Desiccation Cracking of Soil Layers

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ABSTRACT: The current paper presents a brief review of the available and emerging theories of desiccation cracking of clay soils, and an analysis of some laboratory tests undertaken on desiccation of relatively thin soil layers. The laboratory test data analysed included those reported by Corte and Higashi (1960) and Lau (1987). The experiments were conducted to study the effects of soil thickness, initial soil density, base adhesion and desiccation rate. The thicknesses of soil layers were in the range 3 mm to 60 mm. The results of the experiments indicated that cracking occurred predominantly in orthogonal patterns although non-orthogonal (hexagonal) patterns occurred in some instances. The results also indicated that the initial cracking water content decreases as the desiccation rate increases. The analysis of results indicated that cells created by cracking followed a log-normal distribution, and the mean cell area was a function of soil thickness, base adhesion, and initial soil density, but was not strongly related to the desiccation rate.

1 INTRODUCTION

It is common knowledge that clay soils can crack during desiccation. Cracks occur when soils are restrained while undergoing volume change produced as a result of the soil suction generated within the desiccating soil matrix. The desiccation cracking of clay soils can have a severe impact on the performance of clay soils in various geotechnical, agricultural and environmental applications. For example, desiccation cracking has the potential to render a low conductivity barrier constructed of clay soil virtually ineffective. Despite this significance, the essential mechanisms of desiccation cracking are not well understood, and consequently, predictive tools are inadequately developed.

Previous studies on desiccation cracking are spread across several disciplines and they date back to the early twentieth century. These studies have been predominantly qualitative and behavioural in nature. The field evidence reported is wide-ranging, generally incomplete in details and sometimes conflicting. For example, wide ranges in crack spacing, varying from about 75 mm to 76 m have been reported. Similarly, the depths of desiccation cracks ranging from several centimeters to over 10 m have been reported in the literature. The relationship between crack depth and spacing was also not very clear, although a general trend of larger spacing with deeper cracks seemed to exist. Several researchers including Lau (1987), Morris et al. (1992) and Kodikara et al. (1998) have provided detailed summaries of the field evidence of desiccation cracking.

The apparent mysterious nature of desiccation cracking process can only be understood clearly by adopting a systematic research approach to analysis and experimentation. The current paper provides a brief review of the available and emerging theories and an analysis of some laboratory tests undertaken on desiccation of relatively thin soil layers. A fundamental understanding of desiccation of thin soil layers is an initial and useful step and is, specifically, relevant to the behaviour of soil liners used as covers and various material layers of road pavements.

2 THEORIES OF DESICCATION CRACKING

2.1 *General*

It is commonly considered that desiccating clay soils crack when the tensile stress developed in the soil due to the matric soil suction exceeds the tensile strength of the soil. Tensile stresses develop only when the soil is restrained in some way against shrinkage. The restraints can be external (e.g. rough layer interfaces) or internal (e.g. sections of soil undergoing non-uniform drying).

Observed field aerial cracking patterns can be divided into two broad categories, namely orthogonal patterns and non-orthogonal patterns. In orthogonal patterns, cracks tend to meet at right angles. In the evolution of these patterns, cracks usually occur sequentially. First, primary cracking develops dividing the clay surface into blocks and subsequent drying tends to further subdivide these blocks. In non-orthogonal cracking patterns, the cracks do not meet at right angles. Hexagonal patterns (cracks meeting at angles of 120^0) and their deviations fall into this category. The non-orthogonal cracks appear to originate simultaneously and connect up to form a blocky pattern. During, subsequent drying, however, (secondary and tertiary) cracking and opening of the cracks can occur over larger blocks encompassing a number of smaller blocks. Theoretically, this secondary and tertiary cracking behaviour can be considered to be a *bifurcation* from the primary cracking pattern (Bezant and Cedolin, 1991; Kodikara et al., 1999). As postulated by Bezant and Cedolin (1991) for cracks originated by uniform shrinkage (or cooling) in idealised media, Figure 1 shows the theoretically plausible crack patterns. The parallel cracks shown in Figure 1(a) can be considered as two-dimensional whereas other crack patterns are essentially three-dimensional.

