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Time-dependent crack analysis of lime and nano-treated expansive soil using image processing technique

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Abstract:
Crack formation in soil samples due to environmental factors such as chemical exposure has critical implications for geotechnical engineering and environmental applications. Especially in weak soil, when stabilised with chemicals, crack formation is evident, as the failure is brittle. This paper presents a comprehensive investigation into the quantification and analysis of cracks formed in chemically modified soil samples subjected to six distinct combinations. The chemicals used in the study are lime at its initial lime consumption level and nano-alumina under two different water contents (liquid limit and optimum moisture content). The cracks are captured at an interval of 0, 3, 7, and 21 days. The primary objective is to understand and evaluate the effectiveness of crack formation and to explore various techniques for detecting cracks. Digital image processing techniques, such as edge detection and boundary analysis for characterising crack morphology, density, and length of the crack, are proposed. Experimental findings highlight significant variations in crack patterns across the tested environments. The integration of pre-processing techniques with Canny edge detection and contour-based analysis proved effective in automating image-based crack characterisation and enabling precise quantitative assessment. The study proposes an optimised parameter tuning framework for enhancing detection accuracy, thereby contributing to a deeper understanding of crack formation mechanisms under certain conditions.

Keywords:
expansive soil; nano material; curing; image processing; crack width; cod formation

1. Introduction

The expansive soil faces outlash through its swell-shrink behaviour apart from bearing and settlement issues. This type of soil is mostly chemically stabilised through lime to improve its capacity and settlement characteristics. One such popular chemical is lime; when lime is mixed with soil, the soil's engineering properties are modified and improved [1-5]. This not only improves the strength and durability but also the Atterberg's limit of the soil. The main issues with chemical stabilisation concern crack formation and permeability characteristics. The addition of lime leads to the immediate formation of a cluster of clay particles due to agglomeration [6], as well as platy minerals, which increase the clay's micropores. When considering the soil's durability behaviour, crack formation is predominant during the drying period, due to reduced water content. This is associated with the volumetric shrinkage of the soil medium. This leads to crack formation when the volumetric shrinkage reaches the threshold value [7]. The initial orientation of the crack is in the perpendicular direction to the maximum stress followed by reaching the crack to the edge [8]. This is related to the tensile strength of the soil; the crack began to form when the generated tensile stress exceeded that of the soil [9,10]. It is also observed that the water content is almost equal to the fully saturated condition near the initiation of cracks; this further decreases when evaporation starts (Fig. 1). This can be minimised by using nanoparticles because of their surface area. The most common nanomaterials used in soil stabilisation are nano silica [11], nano copper [12], nano alumina [2,13] and nano carbon [14]. The inclusion of nanoparticles increases the density of the soil and improves its permeability characteristics. As the percentage of nanomaterial included for stabilisation requires a minimal quantity, it becomes the most sorted stabilizer in the current scenario.

The crack study helps in understanding soil degradation, provides more information about the complexity of cracks, and is associated with area density [15]. Generally, the occurrence of a crack is in the direction perpendicular to the maximum stress [8]. The crack pattern is classified into various categories with respect to their development: 1. Feeble, 2. Slight, 3. Medium, 4. Intensive and 5. Extremely intensive. The formation of cracks depends upon water content. From the development of cracks, the interior of the prepared sample can be studied [16]. The main factors affecting crack formation are particle size and mineralogical composition [17].

In recent years, considering the importance of desiccated cracks formed in the soil medium, image processing is widely used to understand the surface cracks through 2D and 3D in terms of geometrical and topological conditions. This paved the way for geotechnical engineers to access the properties, directly or indirectly. Image processing also helps study crack patterns and volume changes.

