Investigation of desiccation cracking using automated digital photography

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Abstract

Desiccation cracking can be heavily detrimental on the performance of clay soils in various engineering applications. Typical engineering applications include compacted clay barriers in waste containment, dam cores, canal liners and road pavements. The evolution of desiccation cracks has not been clearly understood and explained. A series of laboratory tests were conducted using Merri-Creek clay and potato starch. The evolution of cracks was captured by automated digital photography and presented in a time-lapse video format similar to the phenomenon of a blooming flower. To the authors' knowledge, this is the first time such a video has been produced. Both simultaneous and sequential types of cracking are investigated. The relationship between desiccation rate, average cell area, thickness of the specimen and etc are examined and discussed.

1. INTRODUCTION

Clay soils undergo shrinkage cracking during desiccation. Cracks can be a major unwanted feature in number of geoengineering applications as well as in some other disciplines. For instance, in geoengineering shrinkage cracking is significant in earth embankments, slopes, foundations and roads. In agricultural engineering, cracks can stimulate the water and solute flow through soil in irrigated land. Geosynthetic clay liners are used for lining and covering waste landfills in geo-environmental engineering. Shrinkage cracks can highly compromise the primary function of these clay liners by promoting water and leachate migration. Mining industry also face difficulties with cracking where the clay slurries undergo desiccation cracks increasing the hydraulic conductivity. A substantial amount of research work has been conducted in materials engineering on this issue to study the glazing and thermal fracturing in ceramics (e.g. Chiu & Cima, 1993) and printing, painting & washing (e.g. Deegan et al., 1997).

Despite the significance of cracking on these applications, the essential understanding about the soil shrinkage crack evolution and propagation is still at an immature stage. A majority of previous research has been qualitative and behavioural (Corte & Higashi, 1960; Muller, 1998; Kodikara et al., 2000). Many researchers have work on the final state of the cracking process (Morris et al, 1991; Konrad & Ayad, 1997; Kodikara et al, 2000). Nahlawi and Kodikara (2006) presented results of cracking tests, where they measured the on-set of first crack, cracking water content and subsequent crack evolution. A similar study was undertaken by Lakshmikantha et al (2006). In contrast, using the time-lapse video technology, we were able to capture the complete process of shrinkage cracking in laboratory test specimens. Results are presented in image format as well as in video clips. These videos will the uploaded to a web link in near future.

2. LABORATORY CRACKING TESTS

Merri-Creek clay and Potato starch were used in the experiments. Merri-creek clay is found in the northeast side of Melbourne. This very heavy and sticky grey to black clay soil has been used by other researchers (Chan et al., 2007) and its basic properties are given in Table 1. Potato starch was bought from supermarket, and was used to examine the shrinkage crack development in a material significantly different to soil. Muller (1998) attempted to simulate basaltic columnar crack formation using potato starch.

Table 1: Properties of Merri-Creek clay

Property	Value
Liquid Limit	74%
Plastic Limit	33%
Plasticity Index	41%
Linear Shrinkage	13%
Colour	Grey/Black

The Merri-Creek clay used for the tests was processed for commercial use and contained a considerable amount of plant roots. This clay is commonly used for construction of cricket pitches in Melbourne including the Melbourne Cricket Ground.

2.1 Potato starch.

The first series of tests were performed with potato starch. Circular glass containers of 140mm diameter were used to make the specimens. Starch and water were measured to an accuracy of 0.01g and mixed at a ratio of 3:2 by weight. After thorough mixing, specimen was tapped in order to release the trapped air. Then the glass container was placed on an electronic balance which was connected to a computer. This system automatically measured and stored the weight of the specimen at every 30 minutes.

Specimens were dried using flood lamps each of 500W. Four lamps were placed above, surrounding the specimen at a distance of 50 cm. A digital camera, which was operated by a computer, was positioned directly above the specimen. The camera took photos at every 5min interval and the data were automatically saved in the computer.

Three specimens with thickness 10mm, 20mm & 30mm were tested. Drying process was normally run for 24 hours. Although the tests were not performed in a temperature or humidity controlled environment, both surrounding temperature and relative humidity was reasonably constant at 50^{0}C and 20% respectively due to the constant heat emitted by lamps.

2.2 Merri-Creek clay

Second series of tests were conducted with Merri-Creek clay. The unprocessed clay samples were lightly crushed using a rubber hammer and sieved through a 1.45mm sieve. The plant roots were removed as mush as possible for the soil samples. The initial moisture content of soil was determined using the oven dry method.