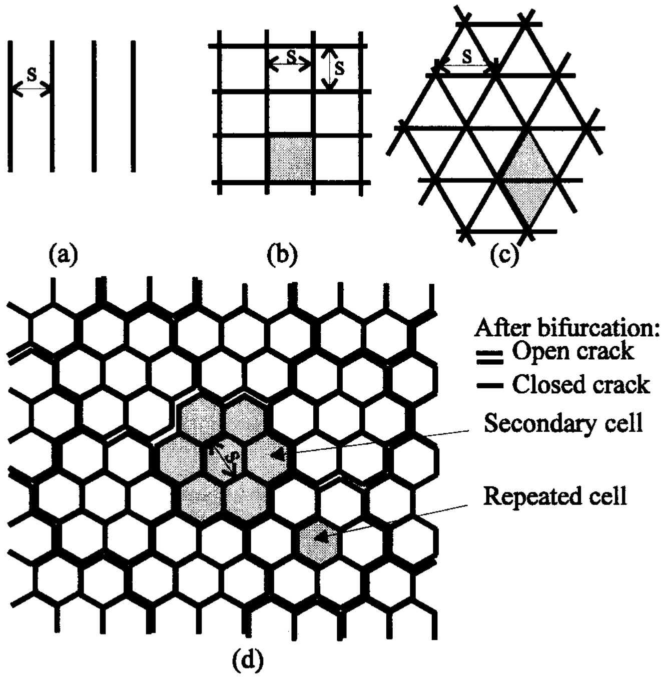

Figure 1. Theoretically plausible patterns of desiccation cracks in idealised media (after Bezant and Cedolin, 1991)

2.2 *Theoretical Models*

The theoretical research on desiccation cracking is not extensive with notable contributions made by Lachenbruch (1961), Fredlund and Morgenstern (1976), Lau (1991), Morris et al. (1992) and more recently, by Konrad and Ayad (1997). The original work of Lachenbruch (1961) involved the use of linear elastic theory and fracture mechanical principles to explain the magnitudes of depth and spacing of thermal contraction cracks in permafrost. Lau (1987) and Morris et al. (1992) made use of the consistent framework proposed by Fredlund and Morgenstern (1976) for unsaturated soils to develop theories for the prediction of the stable depths of desiccation cracking. Konrad and Ayad (1997) presented an idealised model for the analysis of clayey soils undergoing desiccation, utilising fracture mechanical concepts. Despite these advances, theoretical modelling approaches need further development, particularly explaining and predicting the relationship between crack spacing and depth and the evolution of crack patterns generally observed in the laboratory and in the field.

The crack spacing depends on the cracking pattern. Currently, there is no definite approach to the prediction of crack spacing for polygonal cracking patterns or the shape of the polygonal blocks. Instead, researchers have concentrated on prediction of the spacing of parallel cracks (in half-space) as a starting point (Lachenbruch, 1961, Konrad and Ayad, 1997). Lachenbruch (1961) and Konrad and Ayad (1997) considered the stress perturbation (or stress relief) caused by the formation of a single crack in a clay medium subjected to a tensile stress regime. According to this concept, the stresses are totally released at the face of the first crack, but will gradually rise away from the crack face. They considered that a second crack will occur when the tensile stress rises to a certain factor (α) of the tensile strength of the soil. In their analysis, the factor α is arbitrary and has no any physical meaning.

3 EXPERIMENTAL DATA

3.1 *General*

In the current paper, available laboratory experimental data on the desiccation of soil layers are analysed. The data include those reported by Corte and Higahsi (1960) and Lau (1987). The process of desiccation is strongly dependent on the local climatic conditions. The climatic conditions include temperature, relative humidity (RH), wind velocity and solar radiation. In these laboratory experiments, the temperature and RH are controlled. In the following sections, only a brief account of these tests is given.

