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Analysis of Desiccation Crack Patterns of Expansive Soil Treated with Lignosulphonate and Lime

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Abstract. Expansive soils could be a problematic soil in construction industry as it exhibits volume change behaviour due to seasonal moisture changes. Chemical stabilization techniques are usually the most sought-after techniques to curtail the swell-shrink behaviour. The shrinkage behaviour of the expansive soil leads to a network of surface crack development which could progress in to deeper depths. Moreover, the development of cracks could be an important indicator of various physical phenomena of geotechnical importance. The propagation of cracks induces loss of bearing capacity and slope instability and interferes with the functionality of the buried utility systems. In this study, an attempt is made to study the crack patterns of the virgin and the treated expansive soil; to understand the difference in the development patterns and their relation to macroscale properties. In this study, 0.5%, 1.5%, 3% Lignosulphonate and 2%, 4% Lime were used as the chemical stabilisers. The additives amended soil samples for crack tests were laid on frictionless plates in circular shapes with the soil thickness of 3 mm and left to air dry in a constant temperature of 28°C. The crack patterns were analysed through Digital Image Analysis techniques and the crack parameters such as the crack length, crack width, crack intersections, crack segments and crack intensity factor were analysed. The treated soil depicts a variation in the propagation and direction of intersection of cracks. These analyses were interpreted with the fabric orientation and arrangement of the soil samples. The analyses of the crack pattern could help in understanding the macroscale behaviour of treated and untreated soil and many other related geotechnical phenomena.

Keywords: expansive soil, desiccation cracks, stabilization, lignosulphonate, lime.

1 Introduction

Cracking phenomenon of soil is a complex phenomenon and influenced by many parameters which includes soil minerology, temperature variations, thickness of soil layer [1,2]. The alternate wetting and drying of soils, physiochemical properties of the soil also affects the cracking pattern of the soil. Previous studies have indicated that the soil-crack morphology can significantly influence the inherent properties of the soil [3,4]. The desiccation cracks formed on the upper surface of the soil can influence the properties of the soil related to the geotechnical, hydraulic and geo-environmental applications [5]. Cracking patterns can develop through the alterations in moisture content, stiffness and tensile strength of the soil [6]. Cracks are developed on the soil surface as the result of the drying mechanism related to the evaporation of the water from the exposed soil surface, largely related to the volumetric shrinkage of the soil. When the threshold state is reached, desiccation cracks occurs in the soil and manifest on the soil surface [7]. Crack propagation is also related to the tensile stresses developed during the water evaporation. When the generated tensile stresses exceed the inherent tensile strength of the soil, the cracks can propagate and weaken the soil [1,8].

Cracking of soil initiates weaker soil zones and can lead to stability issues in dams, tailing ponds, earthen embankments, landfill liners etc., [9,5]. The higher hydraulic conductivity encountered due to the crack formation can affect the performance of the contaminant barriers very severely [10]. Stability of natural slopes and vertical cuttings and bearing capacity of the foundation are severely affected by moisture ingress due to the cracking behaviour. The crack propagation could be effectively reduced by increasing the soil strength and treating the soil with suitable additives like lime, cement and sand [11]. The morphological characteristics of the soil-crack pattern such as the crack area density, crack length and width are some of the parameters which helps in understanding the connectivity of cracks [12,13,14]. The evaluation and analysis of these parameters can help in understanding the variation in the propagation of the crack pattern and characterization of the soil cracking behaviour and its influence on the geotechnical and geoenvironmental applications. The crack patterns and its propagation can be effectively studied by adopting imaging techniques [15,5]. Further, numerical analysis has also been carried out for the study of crack pattern in soil [16,17,10].

In the present study, the crack pattern analysis has been carried out for the potentially swelling soil and additives amended soil. The conventional alkaline additive, lime and the biopolymer-based additive lignosulphonate had been amended to the soil and a comparative analysis is carried to understand the variation in the propagation of the crack pattern.

