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Effect of Relative Compaction and Wetting-Drying Cycles on Desiccation Cracking Behavior of Compacted Expansive Soil using Digital Image Analysis

Hemant Poonia[1], Brijesh Kumar Agarwal[2], and Ajanta Sachan[3]

[1]*B.Tech. Student, Indian Institute of Technology Gandhinagar, Gandhinagar, India, email: hemant.p@iitgn.ac.in*

[2]*Ph.D. Student, Indian Institute of Technology Gandhinagar, Gandhinagar, India, email: agarwal_brijesh@iitgn.ac.in*

[3]*Associate Professor, Indian Institute of Technology Gandhinagar, Gandhinagar, India, email: ajanta@iitgn.ac.in*

ABSTRACT

Compacted expansive soil undergoes swelling and shrinkage during seasonal moisture fluctuations and causes distress to highway and railway structures built over them. Shrinkage of expansive soil is accompanied by the development of large desiccation cracks. The present research work is focused on studying the effect of different degrees of relative compaction on the desiccation cracking of soil. Different specimens were made using static compaction having different compaction states simulating the compaction process adopted in the construction of highway and railway embankments. The digital image analysis technique was used to quantify the crack propagation using ImageJ software. Desiccation cracks were quantified based on various crack parameters such as crack area, crack length, crack width, and crack intensity factor. Specimens with higher relative compaction exhibited reduced evaporation rates causing the delayed cracking response. A series of wetting-drying tests were also conducted to study the effect of wetting-drying cycles on the desiccation cracking response of specimens compacted at different relative compaction. Only a few cracks were observed during the compaction drying stage, followed by a large number of cracks on the application of the first wetting-drying cycle. However, the crack pattern remained almost similar in further wetting-drying cycles.

Keywords: Expansive soils, Static compaction, Crack intensity factor (CIF), Digital image analysis, Effect of relative compaction, Wetting-drying cycles

1 INTRODUCTION

Expansive soils are considered problematic soils owing to their swelling and shrinkage characteristics due to the abundance of montmorillonite clay minerals. Due to large seasonal moisture changes, engineering issues with expansive soils are more common in arid and semi-arid areas. Desiccation cracking is one of the major issues of expansive soils. The cracks in a soil mass act as weak failure zones which endangers the overall stability of many geotechnical structures such as highway and railroad embankments, canal slopes, retaining wall backfills, and landfill clay liners, etc. (Tang et al., 2008; Singh et al., 2017; Mishra & Sridharan, 2017; Julina & Thyagaraj, 2019). Desiccation cracking of soil is a complex phenomenon influenced by various internal and external factors. The external factors include environmental conditions such as temperature, relative humidity, wind, and wetting-drying cycles. The internal factors include mineralogy, clay content, microstructure, density, and water content of the soil mass. Desiccation cracks occur due to accumulated residual tensile stresses exceeding the tensile strength of the soil (Peron et al., 2009; Tang et al., 2011). Several studies have been conducted to study the crack propagation phenomenon in expansive soils in a slurry state (Lakshmikantha et al., 2012; Tang et al., 2008). However, in most geotechnical applications expansive soils are encountered in a compacted state having a three-phase system. Additionally, the compaction state of the soil in the field may vary, which can result in different densities and moisture contents. Different degree of compaction leads to different microstructure formation within the soil mass (Lloret et al., 2003). Hence, it is necessary to study the desiccation cracking behavior of expansive soils in different compaction states. Further, the compacted expansive soils in the field also undergo many wetting-drying cycles during seasonal variations. These wetting-drying cycles may alter the desiccation cracking behavior and hence, it is important to investigate their effect.

The present study investigates the effect of different degrees of relative compaction on the desiccation cracking response of the Nagpur expansive soil. The desiccation process was simulated inside a stability chamber with controlled humidity and temperature conditions. A total of four wetting-drying cycles were also applied on compacted expansive soil specimens and the crack propagation and patterns were quantified with the help of the digital image analysis technique.