3.2 *Data of Corte and Higashi (1960)*

Corte and Higashi (1960) carried out these experiments as part of early research on patterned ground by the US Corps of Engineers. These tests appear to be the most comprehensive series of laboratory tests undertaken on the desiccation of soil layers, but seemed to have not been published except in their original report. It is noted that about 60 tests have been conducted spanning a period of one year. The test parameters were divided into two categories, namely extrinsic and intrinsic. The extrinsic parameters controlled were temperature, relative humidity, thickness of the soil layer and the base material. The relevant intrinsic test parameters were initial moisture content and density or initial state of the soil.

The soil used for the experiments was Bloomington till obtained from a till deposit near Lily Lake, Illinois. The soil was processed by drying and crushing and passing through a 1mm screen. Table 1 shows the basic characteristics of the soil used.

Table 1.Basic physical characteristics of the soils used in the desiccation tests

Soil Description	Liquid Limit, Plastic Limit, Plasticity Index, Shrinkage Limit, Specific Gravity
Bloomington Till (Corte and Higashi, 1960)	31.4, 13.9, 17.5, 12.0, 2.63
Indian Head till (Glacial till) (Lau, 1987)	34.3, 14.2, 20.1, 14, -
Reginal clay (lake clay) (Lau, 1987)	89.5, 26.2, 54.3, 22.0, -

Most of the experiments were carried out in flat wooden containers of 600 mm x 840 mm plan area and 70 mm depth. The soil was used in two initial states: (1). as a slurry with initial water content of 60% and dry density of 1800 kg/m^3; and (2) as a loosely compacted soil with initial water content of about 45% and a dry density of about 1500 kg/m^3. Various materials were used at the base of the containers in order to provide differing base adhesion characteristics. The base materials used included plain wood, greased wood, and sheet of glass. A 20mm thick base layer of sand in the container having a wood base was also tested. For majority of the tests, the room temperature was kept about 22°C and the relative humidity was in the range 30 to 40%.

3.3 *Data of Lau (1987)*

These tests have been carried out in the soil laboratory at the University of Saskatchewan Canada. As detailed in Table 1, two types of local soils were used in the tests. The cracking tests were carried out in a flat wooden container of 610 mm x 610 mm plan area and 76 mm deep. The soils were prepared so that their initial moisture contents were close to their liquid limits and the soils were close to a slurry state at the beginning of the tests. An additional aspect of these tests was that the soil was instrumented with four embedded ceramic-cup tensiometers to measure the soil suction during the tests. Furthermore, the vertical deformations of the top soil surface was also measured using dial gauges that were mounted at the four quadrants of the container. After the cracking commenced, the soil moisture content during the tests were measured by taking small samples of soil. No special attention was paid to the base condition of the wooden container. Photographs were taken during the tests to record the development of the crack pattern. Unfortunately, in most of these tests, the initiation of cracking was influenced by the presence of instruments in the soil.

4 ANALYSIS OF EXPERIMENTAL DATA

4.1 *Desiccation rates and cracking water content*

Figure 2 shows the reduction of moisture content with time for three typical tests (Experiments 15, 33 and 37) using soil at a slurry state, as conducted by Corte and Higashi (1960). The thicknesses of soil layer in these experiments were 9.6 mm, 9.5 mm and 28.1 mm respectively. Experiments 15 and 33 had wood bases and Experiment 37 had glass at the base. Experiments 15 and 33 had similar conditions except that Experiment 33 was conducted under a higher relative humidity of 90%. Also shown in Figure 2 are (desiccation) curves fitted to the experimental results. These curves are represented by $w = w_0 \exp(-kt)$, where *k* is referred to as the desiccation speed or rate, and w_o is the initial water content. The water contents at the crack initiation (cracking water contents) are also marked (by arrows) on the desiccation curves.

