# INTERNATIONAL SOCIETY FOR SOIL MECHANICS AND GEOTECHNICAL ENGINEERING

*The paper was published in the proceedings of the 20th International Conference on Soil Mechanics and Geotechnical Engineering and was edited by Mizanur Rahman and Mark Jaksa. The conference was held from May 1st to May 5th 2022 in Sydney, Australia.*

*Proceedings of the 20th International Conference on Soil Mechanics and Geotechnical Engineering– Rahman and Jaksa (Eds)*
*© 2022 Australian Geomechanics Society, Sydney, Australia, ISBN 978-0-9946261-4-1*

# Research on autogenous healing of cracks in clay

## Recherche sur la cicatrisation autogène des fissures dans l'argile

**Abbas El-Zein,** David Airey, Yifei Gao, Shunzhi Chen, Yixiang Gan & Daniel Dias-Da-Costa
*School of Civil Engineering, University of Sydney, NSW, Australia, abbas.elzein@sydney.edu.au*

Bowei Yu
*Alliance Geotechnical and Environmental Solutions, Seven Hills, NSW, Australia*

Gwénaëlle Proust
*School of Civil Engineering, University of Sydney, NSW, Australia*
*Sydney Manufacturing Hub, University of Sydney, NSW, Australia*

ABSTRACT: Cracking and healing of clay are widely encountered in geotechnical and geoenvironmental engineering projects and are known to have a strong influence on the hydraulic, mechanical, chemical, and thermal behavior of soil. They can be triggered by human intervention (e.g., fracking), or caused by short-term, weather-related factors (e.g., rainfall and wet-dry cycles), as well as long-term changes in climate and soil physico-chemical conditions (e.g., drought). While cracking has received significant attention in the literature, healing of clay remains under-researched and under-theorized. The paper reports the experience of the research group at the University of Sydney in studying the healing capacity of montmorillonite and kaolinite clay, both unamended and polymer modified. Results from X-ray micro-CT scans, Scanning Electron Microscopy, flexible membrane permeameters, and Brazilian tests for tensile strength are presented. Implications of our findings for the incorporation of healing in theoretical accounts of soil behavior are discussed and future research directions suggested.

KEYWORDS: self-repair, self-healing, clay, montmorillonite, desiccation, clay liners

## 1 INTRODUCTION

The capacity of clay to self-repair its cracks has been in evidence for a long time. The ability to control and leverage self-repair of cracks in clay is a highly promising pursuit with significant social, economic and environmental stakes. For example, fissures are an important factor in many slope and road surface failures, with the former estimated to cause more than US$20 billion in yearly costs worldwide (Bo et al., 2008; Klose et al., 2014). In the USA, damage to buildings and infrastructure, part of which is caused by cracks from shrink-swell subsidence, incurs billions of dollars in cost annually (Jones and Jefferson, 2012). Shale gas extraction is financially and environmentally costly since high pressures need to be maintained to counter the tendency of fractures to self-heal. For example, a single-fracture, horizontal well for shale gas requires up to 30,000 m$^3$ of water and thousands of gallons of chemicals (The Climate Principles, 2013).

Despite its importance, clay self-repair remains vastly under-researched and under-theorized – a gap that constitutes an impediment to the potential for developing self-repairing soil systems. Most studies of clay self-repair have inferred its existence from measurements of hydraulic conductivity, usually without direct observation of crack closure (Eigenbrod, 2003; Shi and Booth, 2005). While these studies can indicate ‘sealing’ of the cracks, this may not be the same as ‘healing’, which usually implies the complete regaining of strength and a loss of memory of the cracks (Bastiaens et al, 2007).

Major breakthroughs in inducing self-repair in cementitious material, paints, coatings and ceramics have been achieved over the last few years, using polymeric hydrogels, fibres, fly ash, biological agents or a combination of these (Snoeck et al. 2014; Mignon et al. 2017; Hong et al., 2020). Soil bio-cementation, in which by-products of microbial digestion have a cementing and pore-clogging effect, is a form of self-healing that has recently received considerable attention. Though most bio-cementation studies focus on sand, some have considered clay too (Ivanov et al., 2015; Cardoso et al., 2018).

Broadly speaking, research on clay healing addresses two related but distinct questions: a) what drives healing, at what pace it does occur, and which variables are most influential? and b) which soil properties are recovered due to closure of crack, under which conditions does recovery take place and how stable is it?

This paper aims to provide a brief overview of current and recent research on autogenous healing of cracks in clay conducted at the University of Sydney. Specifically, we report results from three research projects:

a) X-Ray micro-computed tomography (micro-CT) and Scanning Electron Microscopy (SEM) investigations of the evolution in time of a crack in bentonite clay undergoing sealing,
b) crack sealing and recovery of hydraulic conductivity of thermally desiccated sodium bentonite in geosynthetic clay liners (GCLs), both unamended and polymer-modified, and
c) Brazilian tests for tensile strengths of sealed unamended and polymer-modified kaolinite clay.