2 Materials and Methodology

2.1 Soil

The soil used for the present study is an expansive soil which was collected from depths of 2 m to 3 m in Siruseri, Chennai. The classification and properties of the expansive soil is shown in Table 1. The index properties of the soil were evaluated based on Indian standards IS 2720 [18]. Based on the evaluated plasticity characteristics, the soil is classified as inorganic clay of high plasticity as per IS 1498 [19]. Based on the values of free swell index (FSI) and swell potential, the soil is classified as highly expansive category [20]. The expansive soil is amended with lignosulphonate, a plant-based biopolymer and conventional additive lime. Calcium Lignosulphonate (LS) is a byproduct from paper industry. Both additives were procured commercially.

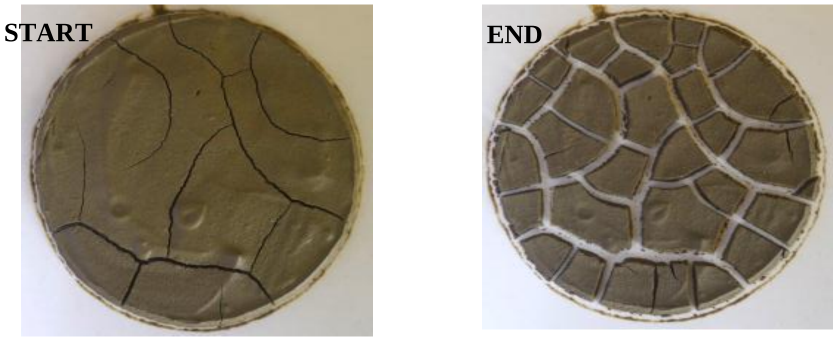
Table 1. Properties of Soil

Sl. No	Property	Values
1	Specific gravity	2.68
2	Liquid limit	64.08%
3	Plastic limit	27.8 %
4	Plasticity index	36.28 %
5	Shrinkage limit	10.37%
6	Clay	64%
	Silt	27%
	Sand	9%
	Gravel	0%
7	Differential Free swell %	111%

2.2 Methodology

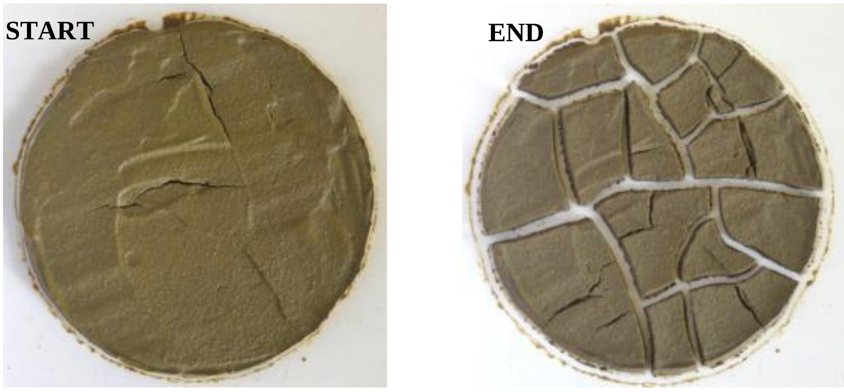
The crack patterns were observed based on the procedure given by Fang and Daniels [21]. Approximately 100g of soil passing through 425μm sieve is made into a paste with water content of 1.5 times the liquid limit. The wet soil paste is then spread on clean glass plate, such that the diameter is 110 mm and the maximum height of the wet mud pad does not exceed 1.27 mm as distinct crack patterns develop in thinner samples. The glass plate is left for air drying at room temperature of 28°C. Similar procedure was carried out for both the treated and untreated soil samples. The crack patterns were observed for untreated soil (S), 0.5%, 1.5%, 3% LS treated sample (S0.5LS, S1.5LS, S3LS respectively) and 2%, 4% lime treated sample (S2L, S4L).