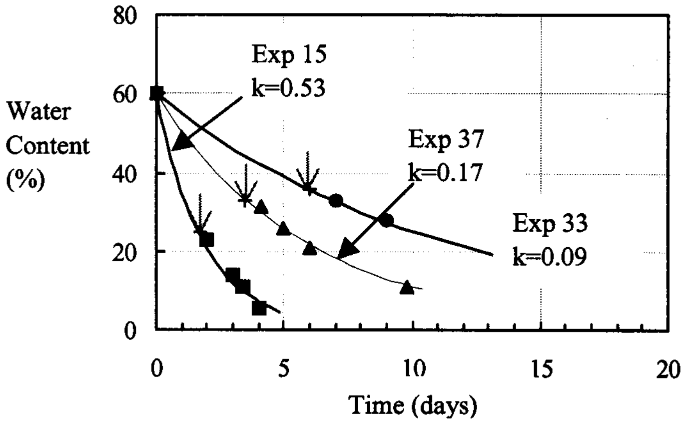

Figure2. Process of desiccation at the surface soil (Corte and Higashi, 1960).

The results of Experiments 15 and 33 show that desiccation rate, which is simplistically chararcterised by the parameter *k* in this instance, is strongly dependent on the local climatic conditions. The desiccation rate is also dependant on the thickness of the soil layer as evidenced from the results of Experiments 15 and 37, where the only relevant test variable is soil thickness. Similar observations can be made with Lau (1987) results. The test results of Corte and Higashi (1960) have generally indicated that the initial part of the desiccation curve becomes more linear as the initial soil density decreases (or is loosely packed). Approximate theoretical analyses of soil evaporation were carried out using SOILCOVER model, a finite element program developed for modelling soil evaporation (Wilson et al., 1990). Owing to the limited space available, the results of these analyses are not presented here, but it was found that this model is capable of emulating test results and is suitable for modelling evaporation from soil layers.

Another important aspect evident from Corte and Higashi test data is the dependence of cracking water content on the desiccation rate. Their overall test data clearly indicate that the cracking water content decreases significantly as the desiccation rate increases. It is not possible to explain this phenomenon from the current desiccation theories, because they do not include a relationship of time (or desiccation rate) to the material behaviour. In the current understanding, the initial cracking is dependent on the soil matric suction, which, in turn, is uniquely related to the soil water content.

4.2 *Observations on crack growth and pattern*

Test results illustrate that crack growth occurs predominantly in orthogonal and sequential manner with primary cracks forming initially and secondary cracks subdividing the initial crack pattern (see Figure 3). However, there is evidence that at higher desiccation rates or at smaller thicknesses, non-orthogonal and predominantly 120^0 crack patterns evolve at the primary cracking stage, and they occur simultaneously and relatively fast over the soil surface. This pattern can be seen in Figure 4, which can be compared to Figure 3. The main test variable between these two tests is the thickness of the soil layer. In certain tests, mixtures of orthogonal and non-orthogonal cracks occur. In addition, hexagonal patterns were more common in loosely packed soil than in soil slurry, indicating an influence of the crack pattern on the soil density.

4.3 *Influence of the base material*

Test results indicate that base material has a significant influence on the resulting crack pattern and the block or cell sizes. This is illustrated in Figures 5 and 6, where the results of comparable crack patterns are shown for glass and wood bases respectively. It is clear that glass base produces smaller cell sizes in comparison to wood base. Generally, this effect is clearly evident as shown graphically in Figure 7. The mean cell area (A) is given by the total cell area divided by the number of cells when the soil was dry. It can be inferred from the adhesion tests undertaken separately by Corte and Higashi (1960) that the peak adhesion at the soil-base interface is approximately 40 kPa and 11 kPa respectively for glass and wood bases. The adhesion at the interface is, however, strongly dependant on the soil moisture content, where the value of adhesion rises gradually to a peak value as the water content decreases from the initial water content, and then decreases rapidly as the soil dries out further. The influence of shear characteristics of the base was further highlighted by a comparable test conducted on a sand base where no cracking was observed, owing to the lower shear restraint exerted on the soil by the base.