Note that proceedings of this conference contain two other papers by our group tackling related topics, namely a new thermodynamically consistent formulation of soil behaviour incorporating damage and healing (Esgandani and El-Zein, 2022) and experiments on cracking resistance of bentonite-polymer mixtures (Taheri and El-Zein, 2022).

## 2 PROJECT 1: HEALING OF SINGLE CYLINDRICAL HOLE IN BENTONITE CLAY

### 2.1 Rationale

Most studies of self-healing in clay are conducted under wet-dry cycles. One advantage of this approach is that it reflects more closely hydraulic conditions on sites. However, it also suffers from two drawbacks. First, it is difficult to control initial conditions to the healing process because crack patterns emerging at the end of the dry cycle depend on local heterogeneities and no two tests will have the same pattern of cracks. Second, several cracks typically appear together, making it difficult to distinguish between processes pertaining to a single crack from those due to the interaction between adjacent cracks.

To address these issues, we conducted a set of experiments on an artificially created cylindrical hole, as a proxy for a crack, in a pre-consolidated sodium bentonite sample, then subjected it to hydration while observing the evolution in time of crack dimensions using X-Ray micro-CT. At the end of the experiments, SEM on specimens taken from the sample, both near and away from the original crack, were used to visualize microstructural changes caused by the healing process. The effects of initial consolidation pressure, sample confinement and chemistry of hydration water on crack sealing were assessed.

### *2.2 Materials and Methods*

The bentonite used in this study was sodium activated and supplied by Commercial Minerals Ltd. It is 73% clay and has liquid and plastic limits of 270% and 35%, free swelling index of 35 ml/2g, maximum dry density of 1.23 g/cm$^3$ and an optimum water content of 20.3%. Distilled water (DW) was mixed with oven-dried bentonite powder with an initial water content of 1.5 times the liquid limit. After evenly mixing in an electric blender, bentonite slurries were sealed for >24 hours to reach water-soil equilibrium. Slurries were then poured into oedometer cells sandwiched by porous stones and filter papers and compressed to different stress levels. The consolidation process followed ASTM D 2435 procedures. After consolidation, samples were cut into small cylinders (22-mm diameter, 12-mm height) and pushed into Perspex containers coated by a thin layer of Vaseline.

A vertical cylindrical hole, which crosses the extracted sample along its entire length, was created by pushing a 2mm-diameter rod through its center, as a proxy for a cylindrical crack. The penetration rate was not measured but the rod was pushed slowly, and as vertically as possible, to help generate a reasonably uniform crack. The diameter was chosen to be a fraction of the container's diameter but large enough to be initially visible to the naked eye. Immediately after, the sample was sealed by a layer of Parafilm to avoid evaporation losses and placed over a porous stone, in contact with a hydrating liquid in a wider container, with the liquid kept level with the top of the hole for faster hydration (see Fig. 1) – this point in time was referred to as t=0. The sample was then scanned using an X-ray micro-CT scanner (Skyscan 1172), at t=0, and this was repeated at various times for up to 6 days. The hydrating liquid was DW, NaCl or $CaCl_2$.

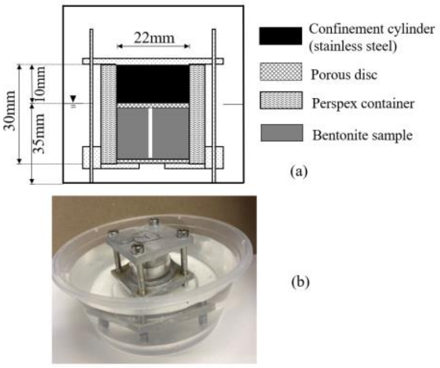


Fig. 1 Experimental setup for hydration experiment.

Changes in the 3D dimensions of the cylindrical hole were quantified through X-ray micro-CT scans. The temperature was controlled at 23 ± 2°C in the scanner chamber and at 20 ± 2°C in the sealed containers during hydration. The X-ray source generated radial beams of 100kV and 100µA. The image pixel size was 29.66µm. NRecon reconstruction software was used to acquire cross-sectional slices from the pictures (Darrow and Lieblappen, 2020). ImageJ was employed to quantify the surface area of the horizontal cross-sectional slices through image binarization, in which a global thresholding value was used to distinguish the boundary between soil matrix and air. Computed surface areas were aggregated by subdividing the height into 10 segments and calculating the average cross-sectional area of the area over each segment. An overall sealing effectiveness (OSE) for the entire sample was defined as the change in cross-sectional area, averaged over the sample height, relative to initial state.