The material that passed through 1.45mm sieve was mixed with water to its liquid limit (74%), and stirred well until it attained a visibly homogeneous state. An air vibrator was used while preparing the specimen in order to remove entrapped air. The prepared clay mixture was placed in a plastic tray, which was then placed into two polythene bags and was sealed for moisture leakage. The tray was kept in a cool, damp place for 48 to 72 hours allowing the clay paste to gain adequate moisture homogenization. The experimental set-up was exactly the same as for the potato starch experiments. However, the tests were conducted at varying lamp distances (35, 50 & 75 cm) as well as with varying specimen thicknesses (5, 10 & 20 mm). Photos were taken at every 30 sec. interval.

3. RESULTS

It is interesting to notice that all three potato starch specimens produced predominantly simultaneous, non-orthogonal crack patterns (Figure 1), whereas all the clay specimens underwent sequential, predominantly orthogonal crack patterns (Figures 2 to 4) . Starch test series is useful in studying the evolution of non-orthogonal crack patterns. The surface of the 30mm thick specimen got burned and a very thin crust was formed obstructing the visibility of cracks.

Figure 1: Crack pattern on potato starch for various specimen thicknesses (lamp distance = 50cm)

Using potato starch, we were able to reproduce the crack patterns previously presented by Muller (1998) and Toramaru and Matsumoto (2004), who simulated the formation of columnar joints similar to cooling of lava. Figure 1 shows that there is no significant difference in crack patterns and spacing with the change in the specimen thickness. All three specimens cracked to their full depth at the first instance, as was observed from the base of the container.

Figure 2: Crack pattern for 5, 10 & 20 mm thick specimens (left to right) at 35cm lamp distance

Figure 3: Crack pattern for 5, 10 & 20 mm thick specimens (left to right) at 50cm lamp distance

Figure 4: Crack pattern for 5, 10 & 20 mm thick specimens (left to right) at 75cm lamp distance

For clay cracking as evident from Figures 2, 3 and 4, the number of cracked cells and the average cell area are dependent on the specimen thickness and the lamp distance (or the desiccation rate). As the thickness of the specimen increases, number of cracked cells decreases, in turn increasing the average cell area for a certain desiccation rate. An increased desiccation rate (or decreased lamp distance) will result an increase of number of cracked cells and a decrease in the average cell area. An exceptional situation can be seen in 5mm thick specimen at 35cm lamp distance where the average cell area is larger than that for 10 mm thickness. Some statistical features of cracked specimens are given in Table 2. The desiccation rates for each test condition were computed on the basis of the automatic weight measurements during drying.

Table 2: Statistical features of clay specimens

Lamp Distance /(cm)	Thickness of the specimen / (mm)	Desiccation rate /(g/hr.cm^2)	Average cell area /(mm^2)
35	5	0.1939	224
	10	0.0884	217
	20	0.0574	296
50	5	0.1196	113
	10	0.0420	326
	20	0.0252	481
75	5	0.0677	134
	10	0.0298	294
	20	0.0220	362

4. DISCUSSION

It is interesting to examine why potato starch produced simultaneous non-orthogonal (close to hexagonal pattern) cracks, while clay produced predominantly orthogonal cracks which formed generally by sequential subdivision. The major reason for this behaviour appears to be related to the fracture energy of the material and the associated strain energy build-up during drying (Kodikara et al., 2007). During desiccation, the strain energy builds up in the soil due to restraining against potential shrinkage strain. The material attempts to dissipate this energy by formation of cracks. Kodikara et al. (2000) evaluated the efficiency of energy dissipation in crack formation by different crack patterns, and highlighted that the hexagonal crack patterns are the most efficient energy dissipater. Thus if a material has a particularly low fracture energy and is associated with significant build-up of strain at the point of cracking, it tends to initiate cracking all over the surface simultaneously. Fracture energy of potato starch falls in the range of 1 – 10 N/m (Charalambides et.al., 1995), whereas the fracture energy of clay can vary significantly (0.35 N/m - Ayad et al., 1997 to 110 N/m - Lee, et al., 1988). Kodikara et al. (2007) highlighted that it is the ratio of fracture energy to strain energy build-up that governs the transition from non-orthogonal to orthogonal crack evolution, which they captured by the ratio $(K_{Ic}/\sigma_t)^2$, where K_{Ic} is the fracture toughness of the material, and σ_t is the rupture stress or tensile strength at the point of cracking. According to fracture mechanics principles, this ratio is a function of the characteristic flaw size in the material. As the particle size increases (as in potato starch), the characteristic flaw size increases. However, detailed data are not available to compare these values for the two materials.

The average cell area of the final crack pattern was dependent on the desiccation rate and the thickness of the specimen. The higher the desiccation rate is, the lower is the average cell area. At higher desiccation rate, more cracks are needed to release the rapid increase of stress in the specimen, subsequently reducing the crack spacing and the size of the cells. With a low desiccation rate, the specimen has enough time to release the stress increment with a few slowly opening cracks.