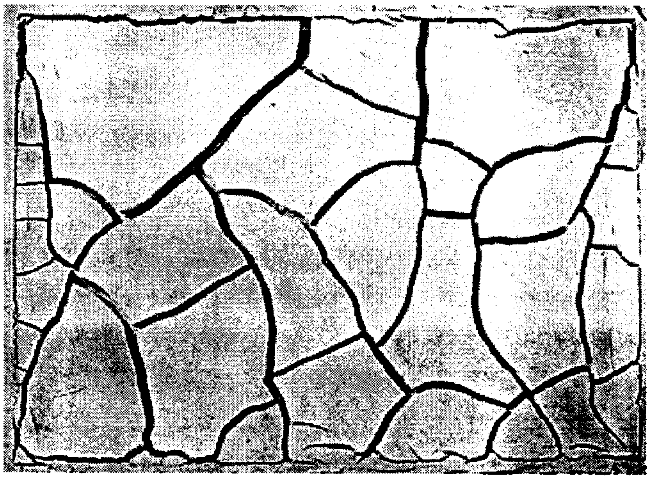

Figure 3. Experiment 7 of Corte and Higashi (1960) when the soil is dry (test details: soil slurry, soil thickness=33.5 mm)

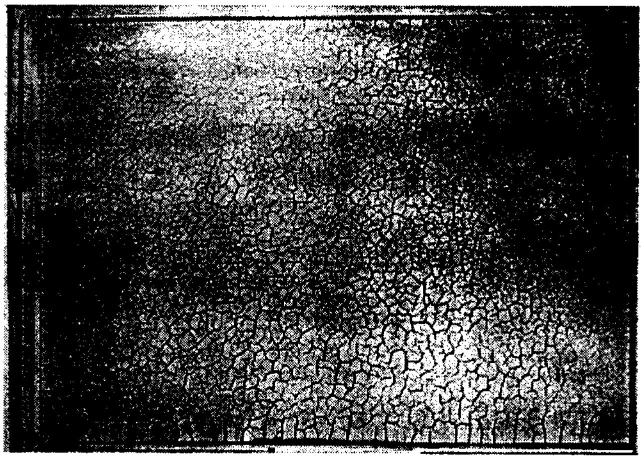

Figure 4. Experiment 1 of Corte and Higashi (1960) when the soil is dry (test details: soil slurry, soil thickness=3.4 mm)

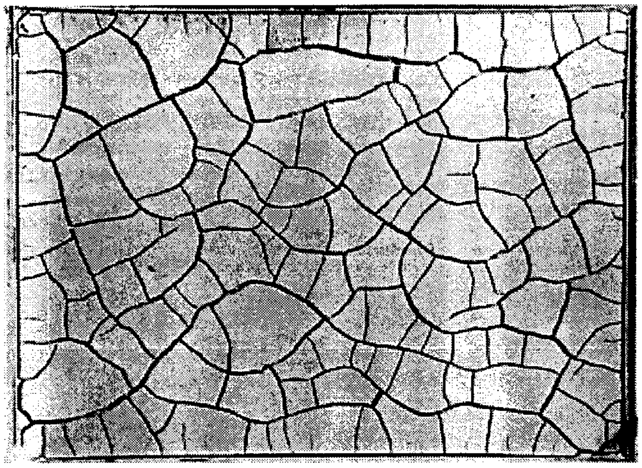

Figure 5. Final crack pattern of Exp 19 of Corte and Higashi (1960) (test details: soil slurry, soil thickness=15.0 mm, glass base)