### *2.3 Results and Discussion*

Fig. 2 shows X-ray images of the evolution of the crack during the sealing process. Fig. 3 shows size of horizontal cross-sectional surface area of crack at different heights of sample for different chemistry of hydration solution. After 68 hours, only the sample hydrated with DW has a fully closed hole. Generally, the higher the ionic concentration, the less hole closure occurs. The clay tested here is sodium bentonite, i.e., the cation prevalent in the interlayer space of the clay is sodium, and changes to the cationic composition of the clay, as a result of interaction with reservoir water, are known to affect its swelling potential. Increases in NaCl concentration of the reservoir solution reduce the concentration difference with clay pore-water, inhibit the osmotic flow of water and reduce the thickness of the diffuse-double layer and clay swelling. In addition, in the case of $CaCl_2$, cation exchange may further reduce osmotic swelling as a result of the prevalence of divalent cations in the interlayer space. These results were also reflected in OSE values (not shown here).

Fig. 3 shows the effect of pre-consolidation pressure of bentonite on the extent of sealing of the crack. The higher the prior consolidation pressure (higher density), the less sealing occurs (results are also reflected in the OSE values, though not reproduced here). This appears to be inconsistent with the literature where there is evidence of higher swelling with higher consolidation pressure (e.g., Dafalla, 2012; Huang *et al.*, 2019). However, this conclusion is usually based on 1D consolidation tests in which the swelling in question is almost always in the vertical, rather than the horizontal, direction, as is the case here.

Sample 3C t=0 Area=3.23mm$^2$

Sample 3C t=4 hrs Area=2.71mm$^2$

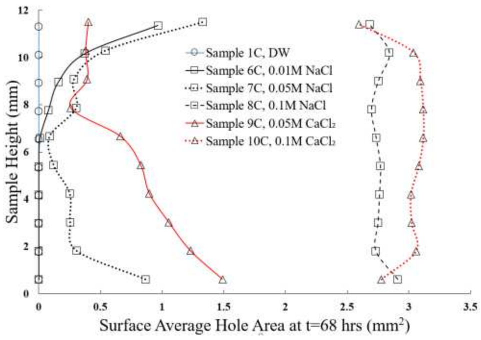
Sample 3C t=22 hrs Area=0.59mm$^2$

Sample 3C t=68 hrs Area= 0.15mm$^2$

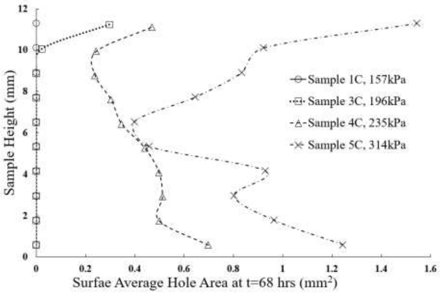
Fig. 2. Crack change at top of sample (157kPa pre-consolidation pressure, vertically confined sample, hydration by distilled water).

Different consolidation stresses can lead to different compressibilities/dilations and hence different swelling behavior are observed. Other contributing factors could be lower hydraulic conductivity with higher consolidation pressure and stiffness-dependent redistribution of stress near the interface between the intact soil and hole known as "arching" (Handy, 1987).

Fig. 4 shows two SEM images taken from the same sample, close to and away from the sealed crack, respectively. The figure reveals a looser microstructure, with more voids, close to the crack. Hence, it appears that the sealed area may have lower density compared to its initial pre-cracked state. This observation may provide a possible explanation for previously observed behaviour in which sealing of crack leads to only partial recovery of density-dependent material properties such as strength, stiffness and permeability.



a. Effects of chemistry of hydrating solution (157kPa)



b. Effects of pre-consolidation pressure (hydration by DW)

Fig. 3 Surface area of crack at different heights at t=68 hours (confined samples).

Overall, the project has demonstrated the feasibility of studying the healing of cracks under controlled initial conditions and has identified several influential parameters. Possible extensions of the work, some of which are underway, include studying several wet-dry cycles, multiple cracks, planar rather than cylindrical cracks and material other than bentonite. This line of research provides an experimental basis for building healing evolution functions for use in soil mechanics models incorporating healing.

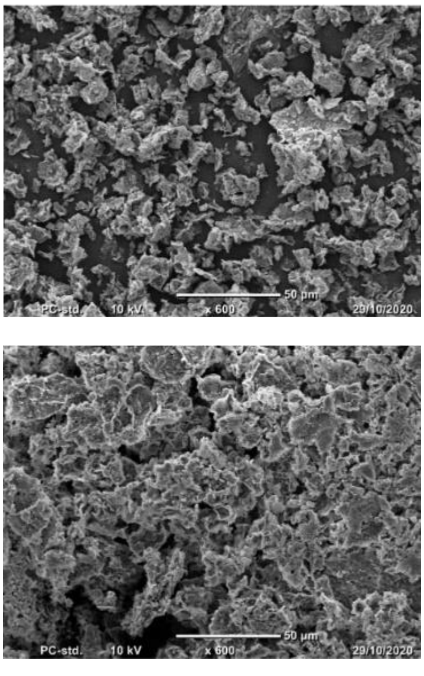


Fig. 4 SEM images showing soil microstructures in an area close to a self-sealed hole (top picture) and away from it (bottom picture).