The decrease of the average cell area with reducing specimen thickness has been presented by several previous researchers (Nahlawi & Kodikara, 2006; Lakshmikantha, 2006). The exceptional behaviour (mentioned in the previous section) of 5mm thick specimen at 35cm lamp distance is being further investigated using thinner specimens. Kodikara et al (2007) theorized that the spacing between cracks decreases when the specimen thickness decreases up to a certain critical thickness, below which the spacing between cracks becomes larger, increasing the area of the cells. It may be possible that this behaviour is relevant for interpreting the current experimental results.

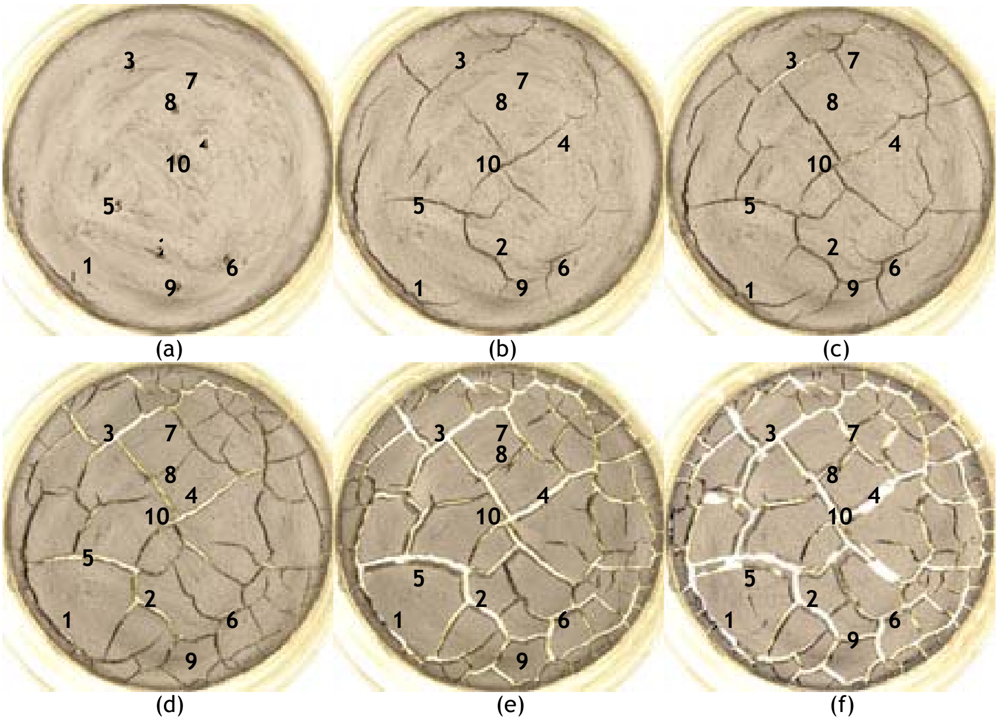

Figure 5 : Evolution and propagation of shrinkage cracks in 5mm thick clay specimen at 75cm lamp distance

The evolution and propagation of shrinkage cracks cannot be categorized as pure orthogonal or pure non-orthogonal patterns. The final state of the crack pattern is generally a mixture of orthogonal, non-orthogonal, simultaneous and sequential cracks. All the clay specimens contain mainly orthogonal, sequential cracks where subdivision was the dominant feature in propagation.

Figure 5 highlights some of the main features of cracking process. Onset of cracking is dependent on fracture energy of the material and flaw distribution as well. As theorized by Kodikara and Choi (2006), the maximum stress is likely to occur at the middle of a layer or cracked cell, if cracks have already formed, otherwise predominantly uniform stress conditions might prevail, as applicable to initial cracking. However, the exact location of crack formation will depend on whether a flaw can be propagated with the corresponding stress level. The initial cracking is mainly associated with edge cracking, where the material can be weakly attached to the container. However, it is possible for several cracks to initiate simultaneously because the stress conditions are relatively uniform at the beginning. Thereafter, cracks can occur somewhere in the vicinity of the centre of a layer or cracked cell. Numbers 1, 2, & 3 in Figure 5(a) refers to the onset of first three cracks respectively. Once a crack is open, it tends to spread in both directions until it intersects another crack or the boundary. It is hardly seen two cracks meet at an angle of 180^0 to form one crack. This can be identified by following the crack no. 1, 2, 3, 4 & 5 in Figure 5 (a) to (f).