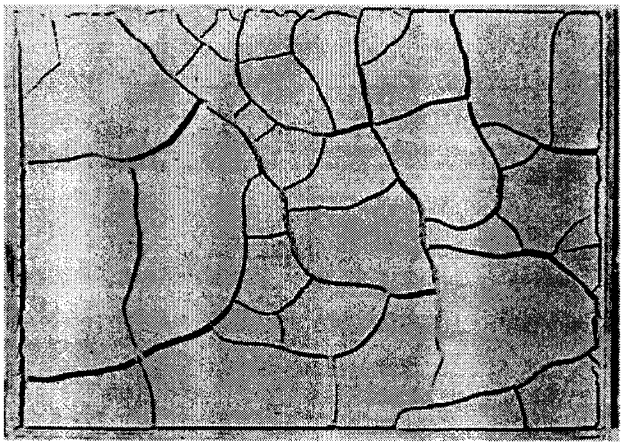

Figure 6. Final crack pattern of Exp 3 of Corte and Higashi (1960) (test details: soil slurry, soil thickness=14.7 mm, wood base)

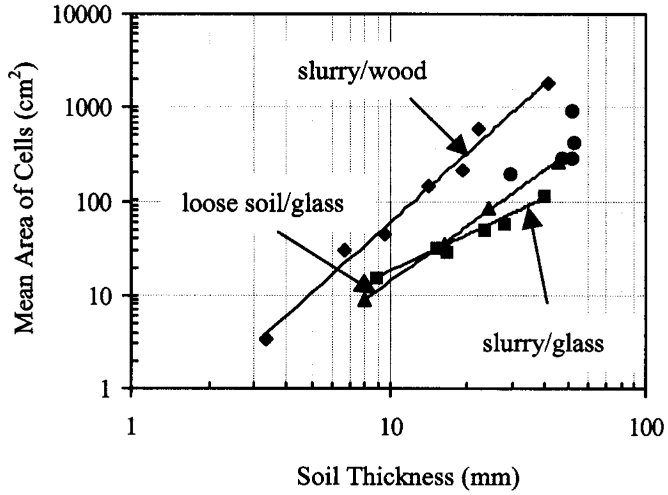

Figure 7. Relation between the mean cell area, $\overline{A}$, and thickness of the soil layer, d (Corte and Higashi, 1960 - ■, ▲, ◆ ; Lau, 1987 - ●)

4.4 *Analysis of cell sizes, cracking patterns and shapes*

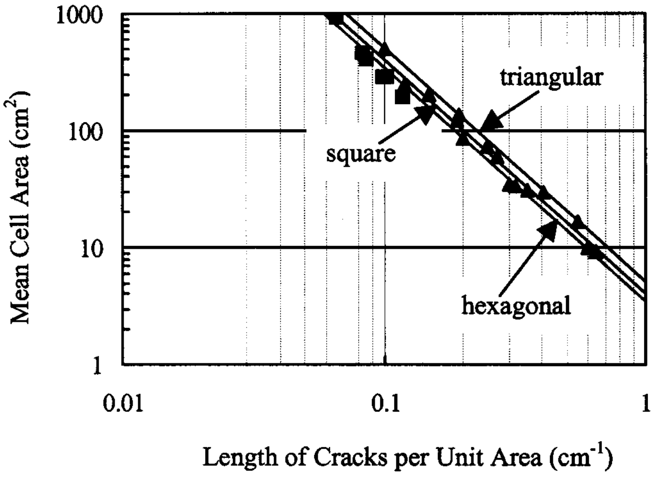

Figure 8. Relationship between the mean cell area, $\overline{A}$, and the length of the cracks per unit area, $\overline{L}$ (Corte and Higashi, 1960 - ▲; Lau, 1987 - ■)

As can be seen from Figure 7, the mean cell area, $\overline{A}$, increases as the layer thickness increases. The results also show that lower soil density or higher adhesion at the base tends to produce lower mean cell area for a given thickness. Total length of the cracks (L) seems to be inversely related to the layer thickness. Corte and Higashi (1960) have shown that cell areas generally follow a log-normal distribution. Interestingly, these relationships seem to be independent of the desiccation rate, despite apparent differences in the cracking patterns (i.e. development of orthogonal and non-orthogonal patterns).