In the present study, images were taken during 24 hours (t1) and 72 hours (t2) to analyse the crack patterns based on crack initiation to the complete dried state. The images were captured by DSLR camera fixed at 216 mm from the sample. The details of the sample designation are given in Table 2. The images of untreated soil taken during the first and third day of crack propagations are shown in Fig.1. The images of LS treated and lime treated samples are shown in Fig. 2 and Fig. 3 respectively.

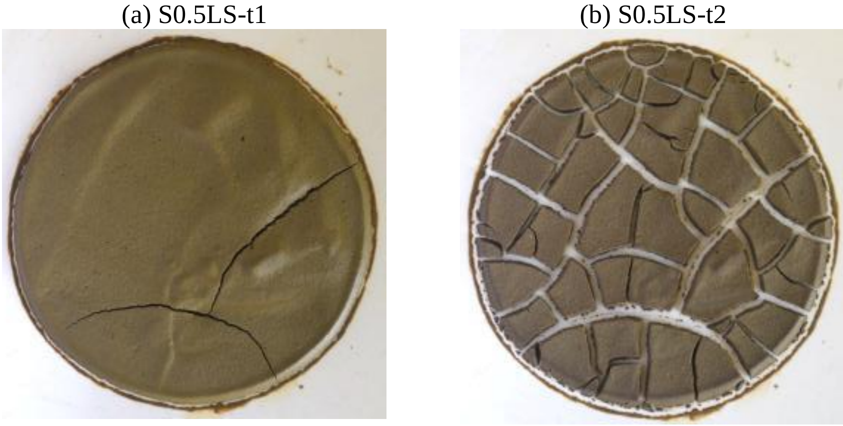


(a) S-t1 (b) S-t2

Fig. 1. Start and end of crack propagation of untreated soil



(a) S0.5LS-t1 (b) S0.5LS-t2



(c) S1.5LS-t1 (d) S1.5LS-t2

(e) S3LS-t1 (f) S3LS-t2

Fig. 2. Start and end of crack propagation of Lignosulphonate treated samples

(a) S2L-t1 (b) S2L-t2

(c) S4L-t1 (d) S4L-t2

Fig. 3. Start and end of crack propagation of Lime treated samples

2.3 Image analysis

The digital images were analysed further for the crack morphology. Preprocessing the image was done in ImageJ software. To quantify the cracks in the image, a software called Particle and Crack analysis System (PCAS) was used. The crack patterns were analyzed for the crack morphology based on the methodology given in Fig. 4.