2 MATERIAL PROPERTIES AND EXPERIMENTAL PROGRAM

The expansive soil was collected from Nagpur, Maharashtra (India), at a depth of 1 meter. The expansive soil contained 56% clay, 38% silt, and 6% sand. The soil was classified as CH (cohesive soil with high plasticity) as per Unified Soil Classification System. The geotechnical properties of the Nagpur expansive soil are reported in Table 1.

Table 1. *Geotechnical properties of the Nagpur expansive soil*

Property	Value
Specific gravity (GS)	2.75
Liquid limit (%)	84
Plastic limit (%)	27
Differential free swell index (%)	125
Gravel (%)	0
Sand (%)	6
Silt (%)	38
Clay (%)	56
Maximum dry density, MDD (g/cc)	1.46
Optimum moisture content, OMC (%)	30

The first series of experiments was conducted to study the effect of the initial compaction state on the desiccation cracking behavior of the soil. Specimens were prepared at four different compaction states, such as 85%, 90%, 95%, and 100% relative compaction (RC). The compaction curve obtained using the standard proctor test of the soil and various testing conditions in the first test series are illustrated in Figure 1.

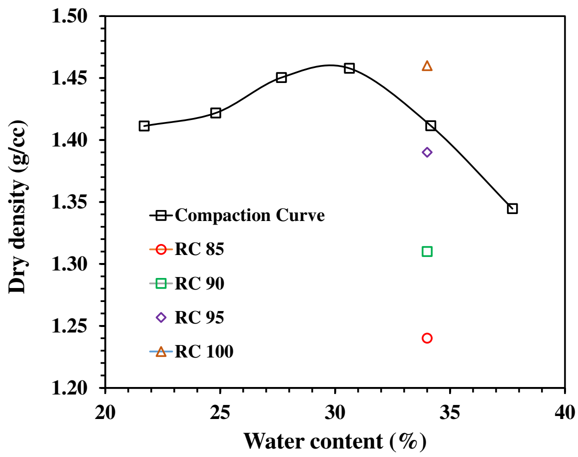

Figure 1. *Compaction curve of Nagpur expansive soil along with the testing conditions*

The specimens were statically compacted at the required dry density and 4% wet of the OMC using the static compaction method in a cylindrical mold of 75 mm diameter and 25 mm height. The static compaction method was chosen as it simulates the compaction process adopted in the construction of highway and railway embankments. The specimens after preparation were shrink-wrapped and kept for curing in a desiccator (at 95% relative humidity) for a day to allow for moisture equilibrium. Two specimens were prepared for each RC effort to ensure the repeatability of the results. The prepared cylindrical soil specimens were kept inside a stability chamber (at 40 °C temperature and 50% Relative humidity) for drying. The diameter, height, and weight of the specimen were measured during the drying/shrinkage process at different time intervals (0, 1, 2, 4, 8, 12, 24, 36, 48, 60, 72, 96, 120, 144, and 168 hrs) for calculation of volume change and water loss.

For the wetting-drying (WD) tests in test series 2, cylindrical specimens were prepared inside a consolidation ring having a 60 mm diameter and 20 mm height as per the compaction conditions described in Figure 1. First, the compaction drying was done inside the stability chamber. After 48 hours of drying, the specimen was placed inside an oedometer setup for wetting at a seating pressure of 5 kPa and allowed to saturate for the next 48 hours. In each WD cycle, wetting was done in an oedometer setup for 48 hours and drying was performed inside the stability chamber for 48 hours. This procedure was repeated till the third WD cycle to replicate the seasonal wetting and drying of soil during the monsoon and summer seasons respectively.