## 3 PROJECT 2: HEALING OF DESICCATED BENTONITE AND BENTONITE-POLYMER MIXTURES

### *3.1 Rationale*

GCLs used in waste-containment systems are commonly exposed to fluctuating temperatures, either due to natural weather variability or because the waste itself is heat-generating (Ghavam-Nasiri *et al.*, 2020). Hence, bentonite clay in the GCLs can be exposed to cycles of thermal dehydration, followed by rehydration caused by leachate leakage (Ghavam-Nasiri and El-Zein, 2015). Under these conditions, the self-healing capacity of bentonite is relied upon to help recover its low hydraulic conductivities (Yu and El-Zein, 2019). On the other hand, polymer-amended bentonite (PAB) has been shown to maintain desirable properties in the presence of aggressive chemicals, such as high swelling potential and low hydraulic conductivity (Haase and Schanz, 2016; De Camillis *et al.*, 2017; Tian et al., Likos and Benson, 2019). Several manufacturers of Geosynthetics Clay Liners (GCLs) have therefore adopted PABs in their products. Macroscopic behaviour of PAB is largely a function of chemical interaction between polymer and bentonite, such as polymer chain conformation and its insertion in the bentonite inter-layer and/or inter-particle space (Kim et al., 2012). Different mixing methods may generate different types of chemical interactions and can lead to very different macroscopic behaviour.

Hence, despite significant research effort invested in PAB over the last two decades, major questions remain about the stability of gains under different site conditions and the effects of key variables such as type and dosage of polymer and mixing method. Unfortunately, the specific type of polymer used in a PAB often remains undisclosed in scientific publications, usually for reasons of commercial protection, which has hindered progress on the questions raised earlier.

One of the topics of interest to our group is the desiccation and self-healing behaviour of GCLs under thermal gradients and the ability of both amended (PAB) and unamended bentonite to recover from thermal desiccation. Our previous research had shown that bentonite in GCLs was at high risk of desiccation cracking, even under surface temperatures as low as 40°C. We are hence interested in two questions about the autogenous healing of bentonite upon rehydration, namely whether it is dependent on the applied temperature that drives desiccation and whether polymer-amendment has a measurable effect on it. The two questions have high relevance to practitioners managing heat-generating waste and are addressed in this project.

### *3.2 Materials and Methods*

A set of dehydration/rehydration experiments were conducted on needle punched, thermally treated GCLs (Na-bentonite sandwiched between two geotextiles) to assess the desiccation and healing behavior of the bentonite. The apparatus used in the tests was designed to replicate field conditions encountered by GCLs exposed to high temperature under low overburden stress (see Fig. 5). The instrumented column consisted of a loading frame with two temperature control cells to create a thermal gradient across depth (Ghavam-Nasiri *et al.*, 2020).
All tests were conducted in three stages:

i) the GCL specimen with as-arrived water content was first installed on top of a hydrostatic layer of well-graded sand and covered with a high-density polyethylene geomembrane, hence letting the GCL hydrate with moisture from the subsoil, under isothermal conditions (20±1°C) and 20kPa vertical pressure.

ii) The temperature control cell at the top was increased to, and maintained at, 43°C, 52°C or 78±1°C, while the bottom temperature was kept at 20±1°C, generating a temperature gradient across the column, under 20 kPa.

iii) At the end of heating (14 or 28 days), the GCL samples were taken out of the column and X-Rayed to visualize any desiccation cracks in the bentonite. Finally, the hydraulic conductivities to tap water and salt solutions of the dehydrated GCLs were measured, hence rehydrating them in the process, and allowing an assessment of the extent of bentonite healing.

Two sets of tests were conducted. In the first set, different samples from a GCL roll (powder bentonite) were exposed to different surface temperatures (43$^{o}$C, 52$^{o}$C, 78$^{o}$C) for 28 days and the effect on desiccation cracking and subsequent healing assessed. In the second set, two GCLs (A and B, fine granular bentonite) were subjected to the same surface temperature (78$^{o}$C) for 14 days. The only notable difference between the two GCLs A and B was that the granular Na-bentonite of GCL-B had been modified with a polyacrylamide polymer.

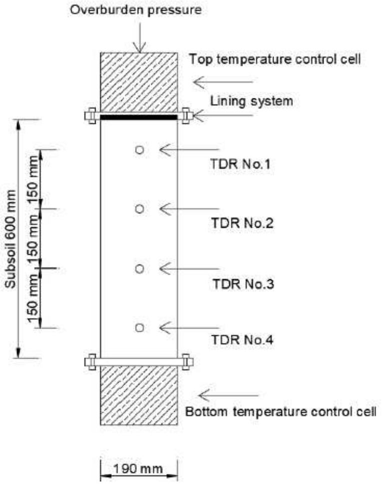
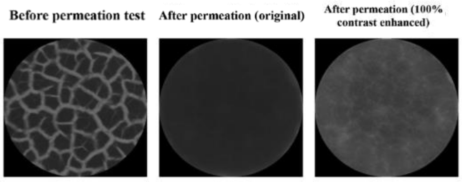


Fig. 5 Instrumented heating column.