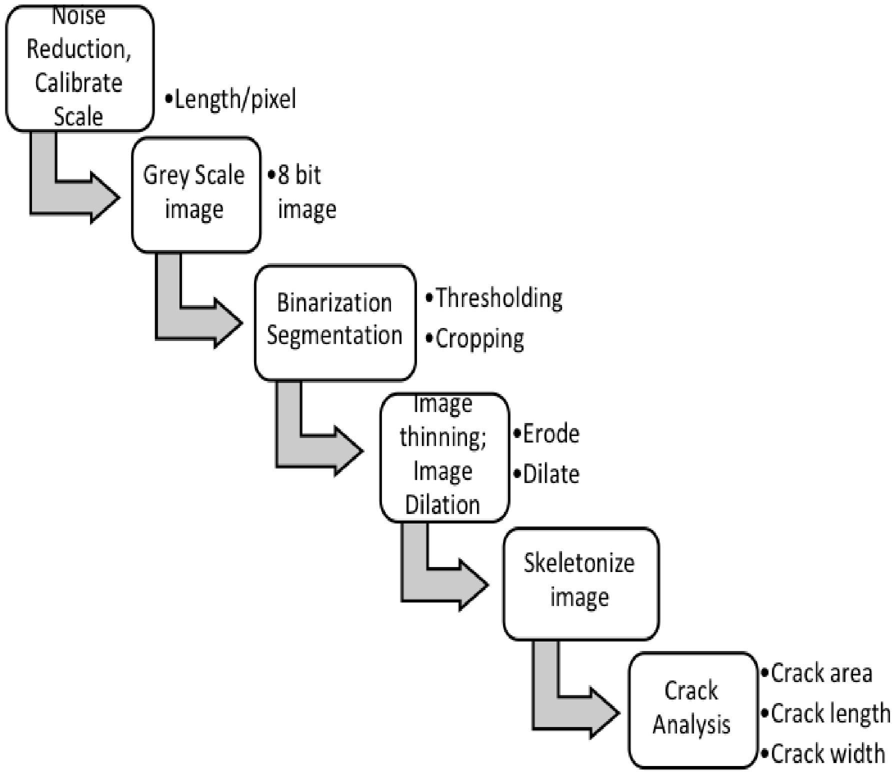
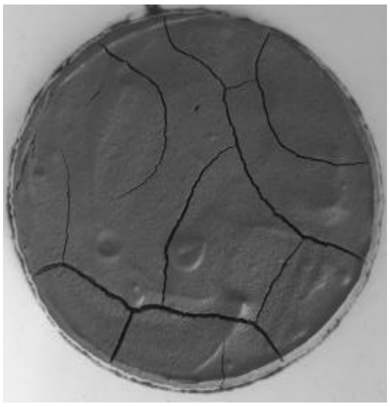


Fig. 4. Schematic of the methodology adopted for the image processing of the crack patterns.

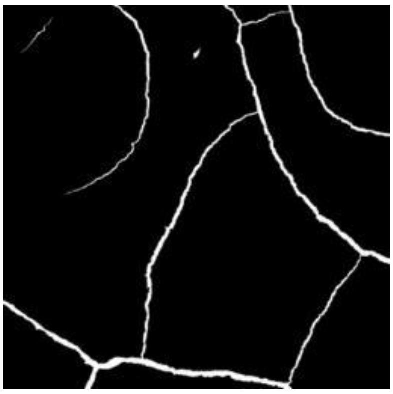
Using ImageJ, the noise in the image is reduced and scale (mm/pixel) of the image was calibrated. Then the image was converted into an 8-bit image (grayscale image). The grayscale image is turned into binary image using a thresholding tool. The presence of white and black dots spread near the cracks due to the shadows and lighting. Were removed by using the erode and dilate tool. The binary image is cropped into a square image. This clearly defines the boundary of the cracks. The typical grayscale, binary and cropped image of the untreated sample St1 is shown in Fig. 5.

After the preprocessing, the image is skeletonized as shown in Fig. 5(e). PCAS software is used to further quantify the length, width and area of the cracks. The boundary of every individual crack was identified (see Fig. 5(f)) and the length of each crack intersections was calculated. The maximum width at 100 random pixels on each crack was acquired and the area of the cracks was computed. All the values derived was in the unit of pixel. The derived values were divided by the calibrated scale to convert the values in mm.

(a) 

(b) 

(c) 

(d) 

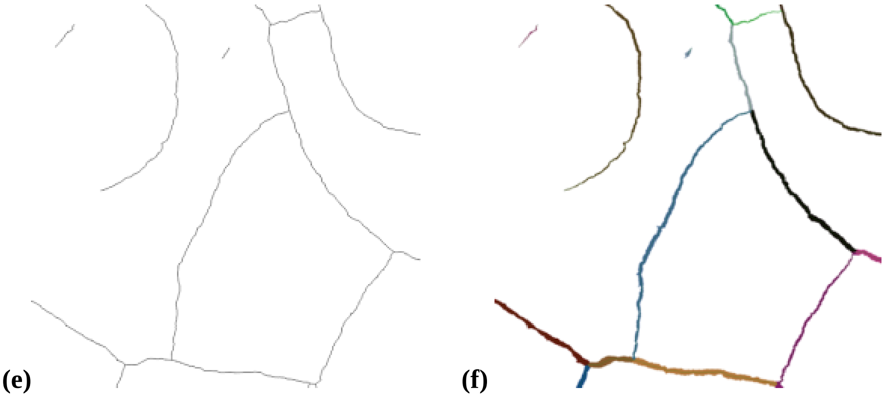


Fig. 5. Typical image analysis of the crack pattern of S-t1. (a) Captured image, (b) Grayscale image (c) Binary image (d) Cropped image (e) Skeletonized image (f) Crack identified image