3 DIGITAL IMAGE ANALYSIS

The Digital image analysis (DIA) technique was used to quantify the surface cracks. Images of the specimen's top surface were captured at regular time intervals using a digital camera of 18 MP resolution. It was ensured that the camera axis always remained perpendicular to the specimen's surface. For more details on image acquisition setup, readers can refer to Agarwal & Sachan (2022). DIA was performed using Image J software (Rasband, 2006). Figure 2 shows the schematic of the step-by-step procedure for digital image analysis used in this study. The input image was binarized according to a chosen threshold grayscale intensity. Then several binary operations were applied for reducing the salt and pepper noise in the images. A procedure similar to Lakshmikantha et al. (2009) was used to quantify the crack parameters. Crack intensity factor (CIF) was defined as the ratio of the area of cracks (A_c) to the total surface area (A) of the drying soil mass (Yesiller et al., 2000). After the calculation of the crack area, the images were skeletonized to calculate the total crack length. The average crack width was determined as the ratio of the total crack area to the total crack length.

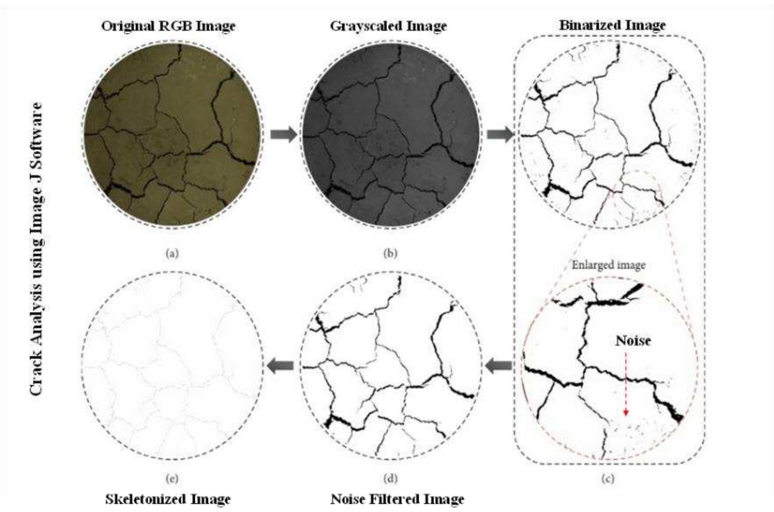

Figure 2. *Schematic showing DIA procedure for quantification of desiccation cracks*

4 RESULTS AND DISCUSSION

4.1 Effect of different degrees of relative compaction on Desiccation Cracking behavior of soil

Figure 3 shows the evolution of surface cracks with the increase in desiccation time in specimens prepared at different relative compaction states. It was observed that more cracks appeared in loosely packed soil specimens as compared to densely compacted soil specimens. This might be because water could easily evaporate in loosely packed soil specimens owing to its larger pores which resulted in high volumetric shrinkage and more crack generation. Further, there were no significant cracks on specimens up to one hour of drying as water loss was not that high in this small duration. However, cracks appeared after 2 hours and continued to grow to a maximum amount and then decreased on further drying. Figure 4a shows the variation of the total surface crack area with water content. Cracks started to appear when the water content was reduced to around 30% in all the specimens. First, the crack area continued to increase until it achieved a maximum value and decreased as water content reduced further.