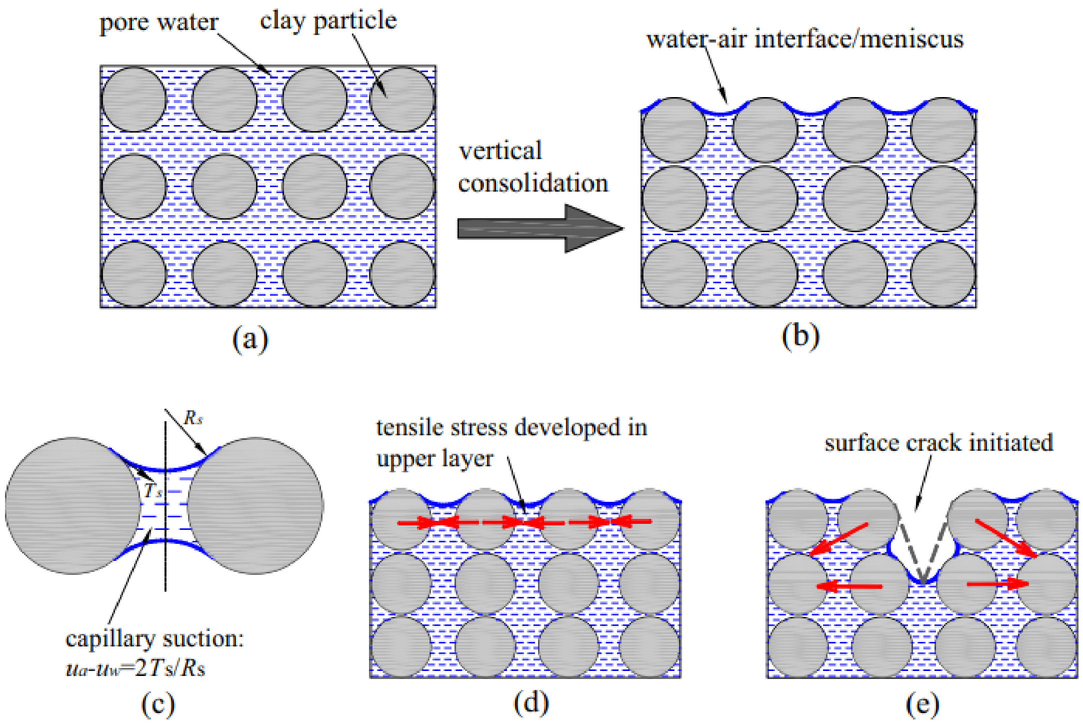

Fig. 1. Formation of a crack [7], a) Fully saturated condition – Initial state, b) Water-air interface/meniscus, c) Capillary suction, d) Developed tensile stress, e) Formation of surface crack

The main objective of this manuscript is to understand the formation of cracks when the lime and a nanomaterial are used to stabilise expansive soil. In addition, this paper presents a comparative analysis of the strengths and limitations of each image-based crack characterisation method in terms of accuracy, efficiency, and the ability to capture intricate crack features. Techniques such as thresholding, morphological filtering, and edge detection are employed to isolate crack features from complex backgrounds. Image processing enables objective quantification of crack geometry, which is otherwise difficult to measure manually in field conditions.

Each day (1, 3, 7, 14, and 21 days) of the experiment involved capturing images of the soil samples subjected to the six different combinations. Notably, the images presented unique challenges due to variations in intensity and size across days. This variability stemmed from factors such as lighting conditions, sample positioning, and potential chemical reactions between the soil and the chemical combinations. The dynamic nature of the images demanded an adaptive approach to accurate image-based crack characterisation. The challenge of intensity and size variations necessitated careful pre-processing and algorithm parameter optimisation to ensure robust and consistent image-based crack characterisation across the dataset.

The findings of this study contribute to a deeper understanding of crack formation in soil samples exposed to lime and nanomaterial and offer insights into selecting appropriate image-based crack characterisation methods based on specific research or engineering goals.

2. Materials and methods

2.1. Sample preparation and testing

The soil clay is collected from the riverbed of Thaiyur Lake in Kelambakkam, India. The soil is oven-dried and tested to assess its index properties in accordance with Bureau of Indian Standards codes [18-21]. The soil has a liquid limit of 75.8%, a plastic limit of 23.5%, a shrinkage limit of 11.2%, and a specific gravity of 2.76. The percentages of clay, silt, sand and gravel in the sample are 68.7%, 28.4%, and 2.9%, respectively, with an optimum moisture content of 28.2% and a maximum dry density of 13.09 kN/m^3.

The sample is prepared for two water contents. The water content adopted is the liquid limit (75.8%) and the optimum water content (28.2%). The water content is chosen, taking into account the soil's liquid condition (liquid limit) and stiff condition (optimum water content). The liquid limit and optimum moisture content were selected to represent critical swelling and field-compaction conditions in expansive soil. The relative humidity of the atmosphere during the experimental study is around 75%. The format for preparing the same is to paste the soil into a transparent plate with a diameter of 10 cm with a thickness not more than 1.5 mm. It is stated in the previous literature that the crack is evident in a thinner soil sample [10].

The soil from the field is transported into the laboratory, air-dried, and relevant tests are conducted. Three combinations are considered: 1. Virgin soil, 2. clay soil + lime, where lime is mixed at the initial lime consumption (ICL) and 3. Clay + ICL + optimum percentage of nano alumina. The ICL percentage, determined using the Eades and Grim pH procedure [22], is 4.5%. The optimum percentage of nano Alumina found for the given soil is 0.5% along with ICL by unconfined compressive strength tests [2,3,13,23]. The detailed parametric study is shown in Table 1

The increase in the strength of soil with low shear strength, with initial lime consumption and nano alumina, is due to mechanisms such as flocculation-agglomeration and pozzolanic reactions, which influence soil strength [24]. Clay particles (expansive soil) undergo a reduction in diffuse double layer, leading to an increase in strength.

Table 1. Parametric study

Sample	Combination	Water Content	Notation
Circular paste	Virgin Clay	Liquid Limit	C1CL
		Optimum Moisture Content	C1CO
	Clay +ICL	Liquid Limit	C2CL
		Optimum Moisture Content	C2CO
	Clay +ICL + Nano	Liquid Limit	C3CL
		Optimum Moisture Content	C3CO

3. Image processing methodology

Effective image-based crack characterisation in soil samples relies heavily on the quality of image pre-processing techniques [23,24]. Pre-processing is a critical initial step that prepares images for further analysis by enhancing relevant features. Given the complexity and variability in soil surface textures and lighting conditions, robust pre-processing is essential to ensure accurate and consistent crack identification. The approach adopted in this study integrates a sequence of techniques designed to improve crack visibility and enable reliable edge detection.