3 Crack Pattern Analysis

The treated samples and the untreated samples were analyzed for the variation in the crack morphology. The crack parameters such as the length, width, number of clods (N_{cl}), and crack intensity factor (I_{cf}) were computed and compared for the various samples. The onset of cracks, progression and distribution of cracks were analyzed based on the analytical measurements. The various crack morphological parameters for both treated and untreated soil are depicted in Table 3.

Table 2. Crack parameters of untreated and treated samples

Sample Designation	N_{cl}	N_c	A_{cl} (mm^2)	A_c (mm^2)	L_c (mm)	W_c (mm)	avg. W_c (mm)	I_{cf} (%)
St1	8	15	5484.89	209.74	327.64	0.89	0.61	3.82
St2	25	49	3463,94	2142.07	542.03	6.12	4.02	61.84
S0.5LSt1	8	15	5077.82	192.16	243.14	1.14	0.73	3.78
S0.5LSt2	20	38	3529.46	1427.01	503.24	4.6	2.89	40.43
S1.5LSt1	1	3	6438.65	79.2	127.29	0.68	0.57	1.23
S1.5LSt2	36	79	3606.60	1977.33	756.22	5.87	2.93	54.83
S3LSt1	1	6	5551.02	4.12	16.57	0.57	0.28	0.07
S3LSt2	19	42	4006.48	1370.82	526.43	5.06	2.78	34.22
S2Lt1	2	7	6168.96	60.07	200.58	0.37	0.27	0.97
S2Lt2	55	110	3878.99	2348.99	974.57	4.56	2.43	60.56
S4Lt1	16	50	5927.39	247.86	572.82	0.75	0.38	4.18
S4Lt2	26	50	4083.68	1262.75	526.42	3.21	2.08	30.92

N_{cl}- no. of clods; N_c- no. of Cracks; A_{cl}- Area of clods; A_c- Area of Cracks; L_c- Length of Cracks; W_c- Maximum width of crack; I_{cf}- Crack Intensity Factor

At the end of 24 hours (t1), the cracks for untreated soil are initiated, as could be observed from Fig. 1(a) and the morphological parameters listed in Table 3. The number of crack segments (8) and the crack area (209 mm^2) is comparatively higher than the lignosulphonate amended soils which depict a very slow crack initiation phenomenon as could be observed from the values of Table 1. However, for lime treated soil, a lesser percentage (2 %) behaves similar to LS amended soil. But for the higher percentage of lime, (4 %), the crack propagation is at a faster rate with higher crack area (247 mm^2) and crack segments (16). These inferences indicate that, though lime addition improves the basic and engineering properties of the soil, the crack propagation depend on the tensile strength of the soil. In the case of lime amended soils, there is considerable alkalinity leading to flocculated particle orientation and increased brittleness of the soil. These properties make the lime amended soil vulnerable to surface crack propagation during the dry seasons [22]. Fig. 6 depicts the changes in the crack area and crack segments for the soil samples under the time duration of t1 and t2. To cover the whole range of crack area (4.12 mm^2 to 2348.99 mm^2), a logarithmic scale of base 10 was used to illustrate A_c.