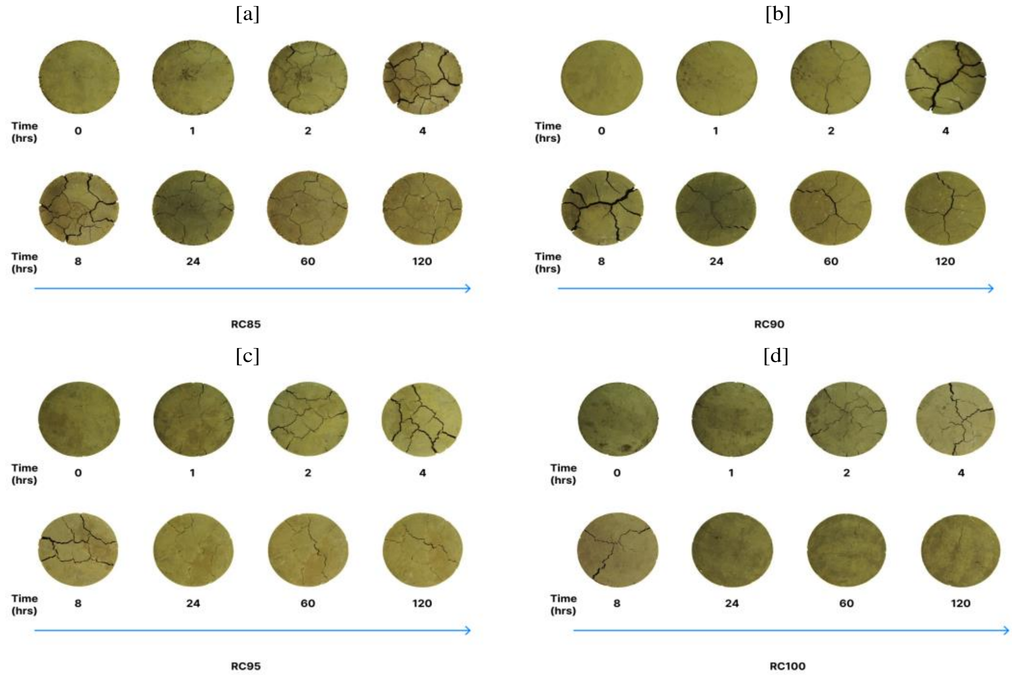

Figure 3. *Evolution of surface cracking with the increase in desiccation time for (a) 85% RC, (b) 90% RC, (c) 95% RC, and (d) 100% RC*