3.1. Image pre-processing

The image-based crack characterisation methods analysed in this study include visual inspection, image processing, edge detection, erosion, and dilation. Each method was evaluated for its effectiveness in capturing crack morphology, measuring crack density, and determining end-to-end crack length distribution. While visual inspection provided a preliminary indication of the presence of cracks, it lacked precision in quantifying their characteristics. In contrast, digital image processing techniques showed strong potential by enabling automated detection and facilitating accurate quantitative analysis. Figure 2 illustrates the soil sample images at 1, 3, 7, and 21 days, as well as the pre-processing steps for image analysis. The pre-processing step involves converting the image to grayscale, making it suitable for morphological erosion. This grayscale image is then processed using erosion, which enhances crack visibility by reducing surrounding features and emphasising the crack regions, resulting in clearer identification of crack patterns. Canny edge detection with default parameters is applied to the eroded grayscale image to detect crack edges accurately. This step enhances the precision of crack boundary detection by focusing on the most significant intensity gradients in the image.

With respect to the total area of the soil sample images, the crack density is the proportion of crack pixels distributed. This crack density is useful for finding the severity and spatial distribution of cracks within the soil surface.

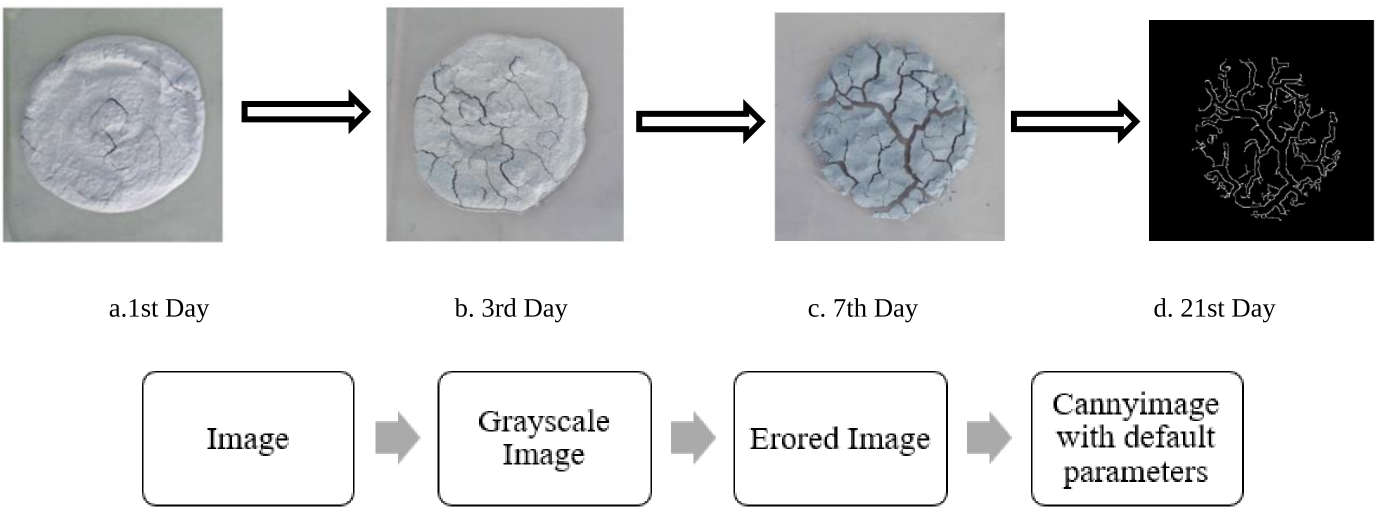

Fig. 2. Image taken on various days and Pre-Processing of soil sample image before crack analysis

3.2. Crack analysis

The edges extracted using Canny edge detection with default parameters serve as input for contour detection to identify crack boundaries. To improve accuracy, a Canny threshold tuning algorithm is applied, optimising the parameters for more precise crack analysis based on the tuned settings. The crack analysis process is shown in Fig. 3. Contour finding is a fundamental technique used in image analysis for delineating boundaries in digital images. It finds applications in computer vision and image processing. In this paper, we propose contour finding as an appropriate methodology for finding the cracks present in the soil samples. This method detects and traces continuous curves that define the perimeters of objects or areas of interest. For the soil samples, this represents the edges of the cracks present in the soil images. The method provides a precise means of assessing the crack density and morphology. When combined with appropriate parameter tuning and image pre-processing, contour detection offers valuable insights into how chemical exposure affects soil integrity. The analysis study includes the observation of the longest end-end crack length, width of the crack, number of clods, area of the clods and area of the crack. These parameters provide a comprehensive characterisation of the crack patterns for further assessment.