### 3.3 Results and Discussion

We restrict our discussion here to the two questions raised at the end of section 3.1 and the healing focus of this paper, rather than the project as a whole. For a fuller discussion, the reader is referred to Yu & El-Zein (2019) and Yu, El-Zein & Rowe (2020). Fig. 6 shows X-Ray results of three samples of the same GCL that have been dehydrated, at different applied surface temperatures for 28 days (first set of tests in project 2). The left-hand side column appears to indicate a similar level of cracking, regardless of temperature exposure, at least within the studied range (43$^{o}$C-78$^{o}$C). This is confirmed by a quantitative analysis of cracking indicating a similar percent cracked surface area, as a percentage of the total area (31%-34%). On the other hand, the average crack width, prior to dehydration, of the 77$^{o}$C case was 28% higher to the 43$^{o}$C case. An examination of the right-hand side column reveals that, after rehydration, the cracks in. bentonite exposed to lower temperature have become more sealed with traces of the cracks more visible in case 1 (78$^{o}$C) compared to case 3 (43$^{o}$C). Hence, the final state of cracking, after self-healing, is dependent on the temperature of dehydration

Fig. 7 shows the hydraulic conductivity of the GCLs (unamended bentonite and PAB) after undergoing thermal desiccation (second set of tests in project 2). Results show that unamended bentonite undergoes significant self-healing and the GCL recovers most of its pre-desiccation hydraulic conductivity to both distilled water (not shown here) and 0.325M NaCl (Fig. 7a). Also, although not shown here, when the hydration liquid is distilled water, recovery of hydraulic conductivity occurs for GCL-B (PAB). What is remarkable, however, is that polymer amendment appears to *inhibit* autogenous healing when the rehydration water is 0.325M NaCl (Fig 7b). This highlights the need for a better understanding of the effects of polymer amendment on the behavior of clay under conditions other than those for which these amendments have been designed.



(a) Case 1

(b) Case 2

(c) Case 3

Fig. 6 X-Ray for 3 test cases with different applied temperatures: a) 77$^{o}$C, b) 52$^{o}$C, c) 43$^{o}$C (adopted from Yu and El-Zein, 2019).

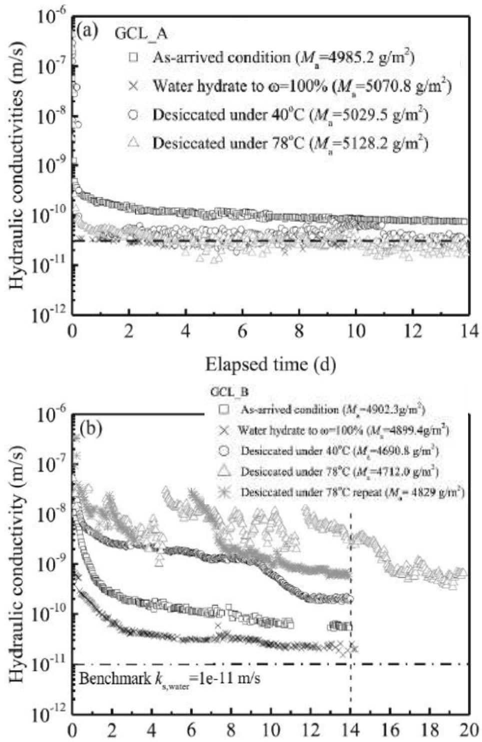


Fig. 7 Effect of polymer addition on self-healing of desiccated bentonite, rehydrated with 0.325M NaCl: hydraulic conductivity of unamended (top graph) and PAB (lower graph) bentonite (adopted from Yu, El-Zein and Rowe, 2020).

## 4 PROJECT 3: HEALING AND TENSILE STRENGTH OF KAOLINITE-POLYMER MIXTURES

### 4.1 Rationale

The tensile strength of clay is relevant to the initiation and propagation of clay cracking. To develop our understanding of cracking and healing we have used indirect tensile tests. The aims were first to establish the conditions that lead to cracking and then to distinguish between the effects of swelling, produced by saturation, and stress level on the healing of the cracks. We have been interested in separating out the effects of sealing indicated by the recovery of hydraulic resistance from the complete healing with loss of memory of the original crack. To further explore the potential to enhance the healing process, tests have also been performed on clay amended with a soluble polymer. Even though polymer solutions are now widely used for excavation-support fluids in geotechnical and geo-environmental engineering practice, the impacts of adding polymers to clays are not well understood and part of the study has been directed at addressing these uncertainties.