As illustrated in Figure 1, theoretically plausible cracking patterns in idealised media undergoing uniform drying are considered as square, triangular and hexagonal patterns. Unique theoretical characteristics of these patterns can be established by considering the relationship between mean cell area ($\overline{A}$) and the specific crack length ($\overline{L}$), which is defined as the total crack length divided by the total plan area of the soil. These relationships for square, triangular and hexagonal shapes (considering one cell) can be respectively expressed as:

$$\overline{A} = 4/(\overline{L})^2, \overline{A} = 5.19/(\overline{L})^2 \text{ and } \overline{\mathrm{A}} = 3.47/(\overline{L})^2 \qquad (1)$$

Figure 8 shows these relationships in graphical form, and they hold independent of the size of the cells. Also shown in this figure are the test results of Corte and Higashi (1960) and Lau (1987). An interesting feature of this presentation is that regardless of the differences in the test conditions, all the data tend to fall close to these lines. Specifically, the majority of the data fall close to the line representing square pattern. Virtually no data fall above the triangular line, and this line represents the upper bound for the relationship between $\bar{A}$ and $\bar{L}$. Some data seem to fall close and below the line representing hexagonal pattern. Theoretically, the hexagonal pattern should provide the lower bound for the relationship between $\bar{A}$ and $\bar{L}$.

In an actual cracking pattern, there are mixtures of patterns containing cells that feature a distribution of number of sides in a cell. As the number of sides in cells of a pattern increases, the points representing the relationship between $\bar{A}$ and $\bar{L}$ will shift from triangular line towards hexagonal line. For instance, if a pattern contains mostly cells having five sides, then that result would plot between the square and hexagonal lines. As can be seen from Figure 8, this explanation agrees with the experimental evidence, which indicated that the majority of the cells had four and five sides. It is, however, possible to get values slightly under the hexagonal lower bound relationship when the pattern contains cells having more than six sides or when the sides of cracks are curved. However, the experimental evidence indicates that the occurrence of cells containing more than six sides is not common.

5 DISCUSSION AND CONCLUSIONS

Essential points of the preceding presentation can be considered as: (i) The dependence of cracking water content on the desiccation rate; (2) Apparent uniqueness of the relationship between $\bar{A}$ and soil thickness d for a given soil condition and base material; (3) The dependence of the relationship between $\bar{A}$ and d on base material and soil density; (4) The development of different cracking patterns predominantly depending on desiccation rate and soil thickness; and (5) The variation of A according to a log-normal distribution.

As far as the first point is considered, Corte and Higashi (1960) were able to explain this behaviour on the basis that the probability of cracking may be proportional to the tensile stress generated in the soil at a particular water content and to the time duration soil experiences at this water content. This explanation results in increase in tensile stress at cracking (or decrease in cracking water content) with the increase of desiccation rate. Alternatively, this phenomenon may be explained by arguing that soil material properties (e.g. tensile strength) may be dependent on the desiccation rate.

The Points (2), (3), (4) and (5) highlight the mechanics of desiccation cracking. The authors believe that explanations to these experimental findings may be found by considering the balance of energy components, which include energy used by cracks during their propagation and the strain energy released due to cracking. It can be seen from Equation 1 that the hexagonal pattern provides the most efficient release of energy because it has the lowest crack length per unit cell volume (The cell volume can be approximated by $\bar{A}d$). This may be a reason why soil containing high strain energy tends to crack in hexagonal pattern when subjected to high desiccation rates. It seems, however, that it is difficult to generate a perfect hexagonal cracking pattern in the laboratory. This difficulty may be associated with the dependency of this cracking pattern on material anisotropy and inhomogeneity, stress non-uniformity and the boundary shape.

The current paper elucidates some important aspects of the desiccation cracking process, specifically related to the desiccation of thin sol layers. Nevertheless, significantly more research is need to further the understanding. In future, consistent explanations and quantitative relationships for these experimental findings need to be searched.

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