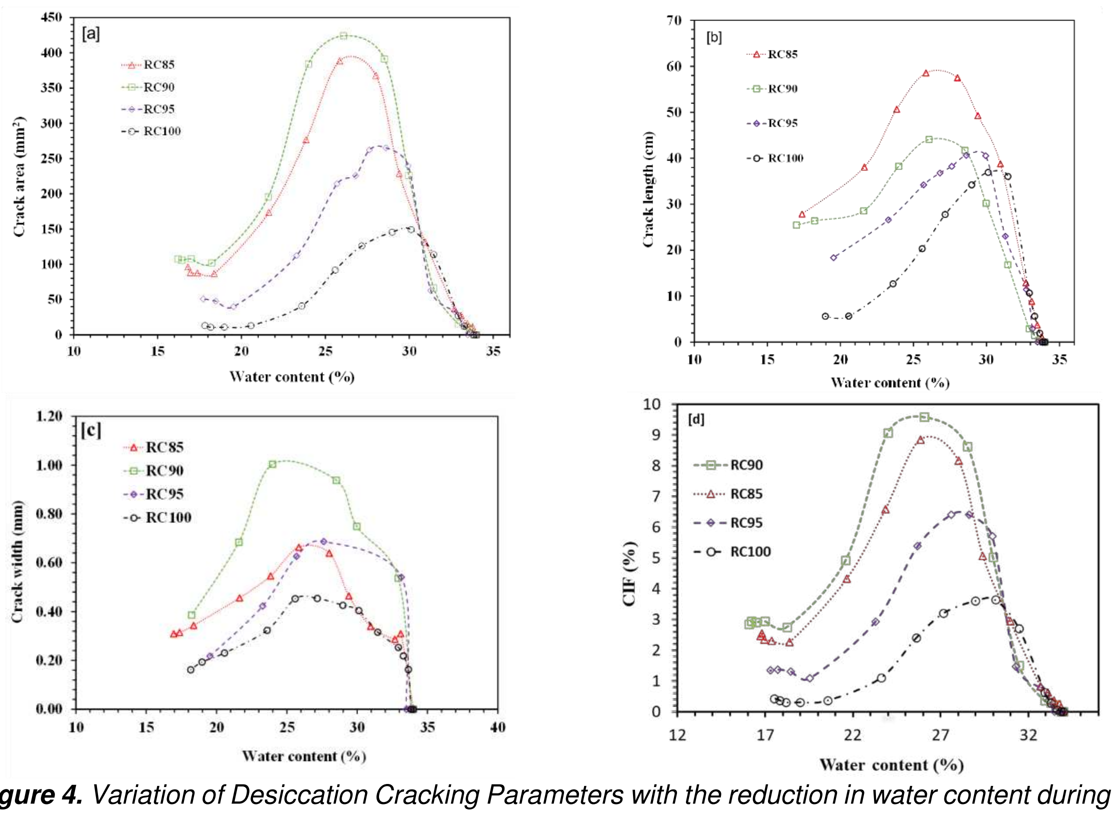

Figure 4. *Variation of Desiccation Cracking Parameters with the reduction in water content during the drying process (a) Crack area, (b) Crack length, (c) Crack width, and (d) CIF*

More densely compacted specimens (RC100 and RC95), had smaller and more uniform pores which resulted in higher water retention capacity. Additionally, a denser state of soil might offer higher tensile strength against cracking as compared to specimens at low RC. These phenomena significantly reduced the crack area in specimens at higher RC.

Figures 4b and Figure 4c show the variation of the crack length and crack width, respectively with the reduction in water content in specimens prepared at different RC. These parameters also followed a similar trend as followed by crack area. The crack length was maximum for the RC85 specimens and lowest in RC 100 specimens. However, the crack width was found to be maximum for the specimens compacted at 90% RC. The specimen with maximum dry density (RC 100) showed the minimum crack length and crack width. Figure 4d depicts the variation of CIF with the reduction in water content. It was found that loose specimens (RC 85 and RC 90) showed maximum CIF values, while the comparatively denser specimens (RC 95 and RC 100) showed lower CIF.

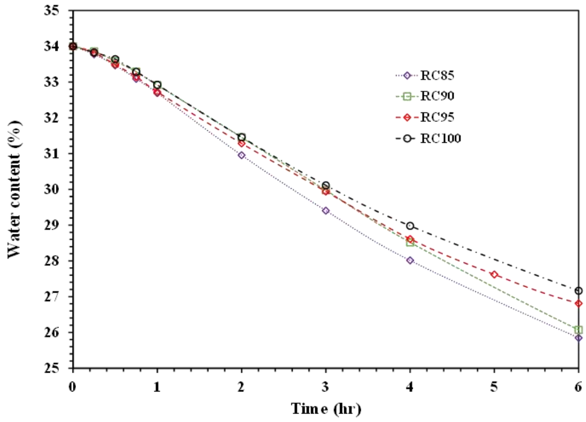

Figure 5. *Effect of initial compaction conditions on the Water Retention Capacity of the soil*

Figure 5 shows the effect of the initial compaction condition on the rate of evaporation or in other words, the water retention capacity. It was found that water could evaporate more rapidly in the RC 85 specimen, which confirmed its lower water retention capacity unlike the RC 100 specimen, which showed the least rate of evaporation. Table 2 summarizes the maximum values of desiccation cracking parameters obtained for specimens with different RC states in the first test series (TS-I) along with images. The maximum values of cracking parameters represent the worst-case scenario that a soil can experience during desiccation.

Table 2. *Maximum values of desiccation cracking parameters obtained in TS-I*

Sample ID/ Parameters	RC 85	RC 90	RC 95	RC 100
Maximum crack area image				
Crack area (mm^2)	388.4	424	265	149
Crack Length (cm)	58.6	44	40.6	36.9
CIF (%)	8.85	9.58	6.41	3.63
Water content (%)	25.8	26	28.6	30.1
Evaporation Rate (Δw/hr)	1.50	1.37	1.35	1.25

4.2 Effect of Wetting-Drying cycle on Desiccation Cracking behavior of compacted soils

Figure 6 shows the variation of axial deformation during WD cycles for specimens compacted at different relative compaction states. The swelling was found to be maximum in the RC100 specimens, followed by RC95, RC90, and RC 85. The swelling nature of the soil reduced after each WD cycle in all the specimens. Reduction in the swelling nature of soil with an increase in the number of WD cycles was also reported in the previous studies (Al-Homoud et al., 1995; Guney et al., 2007).

