate reactivity with clay.

Keywords Clayey soil · Subgrade · Calcium carbide residue · Mineralogical study · Methylene blue value

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1 Introduction

The interaction between water and geomaterial is a key factor in determining how they behave. Alternative calcium-based additives as a replacement for conventional lime in the stabilization of expansive subgrade soils have been the subject of interesting research. Calcium carbide residue (CCR) obtained from acetylene gas production is one such promising waste product that has recently gained attention [1–3].

The efficiency of CCR to reduce the specific surface area (SSA) of the natural soil, thereby reducing the cation exchange capacity, determines the immediate reactivity and solubility of CCR powder with water and natural soil. Because of the additive's immediate reactivity with the soil, the expansive soil's workability and plasticity are altered [4]. The first step in determining this immediate reactivity is to determine the pH of the soil-additive mix using Eades and Grim test procedures [5]. The user will be aided in determining the initial consumption value beyond which the strength properties of soil can be altered with time by analyzing the soil transition from acidic to alkaline phase with varying percentages of CCR. The determination of the pH increase of the soil-additive mix can be utilized as a first-hand result, but a lingering phase of varying percentages of additives will reveal a nonlinear trend in changing the plasticity and unit weight properties. Thus, an uncertain determination of the optimum additive content is expected.

This study will discuss majorly the efficacy of MBV of the soil- additive to be used as an aid in characterizing the ability of CCR to alter the SSA using the French Standard AFNOR (1998) [6]. The results of this study are further substantiated by the morphological and mineralogical studies to characterize the variation in the mineralogy and the chemical bond of the treated soil.

2 Materials

Clay soil collected from Warangal, Telangana, India, was classified according to IS 2720 procedures. The index properties and grain size distribution indicate the soil used in this study is highly compressible clay. The soil selected for the study was confirmed with the clay content and mineralogical composition to ensure reactivity with CCR. The soil was mixed with varying percentages of CCR (6%, 9%, and 12%) to form 3 mixtures identified by adding the acronym to the natural soil as CH6R, CH9R, and CH12R. In this paper, the untreated soil will be referred to as CH.

3 Methodology

3.1 Eades and Grim Test

Eades and Grim test procedures were used to determine the pH value of both untreated and additive-added soil mix. The samples at the required composition were mixed with deionized water and allowed constant mixing using a magnetic stirrer. The soil-CCR mix was allowed to mix continuously for 24 h to ensure the complete solubility of the additive in water. The test identified the minimum dose of CCR required to initiate the immediate reactivity phase such that the pH increased to 10 or more. The limit of pH increase was bound to 12.4 according to the conventional practice for lime.

3.2 Methylene Blue Value

AFNOR's procedure was used to determine the (MBV) of both untreated and treated samples (1998). The spot test procedure was adopted. The tests were carried out at a room temperature of 28 ± 2°C, with duplicate MBV determination trials for each sample to eliminate any immature results. The test is based on cation interactions between clayey minerals and the cations released by methylene blue throughout its dissolution in water. The test was performed following the spot test procedure for which 60 gm of clayey soil passing through a 425 mm IS sieve was used. The methylene blue powder was prepared as a solution with 10g/liter of distilled water. The soil solution was mixed with the MB solution and mixed for about 10 min. The aliquot of the mix was placed on Whatman No. 42 filter paper to assess the formation of a blue halo around the drop. The combination at which the halo is stable for about 5 min for a trial of 3 is selected as the methylene blue value of the clay-CCR mix solution.

3.3 X-Ray Diffraction Analysis

X-ray diffractograms of powdered samples were obtained using a PANalytical X'Pert diffractometer with CuKα radiation and the diffraction peaks were obtained for Bragg's angle of 6° -70°. The chemical progress of the samples with various percentages of CCR was identified using the ICDD database.