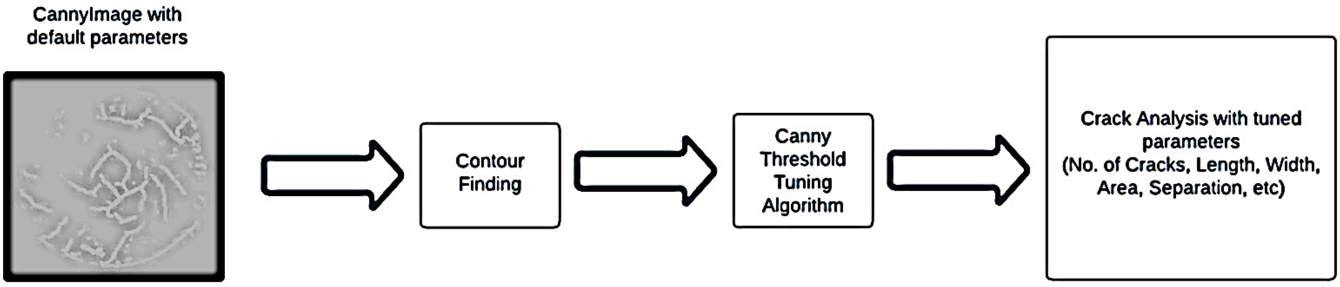

Fig. 3. Sequential flow of processes for crack analysis

3.3. Optimal parameter selection

Accurate detection and quantification of cracks in soil samples exposed to alkaline solutions are crucial for understanding the structural implications of chemical exposure on soil integrity. In this section, we present an approach for optimising the hyperparameters of an image-based crack characterisation algorithm to ensure robust and reliable crack analysis. The proposed approach aims to achieve the best possible configurations to tackle images of varying intensities. It involves the utilisation of the Canny edge detection-based image-based crack characterisation algorithm. The algorithm's performance is influenced by several hyperparameters, including the low and high thresholds for edge detection and the minimum contour area for filtering detected contours. To determine the optimal combination of these hyperparameters, we devised an iterative optimisation strategy.

Three sets of candidate values are established for each hyperparameter are:

- canny_low_thresholds,
- canny_high_thresholds, and
- min_contour_areas.

For each set of input images capturing a soil sample under alkaline exposure, an iterative search is conducted to determine the hyperparameters that yield the most accurate image-based crack characterisation results. This is achieved by minimising the discrepancy between the detected and expected crack counts. The expected crack count is obtained from pre-established mean crack counts for each alkaline solution. The combination that yields the minimum difference is selected as the best set of hyperparameters. This accumulated set of hyperparameters represents a comprehensive configuration that maximises the algorithm's performance across a range of images. With the accumulated optimal hyperparameters, the image-based crack characterisation algorithm is applied to each image capturing soil samples exposed to alkaline solutions. The algorithm's output is the count of detected cracks in the image. Algorithm 1 illustrates the process for tuning the hyperparameters of the Canny edge detection method.

Under controlled experimental conditions, the objective of our proposed work is to automate crack identification with qualitative visual assessment. During pre-processing, for noise removal, a Gaussian filter with kernel size 5 x 5 and $\sigma = 1.2$ is used. During adaptive thresholding, a block size of 11 and for morphological opening, 3 x 3 structuring elements were used. In Canny detection, used for image-based crack characterisation, a lower threshold of 50 and an upper threshold of 150 were set. The validation was done by comparing with other image-based crack characterisation algorithms, such as finding the connected components and Hough transform.

Algorithm 1: Hyperparameter Tuning for Canny Edge Detection

```
Result: All best hyperparameter sets for each day of images taken
for i in range(20) do
    min_diff = ∞;
    for low_thresh in canny_low_thresholds do
        for high_thresh in canny_high_thresholds do
            for min_area in min_contour_areas do
                diff = 0;
                for solution in range(6) do
                    Load the image;
                    Apply the count_cracks function to the image with low_thresh,
                     high_thresh, and min_area, and store the result in crack_count;
                    Update diff by adding the absolute difference between crack_count
                     and means[solution];
                end
                if diff < min_diff then
                    best_params = [low_thresh, high_thresh, min_area];
                    min_diff = diff;
                end
            end
        end
    end
    Append best_params to all_best_params;
end
```

4. Various other methodologies

4.1. Connected components analysis

In this method, each grayscale image capturing the state of the soil samples was first subjected to pre-processing steps. Specifically, the images were converted to binary images. Morphological operations, such as erosion, were applied to remove noise and enhance the clarity of crack features. Once the binary images were prepared, the connected components analysis method was employed. This method identifies and labels distinct connected regions within the binary image. In the context of image-based crack characterisation, each labelled component corresponds to a potential crack. The number of detected connected components (labels) in the image directly corresponds to the number of cracks present. Connected components analysis can merge closely spaced or overlapping cracks into a single region, leading to an underestimation of the actual number of cracks.