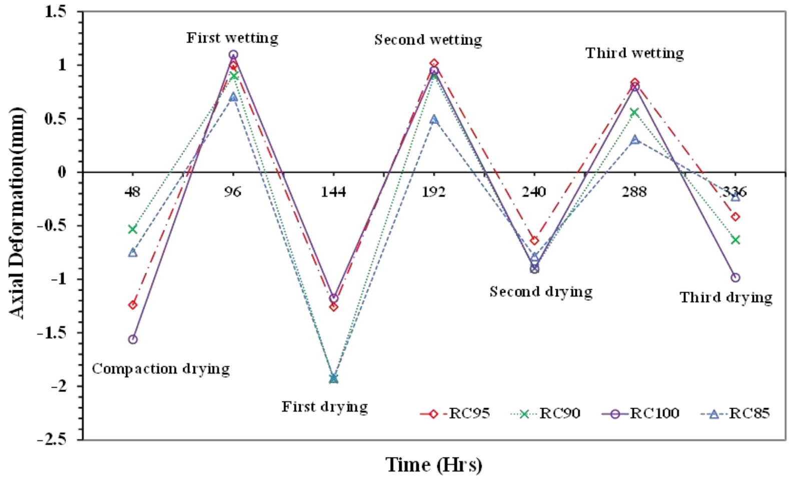

Figure 6. *Axial deformation during wetting-drying cycles for specimens compacted at different RC*

Figure 7 shows the effect of WD cycles on the desiccation cracking behavior of specimen compacted at 100% Relative Compaction. It was observed that no significant cracking occurred in the compaction drying cycle (drying just after compaction). However, after the first wetting, when the drying operation was carried out, very intense cracking was observed. This might be due to the very low tensile strength of the wetted specimen which resulted in higher crack formation. The crack pattern gradually evolved with each number of WD cycles and stabilized after 2 cycles. Cracks appeared at new locations with more WD cycles due to the formation of new sites of low tensile strength within the soil mass. This was evident by almost similar cracking patterns observed in 2nd and 3rd drying operations. A similar trend of evolution of desiccation cracking was found in all the specimens with different RC. Due to alternate wetting-drying operations, the weakening of cohesive bonds between clay particles occurred along with changes in the microstructure (Yesiller et al., 2000). This caused more intense cracking on increasing WD cycles. However, it was observed in the previous studies that after a few WD cycles, the microstructure of the soil ceases to change. Hence, the crack pattern also got stabilized after a few WD cycles.