### *4.2 Materials and Methods*

The clay-polymer mixtures used in this study were prepared using kaolin Q38 and Poly(acrylamide-co-acrylic acid) partial sodium salt (PAS). The kaolinite clay Q38 used in this study was obtained from SIBELCO Australia in powder form and had properties, LL = 55, PL = 26, Gs = 2.6. The PAS used in this study, supplied by Sigma Aldrich, was a water-soluble synthetic organic polymer with high molecular weight of 520,000 g/mol. Its applications include stabilizing soil aggregates; reducing soil erosion; increasing water infiltration, and indirectly increasing crop growth and yield. It has very high-water retention capacity and its physical properties are not sensitive to pH, e.g., viscosity is unaffected by pH in the range from 3 to 10. Most importantly, PAS is resistant to microbial attack and has been shown to be non-toxic to humans, animals, fish, and plants; the only concern has been the toxicity of its residual monomer (acrylamide) content, which is a known neurotoxin to humans.

Samples of kaolin and kaolin mixed with 1% and 2% PAS by dry mass were prepared for Brazilian split cylinder tests to measure the tensile strength. Clay and polymer powders were mixed together thoroughly, adding distilled water to produce slurries with moisture contents of 1.5 times the respective LL. The mixtures were then poured into cylinders of inner diameter 38mm and vertical load increased in stages until reaching a consolidation stress of 200kPa. After consolidation was complete, the samples were extruded from the cylinder, cut into small discs (38mm in diameter, 12mm in thickness) and allowed to air dry at room temperature to reach a wide range of degrees of saturation. Indirect tensile tests were conducted according to the procedures in ASTM D3967, but using a reduced-scale apparatus, constructed for compatibility with smaller loads and specimen sizes (Akin and Likos, 2017). Specimens were loaded at a constant rate of displacement of 0.2mm/min, between a flat top plate and a curved bearing block to avoid local failure (Akin and Likos, 2017). The applied force and displacement were recorded at regular intervals. In addition, a speckled pattern was applied to the face of the specimen and photographs were taken at 5 second intervals and analyzed using DIC to obtain the horizontal and vertical strains at the centre of the specimens. This enabled the tensile stress-strain response to be plotted and the onset of cracking to be clearly established. The tensile stress ($\sigma_t$) was estimated, assuming elastic behaviour, from the applied compressive force (P), diameter (d) and thickness (t) of specimen:

$$\sigma_t = \frac{2P}{\pi d t} \quad (1)$$

Once the crack became visible, loading was stopped, and the specimens were removed from the loading frame. The specimens were then submerged in distilled water for rehydration for at least a week. The specimens were then put back into the 38 mm cylinder and vertical stresses of either 200kPa, 400kPa or 1MPa were applied. After consolidation was complete the specimens were extruded and air-dried as before until they reached the same degree of saturation as in the first tensile test. A second Brazilian test was then conducted by placing the specimen in the same orientation as the first test, to investigate the tensile strength recovery and the extent of healing.

### *4.2 Results and Discussion*

Results of the indirect tensile tests on initially intact specimens are shown in Fig. 8, demonstrating a significant ability of the polymer to increase tensile strength and resistance to cracking. The SWCC curve was not significantly affected by the polymer addition indicating the importance of clay-polymer interactions.

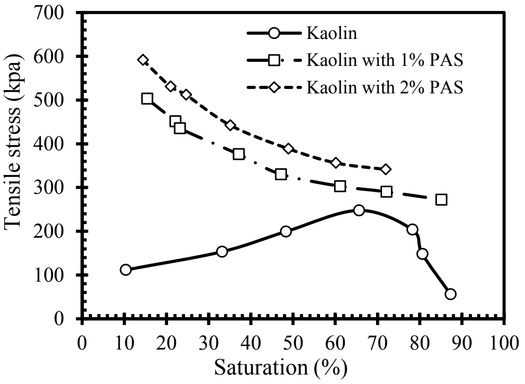


Fig. 8: Brazilian test results.

To show the effects of healing, discussion is limited to pure kaolin samples. Swelling was sufficient to recover the initial saturated hydraulic conductivity with low applied stress. However, as Fig. 9 shows considerable applied stress was needed to fully heal the specimens and recover the initial strength. All specimens in Fig. 9 were initially compressed with vertical stress of 200kPa, and air dried to about 45% degree of saturation. After submerging in distilled water for 1 week, specimens were consolidated to 200kPa, 400kPa, and 1MPa and then allowed to dry back to 45% degree of saturation. Similar effects of stress level were obtained for the polymer amended samples, however the amount of recovery at each stress level was greater with the added polymer.

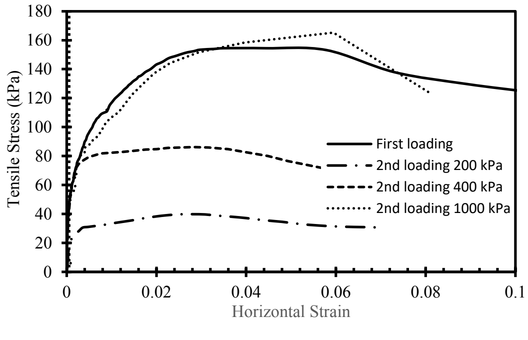


Fig. 9: Stress-strain responses before and after healing.

## 5 CONCLUSIONS AND FUTURE RESEARCH

The experimental results discussed in this paper emphasise the importance of direct observation of healing in real-time under controlled conditions and a better understanding of the healing behaviour of increasingly available polymer-clay mixtures.