Crack no. 7 & 8 in Figures 5 (c) & (d) are examples for subdivision. Instead of subdivision, only rarely cracks bifurcate to form new cracks. A similar situation is shown in Figure 5 by number 9. There are only very few cracks which start from one point simultaneously and propagate in three directions making approximately 120^0 angles among them. Crack no. 6 in Figures 5 (b) to (f) is an example for such a formation. Most of the cracks in clay specimens intersected apparently orthogonally. This is very common when cracks propagate in subdivision, as a requirement of the prevailing stress regimes influenced by formed cracks. An example is shown in Figures 5 (b) to (f) by crack no.10.

5. CONCLUSION

This paper presents the results of laboratory cracking tests undertaken on reactive clay and potato starch. Sequential orthogonal and simultaneous non-orthogonal crack patterns were captured and studied through image and video analysis. Fracture energy of the material and also the flaw distribution govern the crack evolution. The spacing between cracks or the average cell area is controlled by the desiccation rate and specimen thickness. In line in with previous observations on desiccation cracking, clay specimens cracked mainly orthogonally by sequential subdivision after the initial crack initiation, which was associated with some simultaneous cracking, influenced by flaw and tensile stress distributions. In contrast, potato starch showed predominantly non-orthogonal simultaneous cracking, associated with close to hexagonal formations.

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References

Ayad, R., Konrad, J-M. and Soulie, M.(1997). *Desiccation of a sensitive clay: application of the model CRACK*, Canadian Geotechnical Journal, 34:943-951.
Charalambides, M.N., Williams, J.G., Chakrabarti, S.(1995). *A study of the influence of ageing on the mechanical properties of Cheddar cheese*, J. Material Science, 30, 3959-3967.
Chiu, R.C. and Cima, M.J. (1993), *Drying of granular ceremic films: II, Drying stress and saturation uniformity*, J. American Ceremic Society, 76(11), 2679-2777.
Corte, A. and Higashi, A. (1960). *Experimental research on desiccation crack in soil*, U.S. Army Snow Ice and PermafrostResearch Establishment, Research report No.66, Corps of Engineers, U.S.A.
Deegan, R.D., Bakajin, O.,Dupont, T.F., Huber, G., Negal, S.R. and Witten, T.A.(1997), *Capillary flow the cause of ring stains from dried liquid drops*, Nature, 389, 827-829
Chan, D., Kodikara, J.K., Ranjith, P.G. and Choi, X. (2007). *Data analysis and laboratory investigation of the behaviour of pipes buried in reactive clay*, 10th Australia-New Zealand Conference on Geomechanics, Brisbane, Australia (this proceedings).
Kodikara, J.K., Barbour, S.L. and Fredlund, D. G.(2007), *Theoretical analysis of desiccation cracking of a long soil layer, under review*.
Kodikara, J.K. and Choi, X. (2006). *A simplified analytical model for desiccation cracking of clay layers in laboratory tests*, Proceedings of UNSAT2006 Conference, Edited by G. A. Miller, C.E. Zapata, S.L. Houston and D.G. Fredlund, ASCE Geotechnical Special Publication, Unsaturated Soils Vol. 2, pp. 2558-2567.
Kodikara, J.K., Barbour, S.L., and Fredlund, D.G. (2000).*Desiccation cracking of soil layers*, Proceedings of Asian Conference on Unsaturated Soils: From Theory to Practice, A. A. Balkema, pp. 693-698.
Konrad,J-M. and Ayad, R. (1997b). *Desiccation of a sensitive clay: field experimental observations*, Canadian Geotechnical Journal, 34, 929-942.
Lakshmikantha, M.R., Prat, P.C. and Ladesma,A.(2006). *An experimental study of cracking mechanisms in drying soils*, Proceedings of 5th International Conference on Environmental Geotechnics, Thomas Telford, London.
Lee, S.L., Lo, K.W. and Lee, F.H.(1982). *A Numerical model for crack propagation in soils*, Proceedings of the International Conference on Finite Element Methods,Shanghai, China, pp.412-418
Morris, P.H., Graham, J.and Williams, D. J.(1992). *Cracking in drying soils*, Canadian Geotechnical Journal, 29, 263-277.
Muller, G. (1998). *Experimental simulation of basalt columns*, J.Volcanology and Geothermal Research 86, 93-96.
Nahlawi, H., and Kodikara, J.K. (2006). *Laboratory experiments on desiccation cracking of thin soil layers*, Journal of Geotechnical and Geological Engineering, GEGE2281, Springer Netherlands, Vol. 24, No. 6, pp. 1641-1664.
Toramaru, A. and Matsumoto, T. (2004), *Columnar joint morphology and cooling rate: A starch-water mixture experiment*, J. Geophysical Research, 109, B02205, doi:10.1029/2003JB002686.