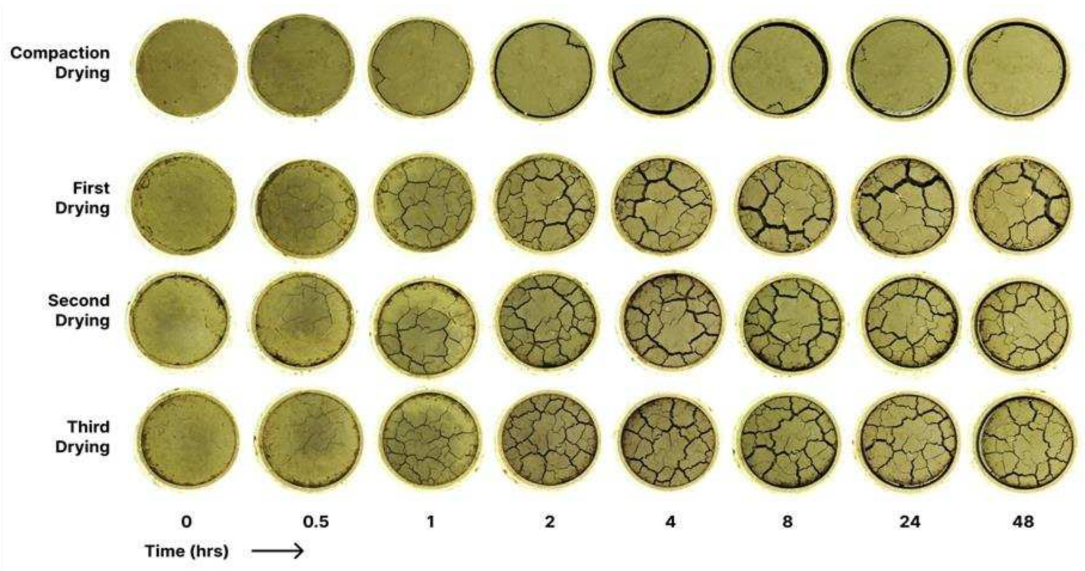

Figure 7. *Effect of WD cycles on desiccation cracking behavior of specimen compacted at 85% RC*

Table 3 summarizes the results obtained in the second test series (TS-II) for all the specimens with different RC values. The maximum values of cracking parameters obtained after each WD cycle are reported in this table along with the maximum crack area images. It was observed that all the specimens cracked severely on the application of WD cycles irrespective of the initial compaction state, which suggested that the effect of microstructural changes due to WD drying dominated the effect of the initial compaction state on desiccation cracking response of Nagpur expansive soil.

Table 3. *Maximum values of desiccation cracking parameters obtained in TS-II*

Sample ID: RC 100	Compaction Drying	First Drying	Second Drying	Third Drying
Maximum Crack Image				
Crack Area (mm²)	27.6	410.7	432.8	451.8
Crack Length (cm)	5.5	36.0	35.5	39.8
Crack Width (mm)	0.50	1.14	1.22	1.13

Sample ID: RC 95	Compaction Drying	First Drying	Second Drying	Third Drying
Maximum Crack Image				
Crack Area (mm²)	1.8	339.2	429.9	433.7
Crack Length (cm)	1.0	27.5	29.0	39.2
Crack Width (mm)	0.17	1.23	1.48	1.11

Sample ID: RC 90	Compaction Drying	First Drying	Second Drying	Third Drying
Maximum Crack Image				
Crack Area (mm²)	41.5	390.6	419.0	423.2
Crack Length (cm)	8.0	30.8	31.4	29.5
Crack Width (mm)	0.52	1.27	1.34	1.43

Sample ID: RC 85	Compaction Drying	First Drying	Second Drying	Third Drying
Maximum Crack Image				
Crack Area (mm²)	2.31	404.03	430.99	293.09
Crack Length (cm)	1.9	46.2	39.4	29.9
Crack Width (mm)	0.12	0.87	1.09	0.98

5 CONCLUSIONS

The present research work investigated the effect of initial compaction conditions and wetting-drying cycles on the desiccation cracking behavior of highly expansive soil. The specimens were prepared on the wet side of OMC at four different Relative Compaction levels (85%, 90%, 95%, and 100 % Relative Compaction). A series of wetting-drying tests were also conducted on all the specimens to observe the effect of WD cycles on desiccation cracking response at various initial compaction states. Crack parameters were calculated by performing digital image analysis in ImageJ software. Specimens with higher initial dry density (RC 95 and RC 100) showed a lesser value of crack parameters (crack area, crack length, crack width, and CIF) than loosely compacted specimens (RC 85 and RC 90). Wetting-drying cycles were found to significantly influence the desiccation cracking patterns irrespective of the initial compaction state of the soil. Very few cracks were observed in compaction drying cycles. However, a sudden increase in desiccation cracks was observed on the first wetting. The crack parameters increased initially with the increase in the number of WD cycles which acquired equilibrium after 2nd cycle of wetting-drying. The results showed the importance of the initial compaction state and WD cycles on the desiccation cracking behavior of compacted highly expansive natural soils.

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