More broadly, several knowledge gaps on clay self-healing are worth highlighting. First amongst them is perhaps the vast array of clay minerals and clayey soils that exist in nature and industry. Indeed, self-healing in different types of clay minerals, such as kaolinite versus smectite, may be driven by very different mechanisms (Eigenbrod, 2003). The swelling-clay fraction of a given soil has been shown to be an important variable determining the extent of cracking and healing (Omidi et al., 1996; Lin and Benson, 2000; Yesiller et al., 2000; Cripps and Parmar, 2015). However, our understanding of the cracking-healing behaviour of soil mixtures and reconstituted soils remains incomplete, especially the effects of the coarse-grained fractions and non-swelling clay.

Second, studies of clay healing are dominated by laboratory experiments on compacted soils and much less effort has been expended towards understanding *in-situ* opening and closure of cracks over both short and long-time scales (e.g., crack dynamics in response to diurnal and seasonal cycles, as well as long-term droughts). Experimental research programs associated with deeply buried nuclear waste repositories, have produced a significant body of literature, recording and interpreting cracking in high-density clay (e.g., Bastiaens et al., 2007; Blümling et al.; 2007; Zhang, 2011). However, there is a dearth of in-situ geotechnical studies, particularly given the widespread presence of cracking and self-healing in a range of geotechnical structures (e.g., slickensides) (e.g., Morris et al., 1992; Ahmadi et al., 2014).

Finally, models incorporating self-repair of clay must be able to predict the evolution of cracks, as well as the effects of cracking on the hydro-mechanical behaviour of clay, with the two endeavours ideally coupled in real-time. This can be achieved in principle through thermodynamically consistent models and/or heuristic healing evolution functions. Cohesive crack models have been shown in the past decade to allow better predictions of cracking in concrete and, more recently, in soil (e.g., compared to linear elastic fracture mechanics). Hence, they provide a possible avenue for developing numerical models that incorporate healing as well. A key obstacle to the development of such models is the lack of experimental data – both site and laboratory-based – specifically derived to validate healing evolution outcomes and research is needed in this space.

## 5 ACKNOWLEDGEMENTS

Research reported in this paper has been funded by an Australian Research Council Discovery Grant DP170104192. SEM and X-Ray micro-CT characterisation for the research has been carried out at the Australian Centre for Microscopy and Microanalysis of the University of Sydney, a node of Microscopy Australia.

## 6 REFERENCES

Ahmadi, M., Taleghani, A. D. and Sayers, C. M. (2014) 'Direction dependence of fracture compliance induced by slickensides', *Geophysics*, 79(4), pp. C91–C96.

Akin, I.D., and Likos, W.J., 2017, 'Brazilian Tensile Strength Testing of Compacted Clay,' *Geotechn. Testing J,* doi: 10.1520/ GTJ 20160180.

Bastiaens, W., Bernier, F. and Li, X. L. (2007) 'SELFRAC: Experiments & conclusions on fracturing, self-healing & self-sealing proc. in clays', *Phy. & Chem Earth* 32(8-14):600-615. 10.1016/j.pce.2006.04.026.

Blümling, P. *et al.* (2007) 'The excavation damaged zone in clay formations time-dep. beh. & infl. on performance assessment', *Phy. & Chem Earth*, 32(8-14):588-599. doi: 10.1016/j.pce.2006.04.034.

Bo, M. W., Fabius, M. and Fabius, K. (2008) 'Impact of global warming on stability of natural slopes', *Proceedings of the 4th Canadian Conference on Geoh.: From Causes to Management*, pp. 112–115.

De Camillis, M. *et al.* (2017) 'Effect of wet-dry cycles on polymer treated bentonite in seawater: swelling ability, hydr. cond. & crack analysis', *Applied Clay Science* 142:52–59. doi: 10.1016/j.clay.2016.11.011.

Cardoso, R. *et al.* (2018) 'Effects of clay's chemical interactions on biocem.' *App. Clay Sc.* 156:96-103. doi: 10.1016/j.clay.2018.01.035.

Cripps, J. and Parmar, K. (2015) 'Investigations into the Self-Healing of Desiccation Cracks in Compacted Clays', in *Eng Geology for Society and Territory - Volume 5* 1327-1331. doi:10.1007/978-3-319-09048-1.

Dafalla, M. A. (2012) 'The Influence of Placement Conditions on the Swelling of Variable Clays', *Geot & Geol Eng* 30(6):1311-1321.

Darrow, M. M. and Lieblappen, R. M. (2020) 'Visualizing cation treatment effects on frozen clay soils through μCT scanning', *Cold Regions Science and Technology*. Elsevier, 175(April), p. 103085.

Eigenbrod, K. D. (2003) 'Self-healing in fractured fine-grained soils', *Canadian Geotechnical J* 40(2), pp. 435–449. doi: 10.1139/t02-110.