At the end of 3 days (t2), when the crack patterns have sufficiently developed, the various morphological features of test samples indicate a progressive increase. The crack area of the untreated soil increases to 2147 mm^2 and crack segments, crack length and crack width depict a corresponding increase at the end 3 days duration (t2). However, for the 2 % lime amended samples, the crack area and segments are higher compared to 4 % lime. At lower contents of lime, there is a complete ion exchange reaction, which imparts a more flocculated structure and hence numerous small cracks segments at the periphery. But in the case of 4% lime amendment, there is a more predominant cementation reaction due to hydration, indicating larger segments comparatively.

The entire changes in the crack morphology could be better indicated by a more collective parameter, crack intensity factor, I_{cf} expressed as a percentage. The crack intensity factor is depicted in Fig. 7 and Fig. 8 for the time duration of t1 and t2. The untreated soil is prone to excessive cracks, as indicated by the I_{cf} value of 3.82 % at t1 time duration and 61.84 % at t2 time duration. The soil is basically highly expansive in nature as indicated by its index properties (Table 1) and the excessive crack propagation is reasonably expected. The increased percentage of LS amended soil depicts a slow crack propagation as indicated by the I_{cf} values and ΔI_{cf} values. This could be attributed to a more aggregated particle orientation, lesser rate of water drying and higher inherent tensile strength, due to the dense bonding between LS additive and soil particles. The lime treated soils are characterized by high brittleness which plays a major role in the crack propagation mechanism. The cracking phenomenon could be majorly attributed to the tensile strength development and shrinkage pattern of the soil, which is the further scope of this study.

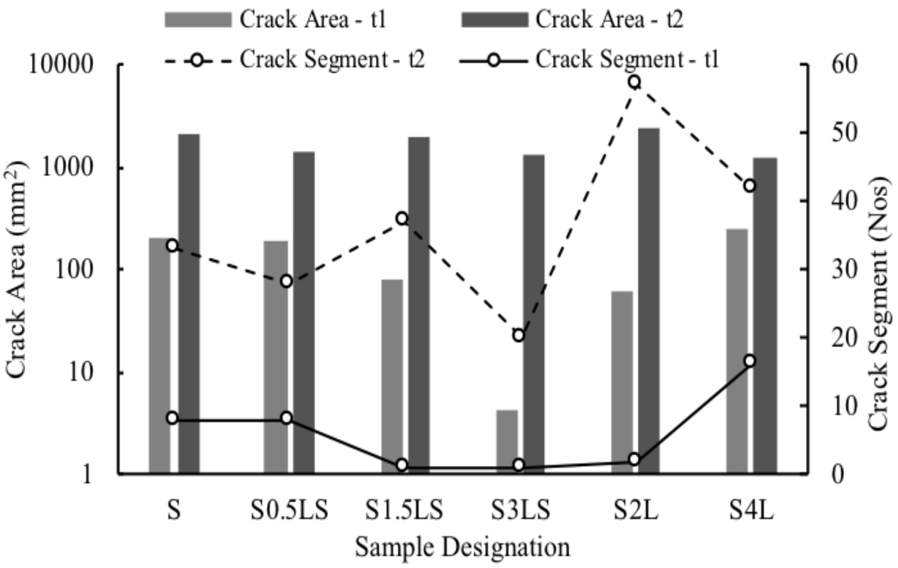


Fig. 6. Variation of crack area and crack segments for treated and untreated samples