4.2. Hough transform and edge detection

In this section, we introduce an image-based crack characterisation methodology based on the Hough transform and edge detection techniques. Each image capturing the state of soil samples was subjected to pre-processing operations. Specifically, the image was converted to grayscale to simplify processing. The Canny edge detection algorithm was employed to highlight significant intensity gradients within the grayscale image. This produced a binary edge map where potential cracks are accentuated as high-contrast edges. The Hough line transform, a well-established technique in image analysis, was applied to the edge-detected image. This method identifies lines in the image space that correspond to linear features. In the context of image-based crack characterisation, linear features indicate potential cracks in soil samples. The number of detected lines by the Hough transform directly corresponds to the number of potential cracks. The algorithm counts the lines and treats them as indicative of cracks, thereby estimating the crack count within the image. Also, the method generates false positives by detecting non-crack linear features, such as texture patterns or shadows, leading to inaccurate crack counts.

5. Analysis and discussion

The analysis study includes observation of the longest end-end crack length, width of the crack, number of clods, area of the clods and area of the crack. The results discussed indicate relative morphological changes and crack progression over time for various combinations. The data is extracted continuously from the very next day of the test results and continues for 21 days. For the convenience of understanding, most of the data are presented for the 1, 3, 7, 14, and 21 days.

5.1. Influence of water content and additives in propagation of cracks – length and width

The major observation in this study begins by comparing the modified soil behaviour at the liquid limit and the optimum moisture content when exposed to various temperatures. The soil is kept on an open surface, and the temperature varies between 32 and 41°C as the test is conducted between April and May. In the current study, the water content at the liquid limit is 75.8%, and at the optimum moisture content, it is 28.2%. The formation of cracks is fast at lower water content, i.e., at optimum moisture content. The longest crack observed at 1 day of exposure is high in modified soil, which has both lime and nano Alumina. The crack started to propagate from the ends and further progressed. With a greater number of days of exposure, the length of the crack rose to a maximum length of 962 mm. When comparing the increase in rate of crack propagation, virgin soil at the liquid limit is much faster, next to it is the virgin soil with optimum moisture content. This further decreases with the addition of additives. The lime inclusion, however, increases the formation of cracks in both the water content. With the further addition of nano, the length of the crack further decreases (Fig. 4).

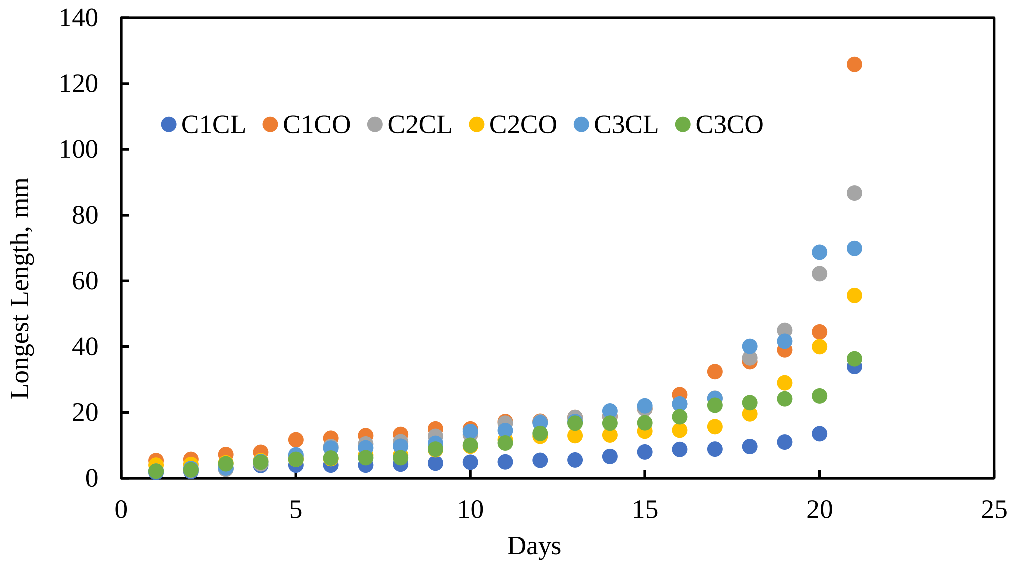

Fig. 4. Influence of water content and additives on crack length (end-end)

The width of the crack in the initial days is very small, and it is almost negligible. With an increase in the number of days, the width of the crack can be seen with the naked eye. However, most of the initial day cracks did not reach the bottom of the sample, and they were surface cracks. The cracks were prominently seen after 7 days of observation. The width of the crack without any additives (C1CL and C1CO) is 0.23 and 0.83 mm at 1 day of exposure; under similar conditions, the crack width increased to

11.9 mm and 16.8 mm after 21 days of exposure. Under the same conditions, if lime at its initial condition is added, the crack pattern widens faster. At 1 day, the widths of the cracks for conditions C2CL and C2CO are 1.02 and 1.41 mm, respectively, and at the end of the test, they widened up to 17.76 and 18.6 mm. The nano is added at its optimum condition to the soil, and there occurs a reaction where the lime becomes more active and consumes more water along with the nano Alumina combination (Fig. 5).