Esgandani, G and El-Zein, A (2022) 'An elasto-plastic damage-healing model for unsaturated soils'. *20th Int Conf on Soil Mechanics and Geotechnical Eng*, Sydney, Australia.

Ghavam-Nasiri, A. *et al.* (2020) 'Thermal desiccation of geosynthetic clay liners under brine pond conditions', *Geosynthetics International*, 27(6), pp. 593–605. doi: 10.1680/jgein.20.00020.

Ghavam-Nasiri, A. and El-Zein, A. (2015) 'Effects of defects in geomembranes on reducing desiccation potential of geosynthetics clay liners', *Japanese Geot Soc Special Publication*, 2(70), pp. 2418–2422.

Haase, H. and Schanz, T. (2016) 'Compressibility and saturated hydraulic permeability of clay-polymer composites — experimental and theoretical analysis', *Applied Clay Science*. 130, pp. 62–75.

Handy, R. L. (1987) 'The arch in soil arching', *Journal of Geotechnical Engineering*, 113(3), pp. 269–271.

Hong, G., Song, C. and Choi, S. (2020) 'Autogenous healing of early-age cracks in cementitious materials by superabsorbent polymers', *Materials*, 13(3). doi: 10.3390/ma13030690.

Huang, C. *et al.* (2019) 'Factors Affecting the Swelling-Compression Characteristics of Clays in Yichang, China', *Advances in Civil Engineering*, 2019. doi: 10.1155/2019/6568208.

Ivanov, V. *et al.* (2015) 'Strengthening of Soft Marine Clay Using Bioencapsulation', *Marine Geores & Geotechnology*, 33(4):325–329.

Jones, L. D. and Jefferson, I. (2012) 'Expansive Soils', in *ICE Manuals*. Institution of Civil Engineers, UK.

Kim, S., Palomino, A. M. and Colina, C. M. (2012) 'Responsive polymer conformation and resulting permeability of clay-polymer nanocomposites', *Molecular Simulation*, 38(8–9), pp. 723–734.

Klose, M. *et al.* (2014) 'Estimation of direct landslide costs in industrialized countries : challenges , concepts , and case study', in *Landslides for a Safer Geoenvironment*, pp. 661–667.

Lin, B. L. and Benson, C. H. (2000) 'Effect of Wet-Dry Cycling on Swelling and Hydraulic Conductivity of GCLs', *Journal of Geotechnical and Geoenvironmental Engineering*, 126:40–49.

Mignon, A. *et al.* (2017) 'Mechanical and self-healing properties of cementitious materials with pH-responsive semi-synthetic superabsorbent polymers', *Materials and Structures/Materiaux et Constructions*. Springer Netherlands, 50(6), pp. 1–12.

Morris, P. H., Graham, J. and Williams, D. J. (1992) 'Cracking in drying soils', *Canadian Geotechnical Journal*, 29, pp. 263–277.

Omidi, G. H., Thomas, J. C. and Brown, K. W. (1996) 'Effect of desiccation cracking on the hydraulic conductivity of a compacted clay liner', *Water, Air, and Soil Pollution*, 89(1–2), pp. 91–103.

Shi, C. and Booth, R. (2005) 'Laboratory dev. & field demonstration of self-sealing/self-healing landfill liner.', *Waste Man*, 25(3), pp. 231–8.

Snoeck, D. *et al.* (2014) 'Self-healing cementitious materials by the combination of microfibres and superabsorbent polymers', *Journal of Intelligent Material Systems and Structures*, 25(1), pp. 13–24.

Taheri S. and El-Zein A. (2022). 'Desiccation cracking of polymer-bentonite mixtures: effects of polymer dosage and degree of substitution'. *20th Int Conf on Soil Mechanics and Geotechnical Eng*, Sydney, Australia.

The Climate Principles (2013) *Shale gas exploration and production Key issues and responsible business practices Guidance note for financiers*. http://iehn.org/documents/CPFIShaleGasGuidanceNoteApril2013.pdf.

Tian, K., Likos, W. J. and Benson, C. H. (2019) 'Polymer Elution and Hydraulic Conductivity of Bentonite-Polymer Composite Geosynthetic Clay Liners', *J Geot & Geoenv Eng,* 145(10), pp. 1–12.

Yesiller, N. *et al.* (2000) 'Desiccation and cracking behavior of three compacted landfill liner soils', *Eng Geol*, 57(1–2), pp. 105–121. doi:

Yu, B. and El-Zein, A. (2019) 'Experimental investigation of the effect of airgaps in preventing desiccation of bentonite in geosynthetic clay liners exposed to high temperatures', *Geot & Geomem* 47(2):142–153.

Yu, B., El-Zein, A. and Rowe, R. K. (2020) 'Effect of added polymer on the desiccation and healing of a geosynthetic clay liner subject to thermal gradients', *Geotextiles and Geomembranes*.

Zhang, C. L. (2011) 'Experimental evidence for self-sealing of fractures in claystone', *Phys. & Chem Earth*. 36(17–18), pp. 1972–1980.