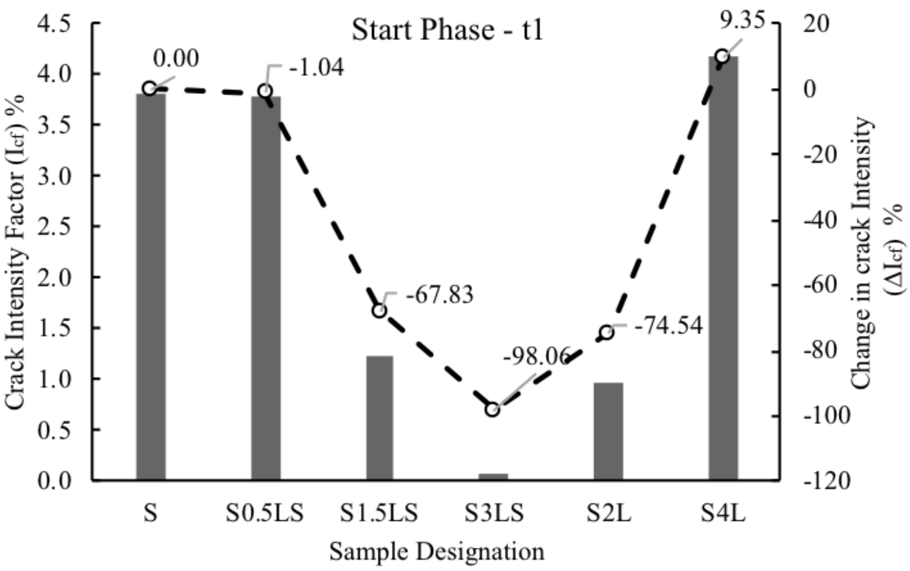


Fig. 7. Variation of crack intensity factor and change in crack intensity for treated and untreated soil at t1 time duration

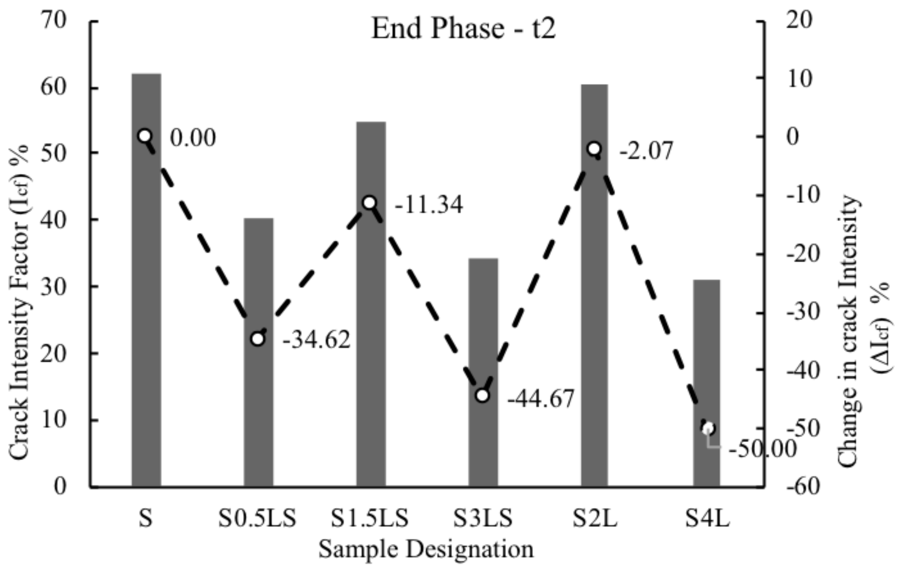


Fig. 8. Variation of crack intensity factor and change in crack intensity for treated and untreated soil at t2 time duration

4 Conclusions

The present study mainly focuses on the crack propagation phenomenon of potentially expansive soil and additives amended composites. Lignosulphonate a plant-based biopolymer and conventional additive, lime is adopted for the study. The crack patterns were analyzed for the various changes in the morphological features based on the image analysis tool. The results depict a reasonable variation between the crack patterns of the untreated soil, LS and lime amended soil. The lignosulphonate addition, imparts particle aggregation and higher moisture retention capacity for the treated soil which slows the rate of cracking and depicts a lesser cracked area compared to untreated soil. However, for the lime amended soil, the crack propagation is higher due to the increased flocculated orientation of the soil particles and increased brittleness of the composites. Nevertheless, these inferences have to be substantiated by the tensile strength variation and shrinkage values of the treated and untreated soil, which is the further scope of the study.

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