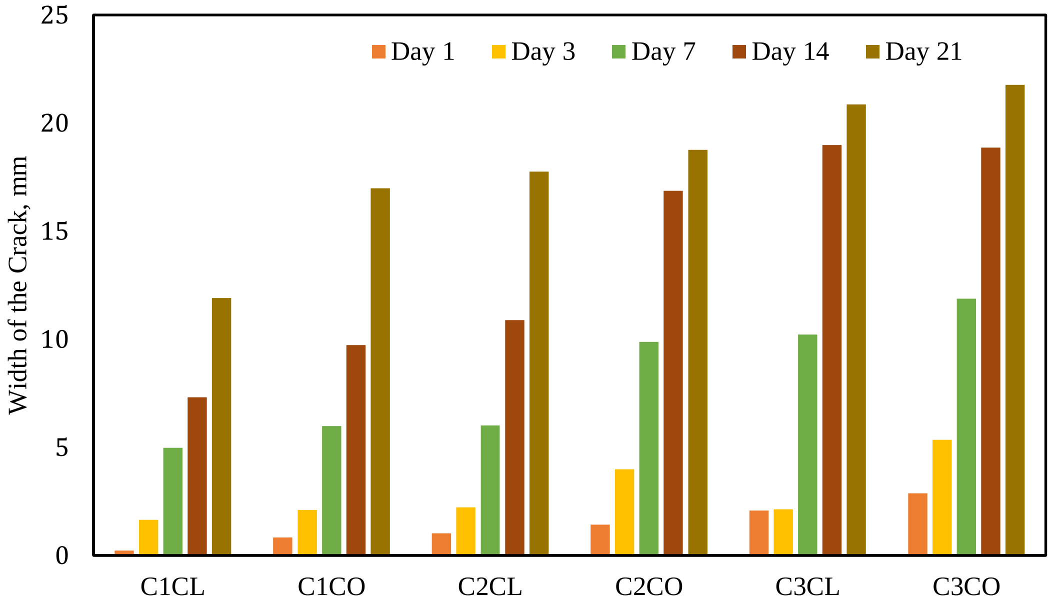

Fig. 5. Influence of water content and additives on crack width

5.2. Formation of clods

At the beginning of the tests, as the width of the crack didn't develop, the entire 10 cm sample almost remained the same. After 7 days, there is a distinct visibility of clod formation. Soil morphological features help in understanding crack formation. At 1, 3, 7, 14 and 21 days, the number of clods formed is 1, 2, 26, 187, and 232 for the C1CL combination. For the C1CO combination, the number of clods is 1, 4, 39, 199 and 287, respectively, for similar day intervals. The number of clods formed is more with a combination of lime and nano with the clay at optimum water content. The addition of additives increases the rate of clod formation, providing an indicator of the reaction. The maximum number of clods formed in C3CO for days 1, 3, 7, 14 and 21 is 1, 8, 98, 298 and 365, respectively (Fig. 6).

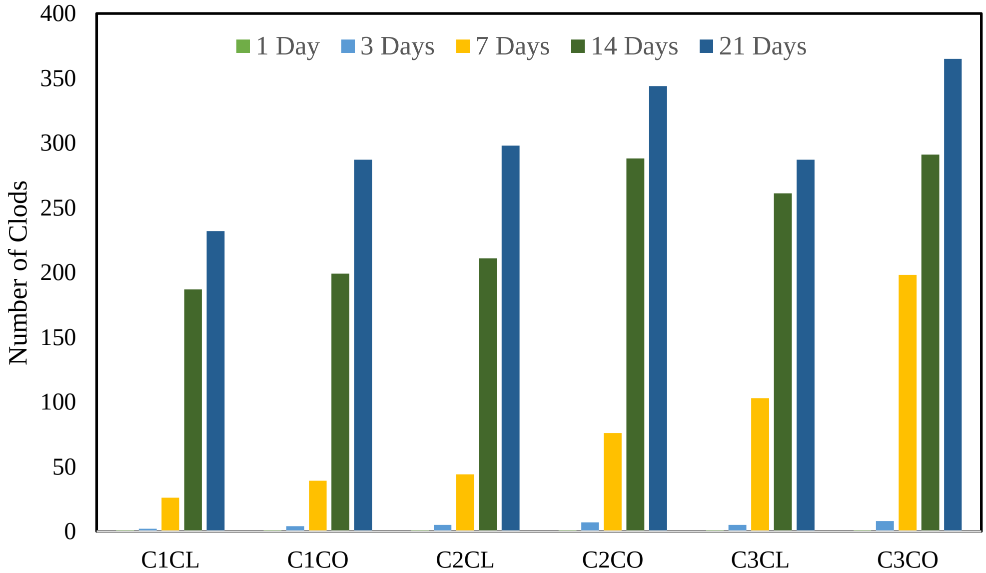

Fig. 6. Influence of water content and additives in the formation of clods

5.3. Intensity of combination in the area of clods

The area of the crack is calculated as the combination of the width and length of the crack. The area of the clod is calculated as the surface area of the clod captured through the image. The area of the clods and crack pattern is similar.

The crack area is less for C1CL, C1CO, C2CL, and C2CO combinations, and the crack area was more pronounced in the soil treated with initial lime consumption (ICL) and the optimum nano-alumina content, reaching 22.77 mm² and 37.95 mm², respectively. The area of the crack increases from the 3rd day, and the growth rate in the crack area is high for virgin soil and soil with lime, whereas the rate of increase decreases with nano addition. As the days increase, the crack area ratio (modified soil crack area on the particular day to the 1st day of the same combination) increases, and the rate of growth is not so significant after 14 days. After 21 days, almost the entire chunk of the sample was in a crumbled state.

The area of clods shows a gradual increase for the combinations C1CL, C1CO, C2CL, C2CO, and C3CL; there is a large jump in clod formation at C3CO. Agglomeration contributes to the rapid formation of pods. With the addition of additives, the soil becomes more brittle, leading to crack formation, which leads to clods due to the development of tensile strength (Fig. 7).

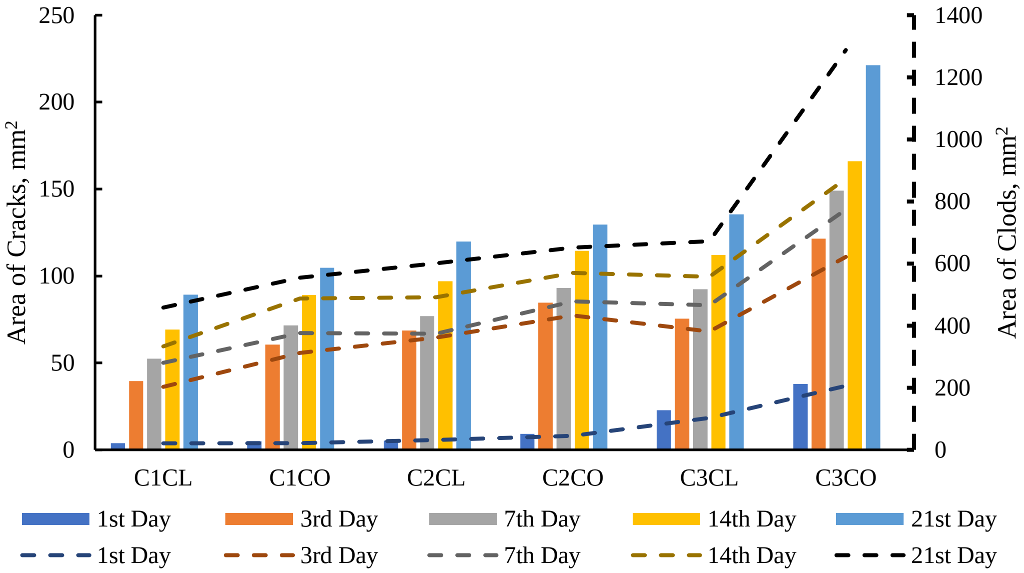

Fig. 7. Area of crack and clods

6. Conclusions

In this study, the crack patterns of expansive soil treated with initial lime consumption (4.5%) and optimum nano content (0.5%) were thoroughly investigated. Soil samples spread over a 10 cm diameter glass plate were analysed to measure crack width, length, area, and clod formation. The limitations associated with irregular crack geometries and image-based interpretation have also been acknowledged. The application of an optimised image-based crack characterisation algorithm centred on Canny edge detection with iterative hyperparameter tuning and efficient contour finding provided valuable and accurate insights into crack distribution and density across soil samples exposed to various alkaline solutions. This combination of techniques significantly enhanced the robustness and accuracy of crack identification, enabling detailed quantification critical to assessing the impact of chemical exposure on soil structural integrity.

The results revealed that crack width and length became most prominent after 7 days of testing, with a similar pattern observed in clod formation. Rapid crack propagation was attributed to flocculation of soil particles, whereas the addition of lime and nanoparticles increased soil brittleness. However, the study of shrinkage properties was limited by the onset of clod formation from the soil sample boundaries. Overall, the integration of Canny edge detection with hyperparameter optimisation and contour analysis proved to be a powerful methodology for understanding crack morphology and soil behaviour under chemical treatment, offering a reliable tool for future geotechnical assessments.

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References

[1] Okeke C., Appropriate use of lime in the study of the physicochemical behaviour of stabilised lateritic soil under continuous water ingress, *Sustainability* 13(1) (2021) 1–26. https://doi.org/10.3390/su13010257

[2] James J., Sivapriya S.V., Ali S., Madhu T.R., Singh B., Wetting and Drying Resistance of Lime-Stabilized Expansive Soils Modified With Nano-Alumina, *Advances in Civil and Architectural Engineering* 12(22) (2021) 70–80. https://ojs.srce.hr/acae/article/view/20080

[3] James J., Vijayasimhan S., Eyo E., Stress-Strain Characteristics and Mineralogy of an Expansive Soil Stabilized Using Lime and Phosphogypsum, *Applied Sciences* 13(1) (2023) 10123. https://doi.org/10.3390/app13010123

[4] Sendilvadivelu A., Dhandapani B., Vijayasimhan S., Strength, mineralogical and microstructural studies on clayey soil stabilized by bio-stabilized waste ash with lime, *Journal of Material Cycles and Waste Management* 25(6) (2023) 3625–3637. https://doi.org/10.1007/s10163-023-01782-w

[5] Firmansyah D.A., Somantri A.K., Sihombing A.V.R., Mase L.Z., Sundara A., Mechanical properties of soft clay soil improved with nanomaterials and chitosan biopolymer, *Geotechnical Engineering Journal of the SEAGS & AGSSEA* 55(2) (2024) 31–37.

[6] Choquette M., Bérubé M.A., Locat J., Mineralogical and microtextural changes associated with lime stabilization of marine clays from eastern Canada, *Applied Clay Science* 2(3) (1987) 1–49.

[7] Tang C.S., Shi B., Liu C., Suo W.B., Gao L., Experimental characterization of shrinkage and desiccation cracking in thin clay layer, *Applied Clay Science* 52(1–2) (2011) 69–77. https://doi.org/10.1016/j.clay.2011.01.032

[8] Izzo M.Z., Miletić M., Desiccation Cracking Behavior of Sustainable and Environmentally Friendly Reinforced Cohesive Soils, *Polymers* 14(7) (2022) 1318. https://doi.org/10.3390/polym14071318

[9] Peron H., Hueckel T., Laloui L., Hu L.B., Fundamentals of desiccation cracking of fine-grained soils: Experimental

characterisation and mechanisms identification, *Canadian Geotechnical Journal* 46(10) (2009) 1177–1201. https://doi.org/10.1139/T09-054

[10] Landlin G., Bhuvaneshwari S., Analysis of Desiccation Crack Patterns of Expansive Soil Treated with Lignosulphonate and Lime, *Lecture Notes in Civil Engineering* 167 (2022) 327–338. https://doi.org/10.1007/978-981-16-3383-6_30

[11] Shahin S.S., Laila P., Fayed A.E., Review of Nano Additives in Stabilization of Soil, *7th International Conference on Nano-Technology in Construction* (2015) 1–11.

[12] Taha M.R., Muhie O., Taha E., Influence of nano-material on the expansive and shrinkage soil behavior, *Journal of Nanoparticle Research* 14 (2012) 1190. https://doi.org/10.1007/s11051-012-1190-0

[13] Sivapriya S.V., Ali S., Madhu T.R., Load–Penetration Behaviour of Composite Soil with Nano-Alumina Material Under Soaked and Unsoaked Condition, *Ground Characterization and Foundations*, *Lecture Notes in Civil Engineering* 167 (2021) 6–10. https://doi.org/10.1007/978-981-16-3383-6_23

[14] Morsy M.S., Alsayed S.H., Aqel M., Hybrid effect of carbon nanotube and nano-clay on physico-mechanical properties of cement mortar, *Construction and Building Materials* 25(1) (2011) 145–149. https://doi.org/10.1016/j.conbuildmat.2010.06.046

[15] Xiong D., Long Y., Yan D., Lu X., Ji Z., Fang H., Surface morphology of soil cracks in Yuanmou Dry-hot Valley Region, Southwest China, *Journal of Mountain Science* 6(4) (2009) 373–379. https://doi.org/10.1007/s11629-009-1059-6

[16] Chertkov V.Y., Using Surface Crack Spacing to Predict Crack Network Geometry in Swelling Soils, *Soil Science Society of America Journal* 64 (2000) 1918-1921. https://doi.org/10.2136/sssaj2000.6461918x

[17] Yesiller N., Miller C.J., Inci G., Yaldo K., Desiccation and cracking behavior of three compacted landfill liner soils, *Engineering Geology* 57(1–2) (2000) 105–121. https://doi.org/10.1016/S0013-7952(00)00022-3

[18] Bureau of Indian Standard, IS 2720 (Part V). *Determination of Liquid and Plastic Limit*, 1995, 1–17.

[19] Bureau of Indian Standards, IS 2720(Part III/2). *Determination of Specific Gravity for fine, medium and coarse grained soil*, vol. 2720, 1997, 1–10.

[20] Bureau of Indian Standard, IS 2720 (Part IV). *Methods of test for soil - Grain size analysis*, 1995, 1–40.

[21] Sridharan A., Sivapullaiah P., Mini Compaction Test Apparatus for Fine Grained Soils, *Geotechnical Testing Journal* 28(3) (2005) 240–246. https://doi.org/10.1520/GTJ12542

[22] Eades J.L., Grim R.E., A Quick Test to Determine Lime Requirements for Lime Stabilization, *Highway Research Record* 1 (1966) 61–72.

[23] Sivapriya V., Jijo J., Yuvaraj K., Sushritha G., Durability performance of a lime stabilized expansive soil with egg shell ash as a subsidiary admixture, *Građevinski Materijali i Konstrukcije* 65(2) (2022) 65–71. https://doi.org/10.5937/grmk2202065v

[24] Sakthivinayagam P., Vijayasimhan S., Muniappan T., Contribution of Nanosilica in Early Strength Enhancement of Lime Modified Clay of High Compressibility, *Iranian Journal of Science and Technology, Transactions of Civil Engineering* 50 (2025) 1897–1917. https://doi.org/10.1007/s40996-025-01912-4